Findings. The research proved the expediency of the effective controlled load consumer operation mode for mine dewatering plants. The formula for determination of equivalent resistance of piping system considering the reduction of inside diameter caused by the mineral sediments was improved. The dependence of the efficiency of pump on its operating parameters was specified with the purpose of its adjustment in case of the pumping unit technical state deterioration. The dependence of the increase of specific energy consumption for pumping on the change of technical state of piping system and pumping unit was obtained. The research proved that the most energy saving mode of pumping in a coal mine can be achieved by taking into consideration the operating parameters of equipment of the main dewatering plant during the energy modes adjustment.

Originality. The change of specific energy consumption for pumping is determined through the model dependences and is compared with the actual values. This allows selecting the energy efficient operating mode for pumps and piping system.

Practical value. It was proved that the developed method of selection of the pumping modes by minimum specific energy consumption, provided that the payment for the consumed energy is done according to minimum time-of-day electricity tariff, allows reducing power consumption and cutting expenses on the power consumed by pumping by 20–25%. It also allows us to control and detect timely the main dewatering plant equipment technical state deterioration.

Keywords: *main dewatering plant, controlled load consumer, regulation of power consumption modes, energy efficiency, coal mine, specific energy consumption, piping*

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LINEAR 3-PHASE TRANSVERSE FLUX MACHINE WITH FLUX CONCENTRATION

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ЛІНІЙНА 3-ФАЗНА МАШИНА З ПОПЕРЕЧНИМ МАГНІТНИМ ПОЛЕМ ТА З КОНЦЕНТРАЦІЄЮ ПОТОКУ

Purpose. To justify the research method for the transverse flux machines (TFM) through the application of the special 3D FEM simulation. To present a new concept of the linear transverse flux machine (LTFM) with flux concentration, which has high force and power density and allows mass production with commercially attractive components.

Methodology. Due to the complicated 3-dimensional field distribution in the LTFM, the calculation of this LTFM was carried out by the 3D FEM simulation of the electromagnetic process inside the machine. The 3D FEM simulation values were compared with the measured values.

Findings. A new concept of the linear transverse flux machine with flux concentration is presented**.** The electromechanical parameters of the linear transverse flux machine have been obtained. It has been confirmed that the 3D FEM simulation measures and the measured values of the linear transverse flux machine are in good agreement.

Originality. The present research method of the linear transverse flux machine through the 3D FEM simulation gives an opportunity to perform highly accurate and qualitative characterization of the electromechanical parameters of the linear transverse flux machines**,** as well as to analyze internal electromagnetic fields without the experimental research of the real electromagnetic processes inside the linear transverse flux machine**.**

Practical value. The developed linear transverse flux machine with flux concentration has high force and power density, and its structure allows mass production of electric machines of this type with commercially available components. The presented research method for linear transverse flux machines can be used for the design and optimization of a linear transverse flux machine. This research method reduces costs and time for the development of a linear transverse flux machine.

Keywords: *transverse flux machine, LTFM, flux concentration, 3D FEM simulation*

Statement of the problem. Since the 1980s, transverse flux machines (TFM) have been investigated due to their high force and power density conditioned by the special structure and functionality. In fact, these values can be tested on suitable laboratory samples which are difficult to construct because of the 3-dimensional field guide. In particular, the lack of a batch production concept for the TFM has led to the fact that this machine has found little practical application so far.

In the present research we shall represent and analyze the example of linear drives and the structure of a linear transverse flux machine (LTFM), which can be assembled with conventional and easily available standard components by means of manufacturing processes known in power engineering. The concept has a strong advantage of flux concentration, which leads to further increase in power density.

Foreword. There is no fundamental difference between rotatory and linear motion electric machines in their function and constructive design. Thus all equations can be applied to both cases: the assumptions for rotating field in rotating machines can be replaced by analogous assumptions for travelling field in linear motors and vice versa. The fundamental difference concerning linear motors consists in the fact that due to the limited length of the motor, the edge effects occur. If these effects are particularly short in length, they have a significant influence on the motor's characteristics. This effect does not exist in rotating machines because of their rotational symmetrical construction and the resulting periodicity.

The main research. Implementation of the linear transverse flux machine with flux concentration. It is shown in [1] that the achievable specific force density f_S is approximately proportional to the current I_1 and inversely proportional to the pole pitch τ_p for transverse flux machines with classic air gap magnet order. Since this concept requires no space competition between the current and field leading areas, very small pole pitches can be constructively realized, that then leads to the specific force or power density p_s.

Moreover, these expected values can be further increased by the application of the flux concentration as described below. The 1-sided LTFM with flux concentration under consideration is constructed in accordance with an earlier patent application [2].

The primary part consists of in total 14 (see fig. 1, *b*), 1, *c*)) linearly arranged pole pairs, while the secondary part is made of identical sections at a distance of 1mas shown in fig. 1, *d*. The LTFM having this structure is a prototype being analyzed in the present research.

The structure of the secondary part, which consists of 2 magnet rows, is particularly interesting. These magnet rows are shifted in z-direction by 1/3 of the pole pitch and tilted by 1 pole pitch (fig. 2). With this offset and correspondence to the specified skew, an approximately symmetrical three-phase field in the core regions of the 3 primary-sheet packs is reached. Since the magnets are as usual magnetized here in the direction of the small magnet height h_M, the flux in the subsequent electrical sheet packages is deflected by about 90 °, so that they form two north and south poles in alternating sequence on the left and right respectively. As the magnet width b_M is defined much bigger than the pole pitch, and flux densities reaching the saturation flux density of the magnetic steel sheets are significantly greater than the remanence of the magnets, they can be achieved by integration of the flux over the magnet widths (= flux concentration = flow compression) in the air gap.

Define: B_Z = flux density in the point of tooth; b_Z = width of the point of tooth in z-direction; B_M = flux density in magnets; b_M = width of the magnets; α = angle of skew of the secondary part.

The following approximation is valid for the achievable air-gap flux density in the tooth region

$$B_Z \approx \frac{1}{b_Z}\int_0^{b_M} B_M \, db_M \approx \frac{b_M}{b_Z}\cdot B_M \le \cos(\alpha)\cdot B_{\text{satur}},$$

which, as indicated, is only limited by the saturation flux density of the used magnetic steel sheets B_{satur}. Through this flux concentration, a significantly increased air gap flux density can be achieved in contrast to versions without flux concentration. The fact that makes this type of machine additionally impressive in terms of force and power is that the power density in electromagnetic energy converters is proportional to effective flux density.

However, the theoretically possible increase in the power density by decreasing pole separation is limited in reality because of increasing leakage effects. In fact, depen-ding on the chosen design, there is one optimal pole pitch with maximum power density. The optimal pole pitch in the concept introduced here is in the range of $\tau_p \approx 10$mm.To reduce the reactive power, as in the present case; the actual pole pitch is selected usually slightly larger than the theoretically optimum value. Due to the flat trend of the force density curve in the region of the optimum, the loss of power density is mostly irrelevant.

Our prototype in particular is designed for air cooling with the following values, for which the FEM simulations have been performed.

Primary part:

3UI 90– standard transformer sheets for magnetic core of the primary part;

M 530-50 A– quality of electrical sheets;

$h_{1P} = 11\ mm$ – height of the individual packages;

$N_1 = 200$ – number of concentrated windings turns;

14 – individual packages at a distance of 2 * pole pitch;

$\tau_p = 13\ mm$ – pole pitch.

Secondary part:

$b_M = 27\ mm$ – magnet width;

$l_M = 35\ mm$ – magnet length;

$h_M = 3.3\ mm$ – magnet height;

$H_{cB} = 890\,kA/m$ – magnetic field strength of NdFeB magnets;

$\mu_{rM} = 1.1$ – permeability of the magnets;

$l_{2ges} = 1\ m$ – length of the secondary part;

$\delta = 1\ mm$ – air gap length.

In addition, the collector packages have been made of conventional stamping parts according to fig. 2 in the electrical sheet quality M 530-50 A, and each one has been screwed as an individual package with the package height $h_{2P} = l_M$ on the aluminum support of the secondary part. The magnets are inserted into the formed clearances and fixed there with a cast polymer.

For the transverse flux machine with flux concentration under consideration, the specific tractive force can be estimated according to [1] from analogous considerations.

Thereby, the swept pole area at the middle strand is also counted only once for a better comparability with the data in [1]. With the amplitude $\hat{I}_1$ or the effective value I_1 of the applied current it can be found that

$$\hat{f}_s \approx \frac{\mu_0}{4}\cdot\frac{H_{cB}}{\frac{h_{1P}}{\mu_{rM} b_M}+\frac{\delta}{h_M}}\cdot\frac{N_1\hat{I}_1}{\tau_p} \sim \frac{I_1}{\tau_p} \quad \text{with} \quad \bar{f}_s = k\cdot\hat{f}_s\,,$$

where $k \approx 0.6 \ldots 0.8 < 1$ is the correction factor by which the average tractive force can be determined through its peak value and in the case of full load is expected to be specified in the known range. Due to the significant cogging torque of this type of machine, k is load dependent and tends to zero with decreasing average tractive force.

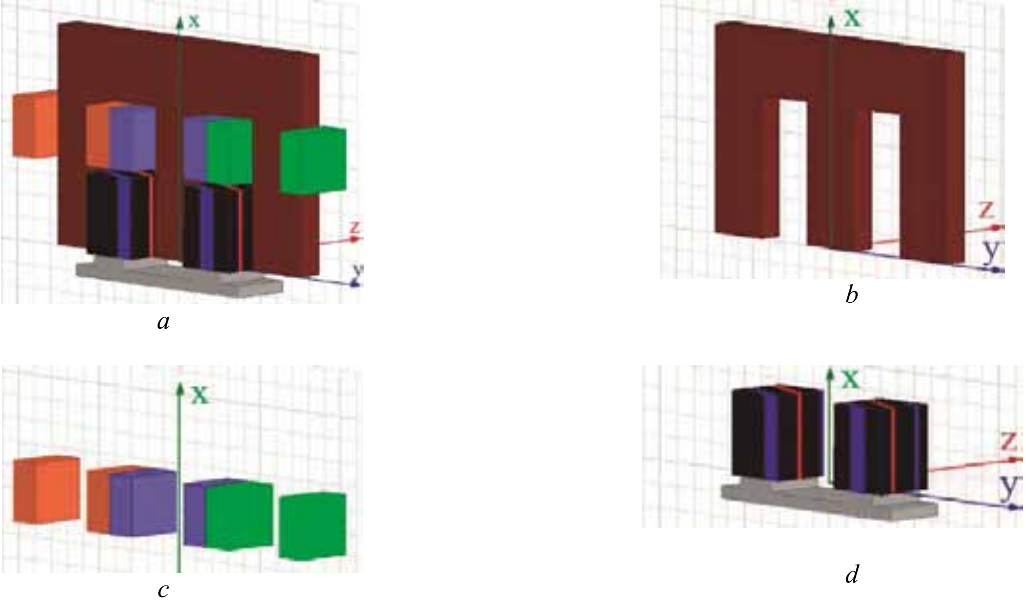

Fig.1. Basic structure of the one-sided LTFM in XYZ-coordinates: a – complete segment of motors; b – primary laminations of transformer standard sheets; c – three-phase winding, forward and return conductors; d – secondary part with gray aluminum support, black horizontally layered electrical sheets as a flux concentrator, blue / red permanent magnets with opposite polarity magnetization

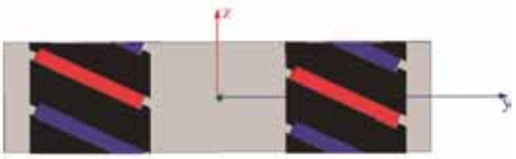

Fig.2. Secondary magnet assembly with flux concentration

Simulation as a linear generator. Through their spatial field structure, a 3D FEM simulation is essential in a TFM. Owing to the periodic arrangement of the 14 identical primary section pole packages in the z-direction and a secondary part, which is extended over the complete movable length, the simulation can be reduced to one section (fig.1, *a*). This saves a great amount of computing time. The calculated values have to be multiplied by the number of pole sections, in this case -14. Only the above mentioned minor edge effects at the package ends are neglected by this simplification in the simulation. It is profitably in such complex systems to start the simulation with a generative idle running. Due to the fact that in generative idle running except the specified rotational speed or the moving speed, no external influences are applied, any errors of the model can be found in most cases in the trend of the simulated induced voltage. This voltage, if a prototype is available, can be measured very easily and can be compared to the calculated values. If the model seems to be correct during this testing phase, the simulation of general load situations can be performed. Fig. 3 shows the induced voltage in the generative idle running with the predetermined velocity v_0 = 1.3 m/s, which corresponds to the operating frequency f = 50Hz of the LTFM. One recognizes, that the voltage values and the voltage waveforms are not fully symmetrical, which ultimately indicates a not fully symmetrical magnetic flux. This small asymmetry, in particular at the strand located in the center, is the result of non-identical magnetic resistances of all 3-legs-core concepts and is observed also in other three-phase designs, such as three-phase transformers. Thereby, the centrally located strand always appears magnetically slightly favored. Furthermore, the calculated effective voltage values are shown in fig.3, which can be easily compared with the corresponding measured values.

Simulation as a loaded linear motor. After this preliminary idling simulation, the actual simulation of the LTFM as a linear motor can be performed. For this purpose, three phase-shifted sinusoidal currents as a symmetrical three-phase system are applied in the three winding phases and the LTFM is loaded with a tractive force F. The currents are mainly chosen in a way that the simulation values are directly comparable to corresponding measurements on the prototype. The measurements on the prototype have been performed on a special test bench, so that when applying a constant DC I_{DC} in two of the serial windings of the primary part, the latter slowly can move over the fixed mounted secondary part and the required tractive force can be measured. As a result, the static force function of the way = pole position is obtained, from which then the important force values such as the peak force or the average tractive force can be deduced. The situation represented in this measurement corresponds to a three-phase current at points, when the current in the non-connected string is 0A.

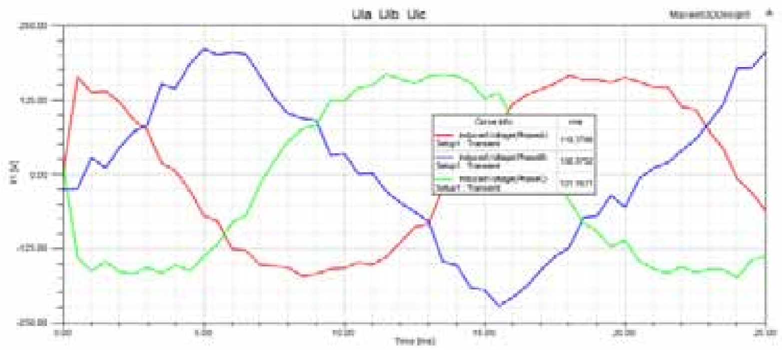

Fig.3. Simulated voltages of the idling with voltage RMS values: 1 – Induced Voltage in Phase A (U_{ia}); 2 – Induced Voltage in Phase B (U_{ib}); 3 – Induced Voltage in Phase C (U_{ic}); Y(axis): induced voltage, V; X(axis): time, ms

The accordingly applied three-phase current has an effective peak value of

$$\hat{I}_1 = \frac{2}{\sqrt{3}} \cdot I_{DC}$$

resp.

$$I_1 = \sqrt{\frac{2}{3}} \cdot I_{DC} \ .$$

The forces of LTFM can’t be measured in dynamic mode or in other three phase current configurations. Fig.4 exemplarily shows the transient simulated trend of the tractive force and the speed of the motor, suitable for the measurement with the constant input of DC $I_{DC} = 4A$, which corresponds to a peak value of $\hat{I}_1 = 4{,}619A$ at the three-phase system in the simulation. Accordingly, the respective maximum, average and minimum values of these variables are presented.

These values are also given in table 1 together with the corresponding values for the measurement with $I_{DC} = 2A$ and $I_{DC} = 6A$, as the comparison of the calculated values and the measured values shows the impact of tractive force.

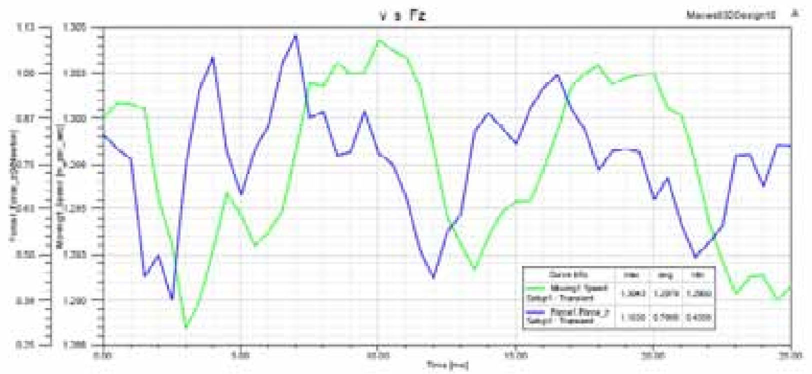

Fig.4. Simulated development of the tractive force and the motor speed for I_{DC}=4A; Y1(axis): F_z – force Z, kN; Y2(axis): v – speed, m/s; X(axis): time, ms

The speed of the motor fluctuates only slightly according to the transient analysis and remains practically constant, averaged over a period, indicating the steady state of the simulation.

Conclusion. The simulation and measured values are in good agreement within the usual tolerance limit for FEM calculations of +/- 10%. There are even some almost identical values regarding the peak force. There isn’t such a good agreement between the average tractive force, where the simulation amazingly tends to give smaller values. A possible reason for the rather unexpected situation could be the above described realization of the measurement. Due to the test bench, measurements have been performed statically with fixed currents, while the calculation was correctly done with a transient simulation. The check of the specific tractive force peak results in a thermally maximum allowed continuous current of $I_{DC} = 6A$ with the measured value

$$\hat{f}_S \approx 37{,}7\,kN/m^2 = 3{,}77\,N/cm^2$$

Despite the flux concentration, this value is slightly smaller than the expected value from [1] for TFM without flux concentration. In fact, torque or linear motors are made preferably with water cooling, which is also considered in

[1]. On the contrary, the motor presented here, due to especially good efficiency, is constructed with air cooling. Therefore, the maximum continuous current is smaller, that determines the lower specific tractive force.

The expected value for the specific tractive force derived from the approximated formula $\hat{f}_s \approx 4{,}4\ N/cm^2$ is in good agreement with the simulation and measurement values.

Summary. On the basis of theoretical considerations one can expect a particularly large force or power density in the transverse flux motor through the possibility of small pole pitches, which can be also confirmed with corresponding prototypes. However, the construction of this machine is very complexdue toits characteristically three-dimensional flux. There is no concept ready for the production of the most investigated rotating transverse flux motors. This is most probably the significant reason why these promising machines have not found practical application yet. The concept presented in this article is feasible because it overcomes these disadvantages and allows a serial production of LTFM with commercially available components. Furthermore, the possibility of flux concentration brings an additional increase in the force or power density. Using the example of an existing motor, simulations have been performed and the calculated values have been compared with the available measurements. The simulation values and measured values are in good agreement within the usual tolerance limit for such simulations of +/- 10%, though it was necessary to create 3D FEM.

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Мета. Обґрунтувати метод дослідження машин з поперечним полем за допомогою спеціального пакета системи автоматизованого проектування (САПр). Представити нову концепцію лінійної машини з поперечним полем з концентрацією потоку, що володіє високою щільністю сили та потужності, а також відкриває можливість створення серійного виробництва з економічно привабливими компонентами.

Методика. Оскільки лінійна машина з поперечним полем має складне трьохвимірне магнітне поле, то розрахунок даної концепції лінійної машини з поперечним полем був здійснений шляхом 3D-моделювання електромагнітних процесів усередині лінійної машини з поперечним полем. Дані 3D-моделювання були порівняні з експериментальними даними.

Результати. Представлена концепція лінійної машини з поперечним полем та з концентрацією потоку. Отримані електромеханічні параметри лінійної машини з поперечним полем. Підтверджена відповідність експериментальним даним результатів 3D-моделювання.

Наукова новизна. Представлена нова методика розрахунку лінійної машини з поперечним полем дає можливість досить точно та якісно визначати електромеханічні параметри даного типу машин і досліджувати електромагнітні процеси, що проходять у них, без експериментального дослідження.

Практична значимість. Розроблена лінійна машина з поперечним полем та концентрацією потоку має високі енергетичні показники, а її конструкція відкриває можливість серійного виробництва даного класу електричних машин з економічно доступними компонентами. Даний метод дослідження може бути використаний при проектуванні та оптимізації лінійних машин з поперечним полем, що значно здешевлює вартість розробки й зменшує її час.

Ключові слова: *поперечний потік, LTFM, концентрація потоку, 3D-моделювання*

Цель. Обосновать метод исследования машин с поперечным полем при помощи специального пакета системы автоматизированного проектирования (САПр). Представить новую концепцию линейной машины с поперечным полем и с концентрацией потока, обладающей высокой плотностью силы и мощности, а также открывающей возможность создания серийного производства с экономически привлекательными компонентами.

Методика. Поскольку линейная машина с поперечным полем обладает сложным трехмерным магнитным полем, то расчет данной концепции линейной машины с поперечным полем произведен путем 3D-моделирования электромагнитных процессов внутри нее. Данные 3D-моделирования были сравнены с экспериментальными данными.

Результаты. Представлена концепция линейной машины с поперечным полем и с концентрацией потока. Получены электромеханические параметры линейной машины с поперечным полем**.** Подтверждено соответствие экспериментальным данным результатов 3D-моделирования.

Научная новизна. Представленная новая методика расчета линейной машины с поперечным полем дает возможность достаточно точно и качественно определять электромеханические параметры данного типа машин и исследовать электромагнитные процессы, проходящие в них, без экспериментального исследования.

Практическая значимость. Разработанная линейная машина с поперечным полем и с концентрацией потока обладает высокими энергетическими параметрами, а её конструкция открывает возможность серийного производства данного класса электрических машин с экономически доступными компонентами. Данный метод исследования может быть использован при проектировании и оптимизации линейных машин с поперечным полем, что значительно удешевляет стоимость разработки и уменьшает ее время.

Ключевые слова: *поперечный поток, LTFM, концентрация потока, 3D-моделирование*

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