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Tel. 67551732, 67558694
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PHYSICAL AND TECHNICAL ENERGY PROBLEMS

ACTIVE ZONE OF PERMANENT MAGNET SYNCHRONOUS MACHINE WITH A NON-OVERLAPPING CONCENTRATED WINDING

S. Orlova, V. Pugachov, R.Otankis

Institute of Physical Energetics,
11 Krivu Str., Riga, LV-1006, LATVIA

The research is devoted to the investigation of NdFeB permanent magnet (PM) based synchronous generators with non-overlapping concentrated windings. The rotor of such a generator has 10 pole pairs (PMs), which is dictated by the nominal voltage frequency (f=50 Hz) and the rotational speed (n=300 RPM). Comparison is made for four generators with three-phase winding coils and stator tooth numbers 18, 21, 24 and 27.

Keywords: *active zone, permanent magnet synchronous generator, torque*

1. INTRODUCTION

Nowadays, in the power range of 0.1–20 kW more than 90 % of wind turbines have synchronous generators with NdFeB permanent magnets (PMs). The absolute majority of such generators are gearless, being driven directly from a wind turbine. Low-speed generators of these wind turbines have a sufficiently high number of poles (i.e., of PMs) on the rotor, which causes certain technological problems for manufacturers of stators and for automatic stacking of multiphase distributed windings.

The PM generators have a variety of advantages as compared with the traditional designs of electromagnetically excited generators. These advantages are:

- Better weight-size relationships; their PMs have lower weight and volume than the excitation windings;
- Possibility to manufacture multipolar generators of smaller weight and size;
- Higher efficiency, since there is no need to spend 10 % of the nominal power on the excitation;

- Increased reliability thanks to the brushless and contactless design as well as to the absence of excitation winding whose characteristic features are accelerated ageing and frequent insulation damage;
- Absence of the brushes and contact rings, which reduces the maintenance expenses;
- Their demagnetizing armature reaction is less expressed, which ensures a high operational stability of the generator;
- The PM generators are highly efficient as well as practically have no losses on the rotor.

At the same time, the PM generators have certain disadvantages. One of them is the uncontrollable magnetic field strength. Therefore, it is complicated to use the wind energy at low rotational speeds of their rotors when the turbine rotational speed is also low. However, the wind speed higher than nominal can also cause a dangerously high output voltage. It should be noted that in the PM generators the magnetic field is constant, even when standing still.

One of the disadvantages of the NdFeB based PM generators is relatively high values of the cogging torque at a cut-in of the wind turbine. This means that there are also relatively high values of the required initial wind speeds, which leads to a significantly reduced operational range for winds in general. In order to reduce the cogging torques of such generators, several solutions are implemented, beginning with skewing the PM teeth and then choosing the optimum relationship between the tooth number on the stator and the number of pole pairs [1], [2]. The present paper considers the conditions that provide selection of the optimum relationship between these numbers in the generator tooth zones, so that it would be possible to gain the maximum values for electromagnetic power of the generator and the minimum value for its cogging torque. A high price of rare-earth magnets is also one of the disadvantages of these generators.

2. ANALYTICAL TREATMENT OF ACTIVE ZONES

In our experiments, we chose the traditional design circuit of a synchronous generator equipped with permanent magnets on the rotor and non-overlapping concentrated winding on the stator. In order to simplify the manufacturing technology and reduce the cogging torque, the connection between the stator tooth number Z_1 and the number p of PM pairs is determined using the expression:

$Z_1 = 2p \pm k$, where k is a whole number *(1, 2, 3, ...)*. (1)

Assuming that the nominal frequency f=50Hz of the voltage across the stator winding and the rotational frequency n=300RPM of the wind turbine and the generator rotor prescribed by technical specifications for a given wind turbine, the main design of generator was chosen in which p=60f/n=10 pairs of PMs were located on its rotor (N_m=20 radial magnetized magnets). Having regard to expression (1) and considering Z_1 as a multiple of the phase number (m=3), comparison and analysis of four generators have been carried out (see Table 1), each with its own number of stator teeth.

Table 1

Configurations of the Machine

Stator tooth number	18	21	24	27
Pole pair number	10	10	10	10
k	-2	+1	+4	+7
Number of teeth per phase	6	7	8	9

The tooth number Z_1 in synchronous generators with coils on stator is chosen as a multiple of the double phase number *2m*. The former number can be Z_1=18 or Z_1=24 for a three-phase generator (*m*=3). In our case, numerator Z_1 in the ratio Z_1/2p and its denominator *2p* are even numbers with multiplier 2. Such geometry of a tooth zone affects positively the shape and symmetry of phase voltage in synchronous machines with the electromagnetic excitation or the excitation from PMs with distributed windings and a large number of teeth on the stator.

Within PM generators of the type a significant cogging torque arises, which leads to appearance of salient teeth on the stator. To overcome this, stronger winds are needed to start up the wind turbine, which would significantly reduce the range of operating winds in general. As research [3] has shown, one of the methods to reduce the cogging torques is to design an active zone with Z_1 and *2p*, i.e., the stator tooth number and the rotor pole number that do not have a common multiplier. Due to the fact that the rotor PM number is always a multiple of 2, it is proposed to choose the stator tooth number Z_1 as a multiple of the phase number *m=3*. This would determine (also taking into account expression (1)) the choice of variants for further research into the operation of generators depending on the stator tooth numbers Z_1=21 and Z_1=27.

In Fig. 1, the cross-section is shown for a PM synchronous generator (PMSG) with Z_1=18 and *p*=10, a stator with teeth and three-phase armature winding coils. On the rotor, NdFeB permanent magnets are situated.

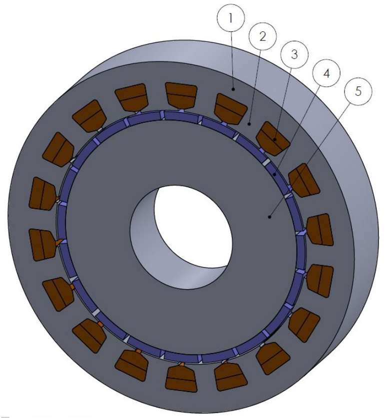

Fig. 1. Cross-section of a PM generator with Z_1/2p = 18/20:
1 – stator, 2 – stator teeth, 3 – three-phase armature winding coils,
4 – rotor, 5 – NdFeB permanent magnets.

3. NUMERICAL MODELLING OF PMSG AND DETERMINATION OF TORQUES

The mathematical modelling experiments were performed with the aim to improve the PMSG design and determine the electromagnetic and cogging torques. The generator under investigation was designed based on calculation of the magnetic field in PMSG cross-section. Using numerical methods for the calculation allows for a detailed analysis of the field distribution in PMSG separate elements. In this study, software based on the finite element method (FEM) was employed for the numerical modelling, taking into account PMSG design elements and material properties. In Fig. 2, the picture of magnetic field in the generator cross-section is presented.

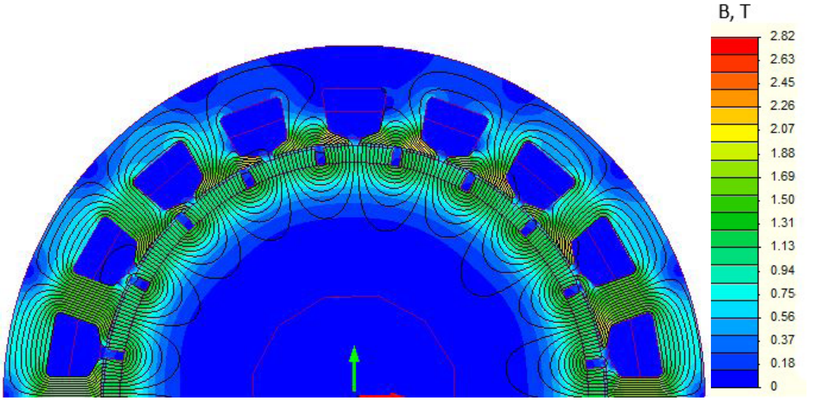

Fig. 2. Magnetic field in the PMSG cross-section.

The electromotive forces of neighbouring coils are shifted in the magnetic field with regard to each other by the angle [4], [5]:

$$\alpha_z = \frac{2\pi p}{Z_1}, \tag{2}$$

which is very close but not equal to 180 el. degrees.

The angle between the electromotive forces of two coils situated on the neighbouring teeth of the armature is:

$$\alpha_c = \begin{cases} \alpha_Z + \pi, when\, Z_1 < 2p \\ \pi - \alpha_Z, when\, Z_1 > 2p \end{cases}. \tag{3}$$

Fundamental winding factor k_w is defined in accordance with the following formula:

$$k_w = k_p \cdot k_d, \tag{4}$$

where k_p is the pitch factor,

$$k_p = \sin\left(\frac{\pi p}{Z_1}\right) \tag{5}$$

and k_d is the distribution factor.
In turn, the distribution factor will be

$$k_d = \begin{cases} \dfrac{\sin\left(\dfrac{2p}{Z_1} - 1\right) \cdot \dfrac{\pi}{2}}{a \cdot \sin\left(\dfrac{2p}{Z_1} - 1\right) \cdot \dfrac{\pi}{2}}, \; when \quad Z_1 < 2p. \\ \dfrac{\sin\left(1 - \dfrac{2p}{Z_1}\right) \cdot \dfrac{\pi}{2}}{a \cdot \sin\left(1 - \dfrac{2p}{Z_1}\right) \cdot \dfrac{\pi}{2}}, \; when \quad Z_1 > 2p. \end{cases} \tag{6}$$

Taking into account expressions (1) and (3), formula (7) will be transformed to the following:

$$k_d = \frac{\sin \dfrac{\pi}{2m}}{a \cdot \sin \dfrac{\pi}{2ma}}. \tag{7}$$

This can be exemplified by the vector diagram of electromotive forces and by the circuit of coil connection into a three-phase armature winding for an inductor machine with the number of stator teeth Z_1=18 and the number of permanent magnets on the rotor N_m=2.

To form a three-phase winding, the following variants of coil connection are possible:

phase A: +1, -2; +3; +10; -11; +12;
phase B: +7; -8;+9;+16;-17;-18;
phase C: +4; -5; +6; +13; -14; +15.

Sign «+» corresponds to the series connection of coils, and sign «-» − to the back-to-back connection.

Figure 3 presents a vector diagram for a PMSG having the stator tooth number Z_1=18 and the rotor pole pair number p=10.

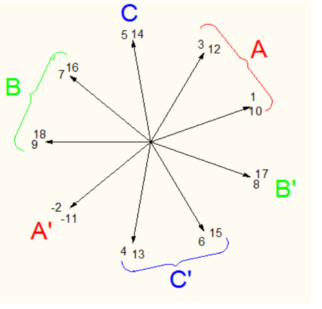

Fig. 3. Vector diagram of PMSG electromotive forces.

In Table 2 the values are given for various parameters:the angle of electromotive forces between neighbouring coils (α_Z), the angle betwen electromotive forces of two coils situated on the neighbouring teeth of armature (α), the fundamental winding factor (k_w), the cogging torque ($M_{cogging}$), the least common multiple (*LCM*), and the greatest common divisor (*GCD*).

Table 2

Parameters of Different Generators

	18/10	**21/10**	**24/10**	**27/10**
α_z	200^0	171.43^0	150^0	133.33^0
α_c	20^0	8.57^0	30^0	46.67^0
k_d	0.96	0.95	0.97	-
k_p	0.985	0.99	0.966	-
k_w	0.945	0.953	0.945	0.877
$M_{cogging,}$ *Nm*	0.011	0.00186	0.011	0.004024
LCM	180	420	120	540
GCD	2	1	2	1

In the case of a generator with the 27/10 tooth zone design the condition for the coil windings on neighbouring teeth is not met. In compliance with expression (1), the *k* value must be minimal (close to 1); then the angle between the neighbouring teeth will be close to 180 degrees.

As seen from Table 2, the least cogging torque value is when there are Z_1=21; *p*=10 and Z_1=27; *p*=10. In [3], recommendations are given as to the choice of combinations with the least cogging torque. A very low value of this torque can be obtained if the slot and pole numbers are chosen so that the least common multiple (*LCM*) between them is large. The closer the number of slots to the number of poles, the higher their *LCM*.

One of the problems of electric machines is vibrations and noises depending on the combinations of stator tooth and pole numbers. Such type vibration and noise are caused by radial magnetic forces in the airgap, while tangential ones act on the rotor thus creating torque. If the distribution of radial magnetic forces along the airgap is non-uniform, their sum creates one-direction pull force that with time begins to rotate causing the above-mentioned vibration and noise in the machine. This gives rise to the so-called unbalanced magnetic pull force, which might be related to asymmetry in windings. For combinations of stator tooth and pole numbers with $2p=Z_1\pm1$ and some combinations with odd tooth numbers there could be the greatest common divisor (*GCD*) when these numbers are equal to *1*. Such type designs are not recommended, since they might provide unbalanced magnetic pull forces.

Figure 4 shows dependence of the generator maximum electromagnetic torque on the rotor rotational angle for different numbers of stator teeth, i.e., for different combinations of PMSG active zones.

The maximum electromagnetic torque is 53 Nm for the stator tooth numbers Z_1=18 and Z_1=21, with the least *k* values in equation (1).

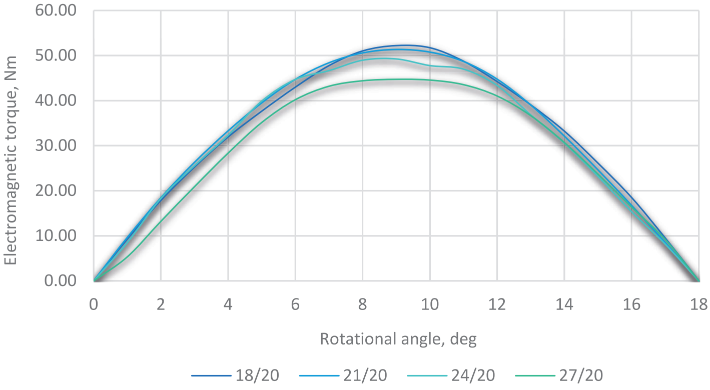

Fig. 4. Electromagnetic torque *vs.* rotational angle for different PMSG active zone combinations.

The dependence of PMSG maximum electromagnetic values on the PM width (in degrees) is shown in Fig. 5 for different stator tooth numbers. From the curve it can be seen that the NdFeB PM width increases up to the point when the pole pitch becomes optimal for the generator electromagnetic torque.

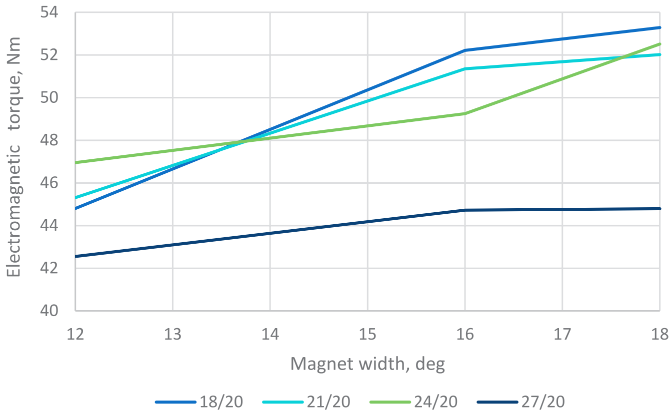

Fig. 5. Electromagnetic torque *vs.* PM width for different PMSG active zone combinations.

Figure 6 presents the dependence of cogging torque on the PM width in degrees. It is seen that at 16 degrees the cogging torque has a lower indicator. This can be explained by close values of the slot opening angular sizes and the interpolar distance. As also discussed in 1, if the interpolar distance is equal to the angular size of the slot opening, pulsation of the torque becomes smoothed, which is due to the constancy of mutually overlapped areas of stator teeth and rotor poles. Therefore, the irregularity of pulsation due to changes in the magnetic field is mainly concentrated in the airgap at the rotor rotation.

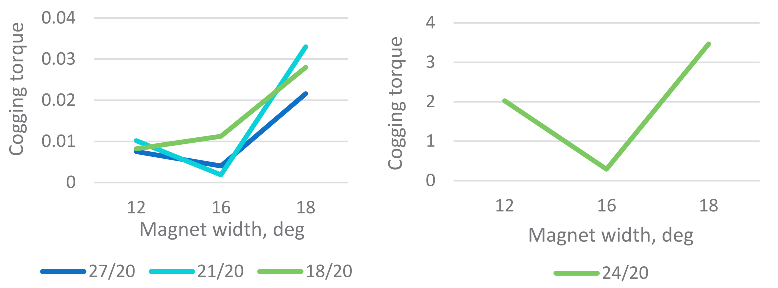

Fig. 6. Cogging torque *vs*. magnet width for different PMSG active zone combinations.

In Figs.7 and 8 the curves of no-load and load characteristics are shown. It can be seen that all the generator designs are close to each other, still a better variant is at Z_1=18 and p=10.

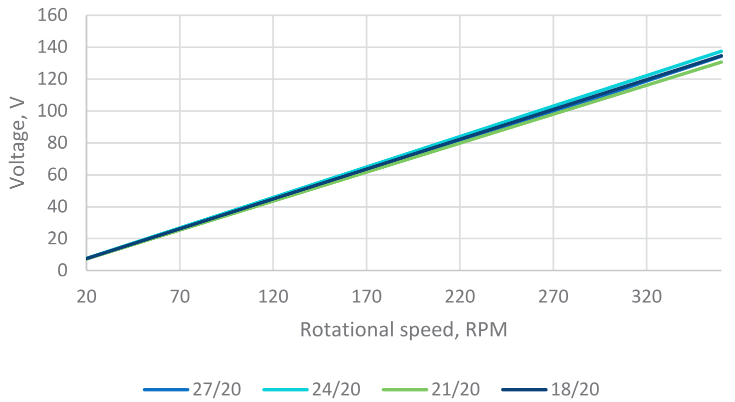

Fig. 7. Phase voltage *vs*. rotational speed for different active zone combinations.

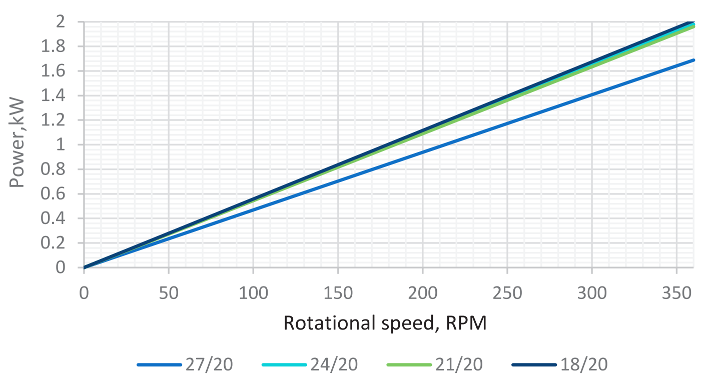

Fig. 8. Power *vs*. rotational speed for different active zone combinations.

As seen in Fig. 8, all combinations are close to each other, while under load the generator with Z_1=27 has a lower indicator.

4. CONCLUSIONS

In the research presented, investigation and comparison have been carried out for the NdFeB PMSGs with non-overlapping concentrated windings in which the coupling between the number of teeth Z_1 and the number of permanent magnets 2p on the rotor is determined by the relationship $Z_1 = 2p \pm k$.

To the investigation four generators were subjected, with the stator tooth numbers Z_1 = 18, 21, 24, 27, and with 20 PMs on the rotor. To improve the design of PM synchronous generators, mathematical modelling experiments have been performed. As a result, the values of maximum and cogging torques have been determined and compared. It is shown that a decrease in parameter k leads to an increase in the electromagnetic moment of generator and a decrease in its breaking torque at the start-up. However, at the minimum *k* values (e.g., at $k = 1$) the winding of each phase is concentrated on *Z/m* neighbouring teeth that occupy 1/3 of the stator recess. This leads to one-sided magnetic attraction of the rotor, which is responsible for elevated vibrations, noise, wear of bearings, etc.

ACKNOWLEDGEMENTS

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PASTĀVĪGO MAGNĒTU SINHRONĀS MAŠĪNAS AR VIENZOBSPOĻU KONCENTRĒTU TINUMU AKTĪVĀ ZONĀ

S. Orlova, V. Pugačevs, R. Otaņķis

K o p s a v i l k u m s

Darbs ir veltīts sinhrono ģeneratoru ar NdFeB pastāvīgajiem magnētiem (PM) un koncentrētu vienzobspoļu tinumiem izpētei. Šāda tipa ģeneratora rotoram polu pāru skaits (PM) ir 10, kuru nosaka nominālā sprieguma frekvence (f=50 Hz) un rotācijas ātrums (n=300 RPM). Tiek salīdzināti četri ģeneratori ar trīsfāžu tinumu un statora zobu skaitu 18, 21, 24 un 27.

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RE-USE AND RECYCLING OF DIFFERENT ELECTRICAL MACHINES

A. Rassõlkin[1], A. Kallaste[1], S. Orlova[2], L. Gevorkov[1],
T. Vaimann[1], A. Belahcen[1,3].

[1]Tallinn University of Technology
5 Ehitajate Tee, 19086, Tallinn, ESTONIA
[2]Institute of Physical Energetics,
11 Krīvu Str., LV-1006, Riga, LATVIA
[3]Aalto University
P.O. Box 11000, FI-00076, Aalto, FINLAND

The paper discusses the current developments in the recycling of electrical machines. The main attention is devoted to three types of motors: synchronous reluctance motor, permanent magnet assisted synchronous reluctance motor, and induction motor. Base materials of such electrical machines are also described in the paper. Rare-earth permanent magnets used in electrical machines are review separately. Moreover, the paper considers the features of the disassembly and recycling options.

Keywords: *electric machines, induction motors, permanent magnet motors, recycling*

1. INTRODUCTION

Nowadays a lot of attention is devoted to the issues of global warming and climate change. Human activities have caused noticeable effects on the environment from the perspective of resource life cycles, starting from resource consumption and pollution produced up to waste product and recycling. Waste of electrical and electronic equipment such as computers, TV-sets, fridges and cell phones is one of the fastest growing waste streams in the Europe Union (EU), with some 9 million tonnes generated in 2005, and expected to grow to more than 12 million tonnes by 2020 [1]. The economic instruments adopted by the EU to promote waste disposal and disposal fees were consolidated in the EU's Waste Electrical and Electronic Equipment Directive (WEEE Directive). Part of equipment such as electric motors, transformers, variable speed motor drives, etc. are not falling within the scope of WEEE Directive [2]. It is estimated that more than 53 % of the electricity consumed globally is used in electric motor systems in industry, buildings, agriculture and transport [3], which means about 6040 Mt of CO_2 emissions per year [4]. As part of the coordinated efforts throughout the world to reduce CO_2 emissions and energy consumption the regulation authorities in many EU countries have introduced the ICE 60034-30-1:2014 regulation to stimulate the production and use of high-efficiency motors [5]. Today there are four energy classes of electric motors:

- IE1 Standard efficiency;
- IE2 High efficiency;
- IE3 Premium efficiency;
- IE4 Super premium efficiency.

Energy efficiency requirements lead researchers to develop alternative technologies for electric motors. One possibility to reach the IE3 and IE4 efficiency class is to use rare-earth permanent magnets (PM) in the electric motors, which in the end may lead to higher environmental footprint compared to IE2 efficiency class motors.

The present research continues previous studies on lifecycle analyses of different electric motors [6], [7].

2. MATERIALS IN ELECTRICAL MACHINES

The main parts of an electrical machine are as follows: windings, cores (stator and rotor), bearings, frame, shaft and possibly PM.

Mostly, windings of electrical machines are made of copper but also other materials can be used such as aluminium in case of squirrel cage induction machines, rotor winding are often made of aluminium. Copper is around three times more expensive than aluminium, but its conductivity is 1.6 times higher, making it more preferable material.

Cores of electrical machine are made of electrical steel laminations that are tailored to produce specific magnetic properties: low Eddy current loss, small hysteresis losses and high permeability. Laminations are separated from each other with the varnish of insulation. Electrical steel is an iron alloy to which silicon is added. Silicon is added to the material as it reduces the conductivity of the material resulting in lower Eddy current losses and narrows the hysteresis loop resulting in lower hysteresis losses. The amount of silicon added to the alloy in a commercial product is usually up to 3.2 % as higher concentrations may provoke brittleness during the cold rolling [8]. Electrical steel used in electrical machines is grain non-oriented and the one used in transformers is grain oriented.

One alternative to the electrical steel laminations is the use of Soft Magnetic Composites (SMC) that can be described as ferromagnetic powder particles surrounded by an electrical insulating film [9]. SMC provide good relative permeability, magnetic saturation and high electrical resistivity. The size of the particles is typically 5–200 µm, to be compared with the thickness of laminations, which is normally 200–1000 µm [10]. SMC offer several advantages over traditional electrical steel, for example, the isotropic nature of the SMC combined with the unique shaping possibilities opens up for 3D-design solutions, i.e., it is possible to lead the flux in three-dimensions. SMC have several advantages, such as reduction in weight and size. On the other hand, SMC materials are characterised by high core losses compared to lamination, at least for frequencies less than 1 kHz. Moreover, the unsaturated magnetic permeability of SMC is lower than that of unsaturated electrical steel. The SMC material is most appropriate for use in high speed PM machines, for which the magnetic reluctance of the magnet dominates the magnetic circuit, making the performance of such motors less sensitive to the core permeability [10].

Rolling bearings used in electric machines support and locate the rotor to keep the air gap small and consistent and to transfer loads from the shaft to the motor frame. Bearings in electrical machines should have minimal friction and should be hardwearing that means the materials should match specific requirements for strength and dimensions. Materials for bearing production depend on electrical machine size and design, as well as on operation properties such as speed and environment. Metal bearings are usually made of chrome steel, stainless steel or carbon alloy steel. Some manufactures provide electrically insulated bearings to prevent current from passing through the bearing. Such bearings could be made of plastic for low power or of ceramics for high power electrical machines. These bearings can improve reliability and increase machine uptime by virtually eliminating the problem of electrical erosion.

For shaft production most manufacturers of electrical machines use carbon steel SAE 1045 (cold-rolled or hot-rolled). SAE 1045 is a medium carbon, medium tensile steel supplied as forged or normalized. SAE 1045 shows good strength, toughness and wear resistance. It is widely used for bolts, axles, forged connecting rods, crankshafts, light gears, guide rods etc. Some other materials used for electrical machine shaft production are SAE 1117, SAE 1137, SAE 1144, hot-rolled SAE 1035, and cold-rolled SAE 1018.

Stator of the electrical machine is fixed to a frame and a rotor, that is arranged to rotate around its axis, supported to the frame by rolling bearings. Usually frame of the electrical machine is equipped with cooling ribs for passive cooling or build-in liquid cooling system for active cooling. Frame of the electrical machine is usually made of non-ferrous aluminium alloy; previously cast iron alloys were also used.

Using PM in electrical machines presents an opportunity to build energy efficient machines. There are three classes of PMs currently used for electric motors:

- Alnicos (Al, Ni, Co, Fe);
- Ceramics (ferrites), i.e., barium ferrite $BaOx6Fe2O_3$ and strontium ferrite SrOx6Fe2O3;
- Rare-earth materials, i.e., SmCo (Samarium-Cobalt) and NdFeB (Neodymium-Iron-Boron).

Figure 1 presents the B-H curves for different types of PM. The remanence and coercivity of NdFeB is higher than of another type of PM. Despite substantial advantages, neodymium (Nd) magnets have a relative low Curie temperature, which is a huge disadvantage in comparison with another type of magnets. However, adding another rare-earth element, such as dysprosium (Dy) helps increase maximum temperature range that is important for use in electric motors. Adding of the small amount of Dy leads to a significant increase in magnet costs, because Dy is rarer and 7 times expensive than Nd [11].

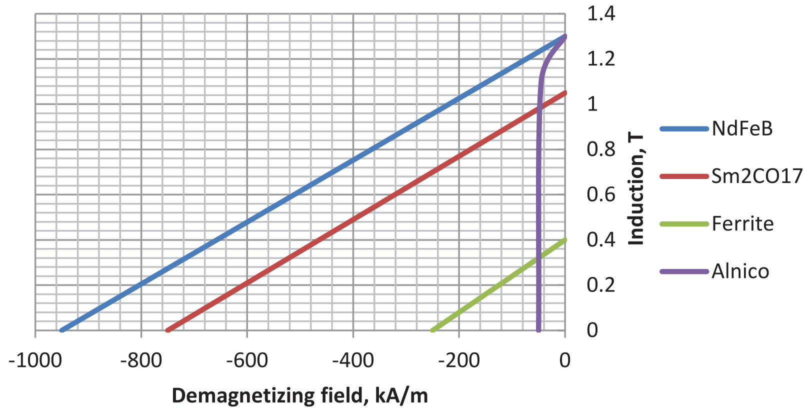

Fig. 1. Demagnetization curves for different permanent magnet materials.

Magnets made of rare earth elements have given a push forward in the development of PM. SmCo magnets usually are too expensive to be used in electrical machines. At the same time, NdFeB magnets are more favourable than SmCo magnets regarding energy density, but their long-term problem has been their endurance of heat. However, in the past decade NdFeB magnets have greatly evolved in their endurance capability to heat and corrosion. This makes them one of the most commonly used magnetic materials in large electrical machines. Consumption of rare earth elements has been rising due to their usage in wind generators and lately also in electric vehicle drives. However, the supply with present consumption should be available for more than 1000 years.

The number of materials used in the machines depends on the machine ratings and the types of the machines. The different types of machines can be compared based on the percentage values of the materials used. For example, the percentage ratio of raw materials used for 10kW motors [7] is presented in Fig. 2. For comparison purposes, three types of machines have been chosen: synchronous reluctance motor (SynRM), permanent magnet assisted synchronous reluctance motor (PMSynRM) and induction motor (IM). It can be seen in Fig. 2 that the main material used in the machines is electrical steel, followed by aluminium that is used for machine frame. The third most popular material is insulation materials, such as winding insulation, impregnation resin, paint, packing material, etc. Then copper and finally other materials and permanent magnets are used.

The stator part of all three presented motors is exactly the same; the main difference in construction and materials comes from the rotor part. The rotor winding of IM consists of parallel conductors and end rings, which are welded or electrically braced or even bolted at both ends of the rotor. The rotor of SynRM consists of soft magnetic material, which has multiple projections acting as salient magnetic poles through magnetic reluctance. In PMSynRM, the projections are filled with PM bars.

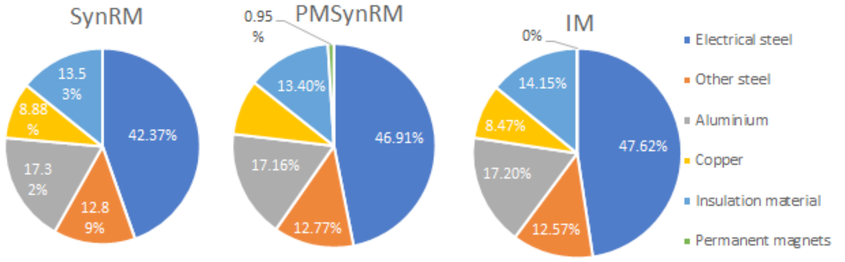

Fig. 2. Percentage ratio of raw materials used for production of different 10kW motors.

3. RECYCLING METHODS

There are only a few methods used for recycling of electrical machine: shredding or disassembling. The method used for recycling depends on the size of the recycled electrical machine and recycled component. After disassembling some parts of the electrical machine could be reused directly and the other parts should be remelted as the same raw material or to a new alloy.

Today recycling of small power electrical machines is based on shredding. During the shredding procedure, electrical machines are cut into small pieces and sorted automatically or manually. There is also a risk that different materials in a product will be mixed in the shredding procedure and therefore not properly separated [12]. Nonferrous metals can be detached from iron materials by magnetic separation, but even small mixing of materials gives a negative effect. For example, the recycled iron has a copper content of 0.25–0.3 %, which makes it useless for high grade iron, in order to have good quality iron the copper content has to be lower than 0.02 % [10].

More powerful electrical machines that are too big for shredding and can damage the grind they are handled separately [13]. Disassembly of powerful electrical machines can be performed by using robotics (automatic), manually or combined. Difficulty of automatic disassembly lies in the deformed shape of some electrical machines, at the same time manual disassembling leads to high labour costs. As the studies show [14], best results of disassembling can be reached by using the optimization models constructed by prioritization of the components and the materials in the product. Separate parts of disassembled electrical machines can be reused in case they do not have any damage and are not worn out.

Disassembling technique is highly dependent on electrical machine construction. For example, magnets of PM assisted electrical machines are either mounted on the surface (surface-mounted PM) or in pockets close to the rotor surface (integrated PM). In case of integrated PM, the magnets could be damaged during disassembling. Direct reuse of PM is only possible for large, easily accessible magnets used in wind turbines and possibly in large electric motors and generators in hybrid and electric vehicles; unfortunately, they are not available in large quantities in scrap today [15]. After disassembling and, if necessary, demagnetization, PM can theoretically be processed in a recycling plant. At present, the recycling of NdFeB magnets does not exist outside China [16] where mainly production waste is recycled. Recycling processes for NdFeB magnets often target sintered rather than bonded magnets since these are of greater recycling value owing to their high energy product [17]. Some other recycling methods for rare earth PM are the following: reprocessing of alloys to magnets after hydrogen decrepitating, hydrometallurgical methods, pyrometallurgical methods or gas-phase extraction [15].

The life of a rolling bearing is expressed as the number of revolutions or the number of operating hours at a given speed that the bearing is capable of enduring before the first sign of metal fatigue (spalling) occurs on a raceway of the inner or outer ring or a rolling element [18]. The bearing industry uses different materials for the production of various bearing components; these materials are processed to achieve desirable properties to maximise bearing performance and life. Due to the friction wear, the rolling bearing could not be reused directly, and remelting is the only way to recycle rolling bearings.

The main parameter of electrical machine winding is the quality of insulation. Lifecycle of insulation is usually around 25–30 years, it is very sensitive to temperature changing and exposed to aging. That is why the copper windings of electrical machines are always remelted after disassembling.

Some researchers present modular construction of electrical machines [19], [20]. The main benefit of such modular construction is that electrical machines can be easily dissembled and damaged parts may be replaced or healthy parts can be separately reused in other electrical machines of that type. Moreover, there are some solutions for direct reuse of rare-earth PM [21] that offer re-using small, unit-cell (segmented) magnets to replace the normal solid pole configuration. The scope of cost aspect evaluation in the research is shown in Fig. 3.

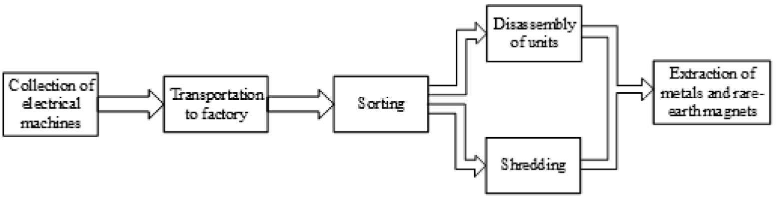

Fig. 3. Evaluation of recycling costs of electrical machines for end-of-life product extraction.

Recycling of electrical machines from end-of-life products comprises the following steps:

- the collection process for disposed end-of-life products;
- the process of transporting the removed units to the disassembly location, where rotor, stator, windings and magnets are removed from the units;
- sorting electrical machines according to their type, power range, dimensions;
- the unit disassembly or shredding process for removing the component containing metals and rare-earth magnets out of the units;
- the process of extracting metals and rare-earths (NdFeB) from rare-earth components.

4. COST ASPECTS AND ENVIRONMENTAL IMPACT

In 2018, cost of material is estimated to be 0.57 €/kg for iron ore, 5.5 €/kg for copper, 1.7 €/kg for aluminium and 2.3 €/kg for electrical steel in rolls. Price of Nd has been unsteadying during the past decade; it has started to grow during the past decade. In 2011, Nd price made a sharp leap and grew almost twenty-five times but decreased to the same price as a decade ago. In 2018, the cost of Nd metal is estimated to be 49.5 €/kg. China is one of the main producers of rare earth elements and also the main policymaker of Nd price. However, building new mines outside China has already started, which should stabilise the market and make rare earth materials more available for consumers; proper exploitation of those mines could take years.

Figure 4 shows a percentage ratio of raw material price based on the production of different 10 kW motors. If the price of IM raw materials is 100 %, the price for producing IM and SynRM is almost equal (100 % and 98 %, respectively), but considering the price of PM the same price for PMSynRM will be 118 %.

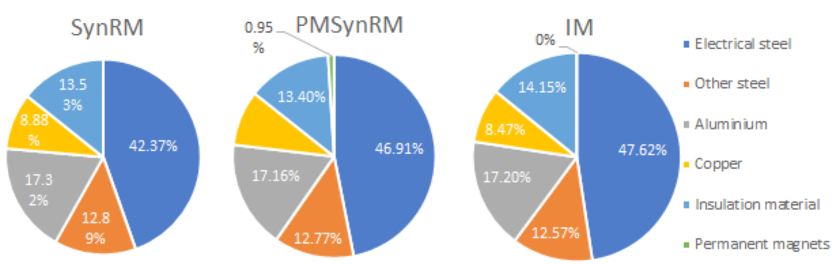

Fig. 4. Percentage ratio of raw material price based on the production of different 10kW motors.

The worst case, if the electrical machine is not recycled then it poses the considerable impact on the environment. Depending on a recycling method, electrical steel can be more environmentally-friendly, but has higher labour cost by direct reuse, or has higher environmental impact and more economical profit by shredding. It is worth noting that electrical steel is an alloy with very specific properties. Any kind of reuse of electrical steel, except direct reuse, is affecting material properties and it could not be reused as electric steel without metallurgical recuperation. Each step of the electrical steel process chain has an impact on the microstructure evolution, e.g., grain size and magnetic texture, which determine the electromagnetic properties [22]”id” : “ITEM-1”, “issue” : “5”, “issued” : { “date-parts” : [[“2016”, “5”]] }, “page” : “1-4”, “title” : “Effect of the Interdependence of Cold Rolling Strategies and Subsequent Punching on Magnetic Properties of NO Steel Sheets”, “type” : “article-journal”, “volume” : “52” }, “uris” : [“http://www.mendeley.com/documents/?uuid=4a30dcdc-c0cd-3ac1-a4e2-ce88b75eacbd”] }], “mendeley” : { “formattedCitation” : “[22]”, “plainTextFormattedCitation” : “[22]”, “previouslyFormattedCitation” : “(Steentjes et al. 2016. Copper and aluminium that are used for winding could not be reused directly due to insulation of conductive parts of electrical machine. The only one solution is remelting, but in this case the remelted copper/aluminium will contain impurities that will decrease the quality of raw material. In this case, economical profit highly depends on melting and processing energy costs and labour cost; moreover, material losses should be considered. The only way to reuse non-electrical steel in electrical machines is melting, while during the usage phase the parts made of iron are usually wearing out (shaft, frame, bearings, etc.) In this case, steel alloys lost their features and after recycling raw steel should be processed once again (e.g., hardening), resulting in higher environmental impact. Nowadays, environmental impact of PM is not taken into account very much. Environmental impact could be decreased by using some advanced recycling methods.

There is less research made on environmental impacts of electrical machine during the end of the life. For example, in [23]the suitable industrial tools for mass production and a transportation system able to bring each motor to its right place. During the use phase, the motor losses correspond to extra energy consumption and the corresponding environmental impacts for a given local electricity production system. End-of-life scenario corresponds also to extra pollution. During each phase, greenhouse gas and other pollutants specific to the manufacture of electrical machine are emitted. Therefore the improvement of the global quality of electrical machines needs a comprehensive analysis of the environmental impact. This study applies the life cycle assessment (LCA for 10 kW IM it is considered that aluminium, copper and steel are recycled, respectively, to 70 %, 70 % and 45 % and the remaining waste is incinerated and buried at a rate equal to 53 % and 47%, respectively. Recovery amount of metals and rare-earth magnets is an important factor in the appraisal of recycling costs. Thus, we first should estimate the costs of the recycling and then compare it to the amount of products obtained from the electrical machines.

The total costs can be estimated by accumulating the labour cost, the utility cost, the depreciation cost for the recycling equipment, the purchase cost for the used products, and the gain on sale of recovered metals and rare-earth magnets. The labour and utility costs can be obtained from disassembly test.

The recycling costs are given by equation (1):

$$G_{total} = \sum_{i=1}^{5} g_i, \quad (1)$$

where G_{total} – is the total cost of recycling and includes costs of all the particular recycling steps according to steps described in Fig. 3. For instance, g_1 -includes cost of the used electrical machines, g_2 – transportation costs, g_3 – manual sorting of the machines according to their type, power range and dimensions, g_4 – costs of shredding or dissembling based on the motor type and its design, g_5 – the cost of extraction of final products with the help of manual and automated processes.

5. CONCLUSION

The present paper has summarised the recent developments regarding the key components of electrical machine, which are windings, stator and rotor cores, bearings, frame, shaft and possibly PM.

SynRM and IM do not have any rare-earth elements and can be shredded. Different materials in a product will be mixed during the shredding procedure, although nonferrous metals could be detached using magnetic separation. PMSynRM contains relatively high concentrations of valuable compounds such as PM magnets that suffer from poor recycling efficiencies during shredding, which means disassembling will be the main recycling method for such electrical machines.

Raw materials obtained during recycling can be reused directly, remelted into different alloy or used in powder metallurgy for further production. The steps described in the paper are designed to increase efficiency of material reuse in order to achieve low recycling cost and high recycling rates. Problems of the electrical machine recycling with modern technologies based on the contemporary social systems are clarified, and the starting point of the research problem is identified.

Meanwhile, we have made a number of assumptions that must be specified in future research to develop a more comprehensive understanding of the accurate cost estimation for electrical machine recycling industry in different countries. We have assumed that the entire recycle chain consists of particular steps but we should take into account that the cost of each step varies and depends on many variables, such as price of the electrical energy, fuel, labour costs, governmental regulations and other factors.

ACKNOWLEDGEMENTS

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DAŽĀDU ELEKTRISKO MAŠĪNU ATKĀRTOTA IZMANTOŠANA UN PĀRSTRĀDE

A. Rassõlkin, A. Kallaste, S. Orlova, L. Gevorko,
T. Vaimann, A. Belahcen.

Kopsavilkums

Šajā rakstā aplūkotas pašreizējās pārmaiņas elektrisko mašīnu pārstrādē. Galvenā uzmanība tiek vērsta trim dzinēju tipiem: sinhronais pārslēdzamais dzinējs, sinhronais pārslēdzamais dzinējs ar pastāvīgiem magnētiem un asinhronais dzinējs. Tiek aprakstītas šo mašīnu galvenie materiāli. Atsevišķi tiek apskatīti retzemju pastāvīgie magnēti. Turklāt tiek apspriestas izjaukšanas un pārstrādes iespējas.

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CONSIDERATION OF SOLUTION FOR ENHANCEMENT OF FREQUENCY CONVERTER SUPPLY POWER PARAMETERS

I. Rankis, G. Zaleskis

Riga Technical University, Faculty of Power and Electrical Engineering,
Institute of Industrial Electronics and Electrical Engineering,
12-1 Azenes Str., Riga, LV-1048, LATVIA
e-mail: rankis@eef.rtu.lv

The paper presents results of analysis of a possible solution for enhancement of frequency converter (FC) AC supply power parameters. The method proposed is based on switched stabilisation of DC current of FC front-end rectifier unit. Such stabilisation allows obtaining rather good AC supply power parameters, i.e., its power factor and total harmonics distortion (THD) indicator for phase current. The paper also demonstrates a possible realisation scheme, a simplified mathematical description of processes in the scheme, as well as methods for consideration of its parameters, accounting the rated power of FC and the appointed level of the rectifier DC current continuity ratio. The results of computer simulation, to a great extent, testify a possible enhancement level.

Keywords: *converter, frequency, inductor, inverter, load, power, rectifier, ripple, stabilisation, switch, switching*

1. INTRODUCTION

Traditionally, frequency converters have the three main blocks. The first one, the front-end, is an uncontrolled 6-pulse bridge rectifier. The second one is capacitor bank that is necessary for smoothing of DC voltage at the output stage of the rectifier and for absorbing a reverse current in the braking regime of FC load – induction motor. The third one is the voltage source inverter that converts DC voltage over the capacitor plates to single or three-phase AC voltage, which is applied to the motor. The capacitor can be connected directly to output DC clamps of the rectifier (usually, a 3-phase one), as well as through an inductor coil. In the second case, the inductor together with the capacitor bank forms a passive LC mode DC smoothing filter, which allows improving the quality of DC voltage at the input of the inverter, as well as improving the quality and electromagnetic compatibility of FC with regard to the AC supply network. Smoothing effect depends on the volume of inductor inductance, which is limited in size, as well as there are price restrictions. At admissible inductance restrictions, a smoothing effect is relatively weak and power parameters are far from achievable at full smoothing of current.

Naturally, in order to decrease size and price of the FC, very often a case without inductor, which is rather bulky, is applied. Electrical current supplied from AC network is greatly distorted and has large content of high frequency harmonics, worsening the THD factor and the power factor, too [1], which in the case really depends on a leakage inductance of a supply network, only. For instance, Fig. 1.a depicts an experimentally obtained diagram of supply phase current of FC of 7.5 kW power, when volume of capacitor is 1 mF, smoothing circuit is without an inductor, and leak inductance of the supply phase is 0.5 mH. The THD factor for this very distorted current is 1.075, but power factor is 0.7297. When an extra inductor of 3 mH is introduced in the circuit, forming the rectifier output current smoothing LC filter, then the shape of supply current is less distorted and THD factor at full loading of FC can be improved to 0.45, but power factor – to a value of 0.917. Naturally, further increase in volume of inductance improves a THD factor, and at absolutely smoothed current and large volume inductor (Fig. 1. b), the harmonic distortion factor THD should be reduced to a value of 0.31.

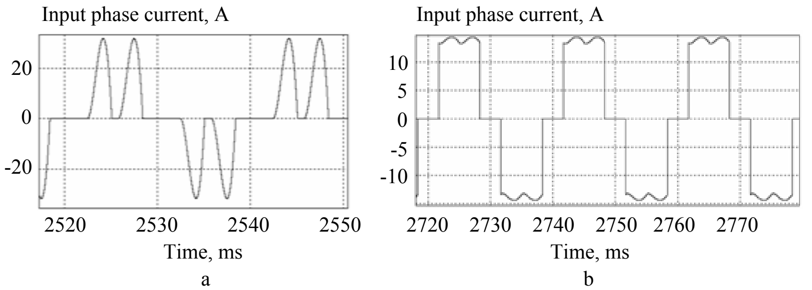


Fig. 1. Diagram of network phase current of FC 7.5 kW at network leak inductance L=0.5 mH without smoothing inductor; THD factor is 1.075; power factor is 0.7297 (a); high quality smoothing LC filter; THD factor is 0.31 (b).

The above-mentioned considerations show that enhancement of FC input DC stage is a topical issue, which asks for efficient solutions. With regard to the input stage, some other improvements should be introduced, too: an electronical limitation of FC turn-on current spike and provision of bi-directionality, which could enable reversion of energy flow at braking processes of induction motors supplied through FC. The paper discusses one method of smoothing of input stage current, realisation of which is relatively simple and based upon power electronics principles, as well as asks for small volume inductance of an inductor, only.

2. ANALYSIS OF TOTAL HARMONIC DISTORTION OF THE DISCUSSED SOLUTIONS

Dependence of power factor (bold lines) and THD (thin lines) for the FC of rated power 7.5 kW, with three different realisation methods of input junction, on the realised power (Fig. 2) is presented: with C-filter at C = 1 mF, inductance L of supply line 0.5 mH; with LC filter at $L = 3$ mH, L of supply line zero; with an ideal smoothing filter.

It should be taken into account that the quality, characterising parameters, to a great extent, depend on loading power of a frequency converter, and if load is lighter, then parameters are worse.

Taking into account problems related to the introduction of a sufficiently large volume inductor, which allows obtaining well smoothed DC current of the rectifier, it is necessary to find solutions, which could provide a sufficiently good shape of supply phase current at acceptable small volumes of filter element parameters. One solution should be related to electronically controlled smoothing of the inductor current, at which it should be possible to reduce volume of inductance and size of input junction of FC, thus providing sufficiently good distortion factor for the supply AC current.

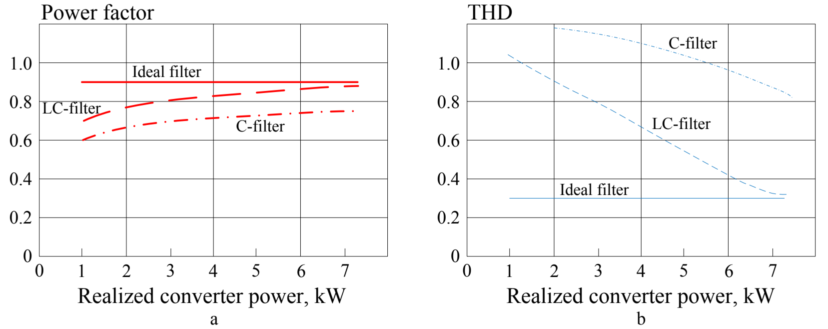


Fig. 2. Dependence of power factor (a) and THD (b) of FC 7.5 kW on a loading level of the device.

3. CONTROL SYSTEM OF THE OFFERED SOLUTION

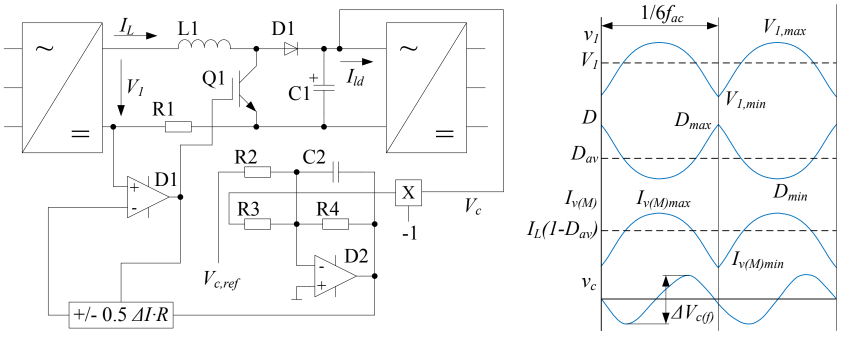
To realise the DC current smoothing feature, it is necessary in the intermediate block of FC to introduce elements of well-known BOOST DC/DC converter topology – an inductor L1, electronic switch Q1, separating diode D1, resistor R1 as a sensor of the DC circuit current (Fig. 3.a).

Periodically **on-off** switching of the switch Q1 is supporting almost constant DC component of current through the inductor L1, i.e., current of inductor is smoothed at the reference level I_L which corresponds to the appointed value by equality of powers at output of the rectifier and at input of the inverter:

$$I_L = \frac{V_{ld} \cdot I_{ld}}{V_1}, \text{A}, \tag{1}$$

where $V_{ld} = V_C$ – the average value of capacitor C_1 voltage;
I_{ld} – the average value of the DC input current of the inverter;
V_1 – the output DC voltage of the rectifier.

Specificity of the system lies in the fact that instantaneous values v_1 of the output voltage of the rectifier v_1 are periodically variating over 1/6 of total cycle of supply AC value V_{AC} (Fig. 3.b). The maximal value of v_1 is $V_{1,\max} = \sqrt{2} \cdot V_{AC}$, the minimal value is $V_{1,\min} = \sqrt{1.5} \cdot V_{AC}$, but voltage V_1 is the average value of output voltage of the rectifier, which for the 3-phase bridge mode rectifier, without accounting for inductance of AC supply lines, keeps value $1.35 \cdot V_{AC}$, where the V_{AC} is RMS value of the AC interphase voltage.



a b

Fig. 3. Realisation scheme of rectifier DC output current electronic stabilisation (a) and rippling waves of rectifier output voltage v_1, variations of duty ratio D indicator, variations of diode V1 average current I_v, rippling waves of capacitor C1 voltage due to the variations of D (b).

The automated control of the system is provided using the proportional regulator, which generates negative polarity signal $-I_L{\cdot}R$ proportional to difference between real capacitor plate voltage V_C and the reference value $V_{C,ref}$, and prescribes the automatically supported DC value I_L of the inductor L1 current.

Taking into account the described principle, a control system must provide the comparison of voltage signal across a measure resistor R1, i.e., signal $v_R = i_L{\cdot}R$, with the prescribed by control feed-back reference signal $V_L = I_L{\cdot}R$ +/- $0.5{\cdot}\Delta I{\cdot}R$. When v_R is less than V_L, the switch must be **on**, but when situation is opposite, then switch is in position **off**. To define switching quality, in the comparison system it is necessary to introduce dead gap signal $\Delta v = \Delta I_L{\cdot}R$, where ΔI_L is a ripple range of inductor current. When switch stands in its **on** position, gap correction signal minus $0.5\Delta I_L{\cdot}R$ is added to the negative polarity signal $I_L{\cdot}R$, but when switch stands in off position, then signal $+0.5\Delta I_L{\cdot}R$ is added.

Applying the main relations for the BOOST converter, it is possible to state that ripple range of the inductor current, at zero values of AC supply line leakage inductances, can be found as follows:

$$\Delta I_L = \frac{v_1 \cdot D}{L \cdot f}, \text{A}, \tag{2}$$

where v_1 – the instantaneous value of the rectifier output voltage;

D – the duty ratio of the electronic switch;

L – the inductance of the coil.

The input voltage of the inverter, DC voltage across the capacitor C_1, can be defined [2] as follows:

$$V_C = \frac{v_1}{1-D}, \text{V}, \tag{3}$$

but module of the current i_L ripple range, at **off**-position of the switch and continuous current of the inductor, is:

$$\Delta I_L = \frac{(V_C - v_1)\cdot(1-D)}{L\cdot f}, \text{A}. \tag{4}$$

Taking into account the both expressions of the ripple range, a duty ratio for each instantaneous value of the rectifier output voltage can be expressed as follows:

$$D = 1 - \frac{v_1}{V_C}. \tag{5}$$

As a result, diode V_1 current average value in each modulation cycle of switch depends on the instantaneous value of v_1 (see Fig. 3.b):

$$I_{v(M)} = \frac{v_1}{V_C}\cdot I_L, \text{A}. \tag{6}$$

As consequence, an average value of capacitor current over each modulation interval is formed with similar shape to the voltage v_1:

$$I_{C(M)} = I_{v(M)} - I_{ld} = I_{ld}\cdot\left(\frac{v_1}{V_{1av}} - 1\right), \text{A}. \tag{7}$$

Rippling of capacitor voltage over 1/6 of AC supply cycle $1/f$ due to the instantaneous variations of supply DC voltage can be simplified as follows:

$$\Delta V_{C(f)} = \frac{0.6\cdot 0.0476\cdot I_{ld}}{12\cdot f\cdot C}, \tag{8}$$

where it is accepted that this voltage ripple is formed by a positive part of the capacitor average current over each modulation interval. At the same time, rippling of the capacitor voltage is raised due to the impact of modulation processes with frequency f_M. These ripples are with higher frequency and spread upon relatively low frequency ripples discussed before. Range of the capacitor voltage ripples can be calculated as follows:

$$\Delta V_{C(M)} = \frac{I_{ld} \cdot D}{C \cdot f_M}. \tag{9}$$

These ripples are much smaller than the created ones due to variations of DC supply voltage. For instance, if load DC current is 15 A, an average duty ratio is 0.1, modulation frequency 20 kHz, but capacitor is with C = 1 mF, then voltage ripple range due to the modulation reason is 0.0075 V, but due to the voltage variation reason it is 0.714 V. Anyway, the capacitor voltage ripple range in the scheme is much smaller than that at the application of a passive LC-filter, when the parameter stands for 5.4 V. It means that in the proposed scheme the volume of capacitor C_1 should be lowered substantially.

With regard to the switching frequency, its value also depends on an instantaneous value of the DC supply voltage v_1:

$$f_M = \frac{V_C \cdot v_1 - v_1^2}{L \cdot \Delta I_L \cdot U_C}, \text{Hz} \tag{10}$$

and its maximum value is at the minimal value of v_1:

$$f_{M(\max)} = \frac{V_C \cdot \sqrt{1.5} \cdot V_{AC} - 2.25 \cdot V_{AC}^2}{L \cdot \Delta I_L \cdot V_C}, \text{Hz}. \tag{11}$$

Its minimum value stands at the maximal value of v_1:

$$f_{M(\max)} = \frac{V_C \cdot \sqrt{2} \cdot V_{AC} - 2 \cdot V_{AC}^2}{L \cdot \Delta I_L \cdot V_C}, \text{Hz}. \tag{12}$$

The average value of switching frequency can be found as follows:

$$f_{M(av)} = \frac{V_1 \cdot (V_C - V_1)}{V_C \cdot L \cdot \Delta I_L} = \frac{V_1 \cdot (I_L - I_{ld})}{I_L \cdot L \cdot \Delta I_L}, \text{Hz}, \tag{13}$$

where I_L – the average current of the inductor.

As it can be seen, at other constant parameters, switching frequency is increasing along with an increase in capacitor C_1 voltage level, which must be above the value of $V_{1,max}$. For instance, if V^*_C (with regard to V_1) is raised from 1.05 up to 1.1, then frequency is raised by 1.82 times. Conclusion can be made that parameter D should be kept at small values, which corresponds to the admissible low values of V_C. The last expression (13) should be rewritten as follows:

$$\frac{V_C - V_1}{V_C} = 1 - \frac{I_{ld}}{I_L} = D. \tag{14}$$

It can be stated that organising the control system with stabilisation of voltage V_C, at first it is necessary to take into account parameter V^*_C , then product of comparison of real capacitor voltage with the reference one can produce the reference value for providing automated stabilisation of inductor L1 current, which will be proportional to load current as $I_L = I_{ld}/(1 - D_{av})$. At such realisation of a control system, the capacitor voltage will be kept at level $V_C = V_I/(1 - D_{av})$.

The efficient realisation of control can be provided only at continuity of the inductor current i_L. It can be provided if a half of prescribed current ripple range $0.5\Delta I_L$ is not greater than average current I_L of the inductor. At the boundary case $I_{LB} = 0.5\Delta I_L$, but at $I_L > I_{LB}$ current will be continuous.

Due to the fact that load current $I_{ld} = (1 - D_{av})\cdot I_L$, it can be stated that boundary value of the load current of an input junction of FC is:

$$I_{ldB} = (1 - D) \cdot 0.5 \cdot \Delta I_L, \text{A}. \tag{15}$$

Taking into account dependence of the factor D_{av} on switching frequency, all parameters of the stabilisation system can be generalised into expression:

$$f_{Mav} = \frac{V_1 \cdot D_{av} \cdot (1 - D_{av})}{2 \cdot L \cdot I_{ldB}} = \frac{V_1^2 \cdot D_{av}}{2 \cdot L \cdot I^*_{ldB} \cdot P_N}, \text{Hz}, \tag{16}$$

where P_N – the rated power of the converter;
I^*_{ldB} – minimal rated load current at continuity of inductor current.

If, for instance, $V_I = 540$ V, L = 0.5 mH, $I_{ldB} = 2$ A, then, for operation under rectifier output voltage ripple, switching frequency must be f_{Mav}=30 kHz, parameter $D_{av} = 0.127$. This means that the prescribed ripple range $\Delta I_L = 4.58$ A, capacitor voltage stands for 618.5 V, but at the average duty ratio $D_{av} = 0.127$ on-duty interval of a switch is about 4.24 μs. As it can be stated from expression (16), switching frequency depends on accepted parameters D_{av}, L and I_{ldB}: if L and I_{ldB} are accepted smaller, then an average frequency is higher, which provokes an increase in switching power losses. Estimating switching frequency changes over a characteristic rectifier voltage interval with time duration 3.33 ms (at frequency of supply 50 Hz), instantaneous change in rectifier voltage level and duty ratio variations have to be considered.

It should be mentioned that real frequency of switching also depends on leak inductances of AC supply network lines. Since these parameters are occasional by their value, zero values of the parameter can be applied, only.

4. EXPERIMENTAL INVESTIGATION OF THE SYSTEM

Experimental investigations have been done in computer simulation system, where parameters of elements were suited to the case calculated above at V_{int} = 400V and for FC of rated power 7.5 kW. In Fig. 5.a, there is a diagram of coil with L = 0.5 mH and supply phase current at continuous current mode of the coil and with zero value of supply line leak inductance. The ripple range was accepted 4.48 A, and control system was arranged in accordance with principles presented in Fig. 2, applying as sensor current resistor $R = 0.01\ \Omega$. The reference level of capacitor voltage is applied as U_{Cref} = 615 V. The main parameters of the system at some load levels for continuous mode of current are presented in Table 1.

Table 1

Operational Parameters of the FC with Rated Power 7.5 kW at Different Loadings (computer simulation results)

Parameters	Load			
	7.6 kW	2.53 kW	1.31 kW	0.97 kW
Load DC current, A	12.45	4.13	2.136	1.581
Inductor DC current, A	14.08	4.71	2.44	1.84
Inductor RMS current, A	14.15	4.9	2.79	2.42
AC supply phase current, A	11.57	3.96	2.28	1.98
Capacitor DC voltage, V	610.4	612.9	613.4	613.5
AC supply app. power, VA	8015.9	2743.5	1579.6	1370.2
Power factor P/S	0.948	0.922	0.829	0.708
THD factor for phase current	0.345	0.447	0.66	0.68
Av switching freq., Hz	27,027	29,129	28,059	28,070
Max switching freq., Hz	40,000	42,735	42,427	42,500
Min switching freq. , Hz	18,367	20,134	22,222	22,345

As it can be seen from Table 1, power factor for the AC supply input at continuous current of the inductor L1 (the two left side columns) is 0.9, but if inductor current is at discontinuous shape, then power factor is smaller. Similarly, THD factors for continuous shape of inductor current are rather good and close to the values at ideally smoothed inductor current (Fig. 4). Again, at a discontinuous shape of inductor current, THD factor is worse, but anyway it is better as for the case of application of a passive LC smoothing filter.

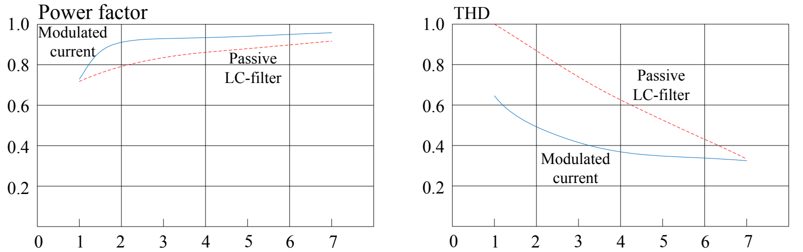


Fig. 4. Dependence of power factor and THD factor on the realised power of FC with rated one 7.5 kW for the cases with modulated current of the inductor (solid lines) and for the case with a passive LC-filter (dashed lines).

For a better effect, modulation of inductor current has to be done with a smaller ripple range and smaller load current for the boundary case. Then, if a switching frequency is to be supported on a sufficiently low level, factor D_{av} must be kept smaller, i.e., excess of capacitor voltage level has to be lowered. If, for instance, factor D_{av} is applied at a value 0.05, and voltage of the capacitor at a level 570 V, then, for the case when average frequency 30 kHz is applied, the accepted ripple range must be installed as ΔI_L = 1.8 A. The minimal value of load current will be 1.71 A, or load power of the FC at a level 974 W. This means that a range of realised powers, at continuous current of the inductor and at good values of THD and PF, will be widened compared to the above-mentioned case with ΔI_L = 4.58 A. The application cases have been considered for a zero value of AC phase leakage inductances. Really such inductances, though eventually defined, could be accounted, and then switching frequency and ripple range will be lesser. The switching frequency at the same ripple range ΔI_L = 4.58 A is 3-fold smaller now, because the total loop of current way in each 1/6 of the supply voltage cycle content in summary is 1.5 mH, instead of 0.5 mH at zero value of the leak inductance. It means that expression for estimation of switching frequency should be, more correctly, applied as follows:

$$f = \frac{V_1^2 \cdot K}{2 \cdot (L + 2 \cdot L_n) \cdot I_{ldB}^* \cdot P \cdot P_N}, \text{Hz}. \tag{17}$$

where L_n is leakage inductance for the phase of AC supply.

If this inductance should be sufficiently large, then the discussed scheme could operate without any extra inductor in the circuit of rectifier output. At that shape of AC phase current is even better as with an extra inductor (Fig. 5.b). At full loading of FC 7.5 kW, power factor with regard to supply is 0.96, but THD factor for the presented wave of current is 0.283. Average switching frequency is 15916 Hz. The obtained parameters prove the possibility to provide stabilisation of the rectifier output DC current even without the application of some extra inductor in the circuit, if leakage inductance is sufficiently great. Real value of leakage inductance should be considered using a loading experiment for supply network with regard to an input AC terminal of FC.

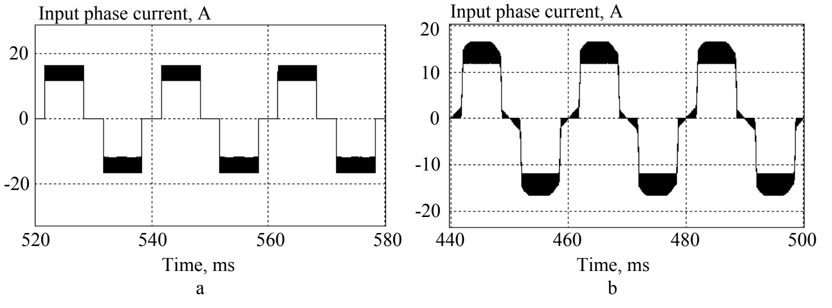


Fig. 5. Simulated diagram of AC phase current at modulated stabilisation of inductor L = 0.5 mH DC current and full loading of FC 7.5 kW (a) and at leak inductance of power supply lines at the level of 0.5 mH, excluding an extra inductor at the intermediate stage of FC (b).

5. CONCLUSIONS

Stabilisation (smoothing) effect of application of a passive LC filter is restricted by admissible volume of inductance of inductor applied to the filter and, therefore, it is not possible to obtain good AC power parameters within the entire operation range of FC. AC power parameters (power factor and THD) of frequency converter, as well as volumes of applied L and C reactive elements can be enhanced providing stabilisation (smoothing) of the front-end device of FC – rectifier – DC output current. Stabilisation of rectifier output current can be organised applying relatively small, with regard to the passive filter case, volume of inductor and, at sufficiently great leakage inductance of the network lines, without any extra inductor, using electronic switch supported modulation of rectifier output current in a scheme based on BOOST converter topology, which defines the level of filter capacitor DC voltage above an amplitude value of voltage of rectifier output. Value of an applied ripple range of the stabilised current, for providing continuous shape of the current, at which enhanced power parameters could be provided, depends both on minimal accepted load DC current and on the ratio between the output voltage levels of capacitor and that of rectifier.

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FREKVENČU PĀRVEIDOTĀJA BAROŠANAS JAUDAS PARAMETRU UZLABOŠANAS RISINĀJUMU APSVĒRUMS

I. Raņķis, G. Zaļeskis

Kopsavilkums

Šajā pētījumā ir parādīts viens no iespējamiem frekvenču pārveidotāja (FP) maiņstrāvas barošanas avota jaudas parametru uzlabošanas risinājumiem. Pielietotā metode balstās uz FP ieejas moduļa – taisngrieža - izejas strāvas komutējamas stabilizācijas. Šāda stabilizācija ļauj iegūt diezgan labus maiņstrāvas barošanas parametrus – tīkla fāzes jaudas koeficientu un strāvas harmoniskā kropļojuma THD faktoru. Tiek parādīta iespējamā īstenošanas shēma, dots vienkāršots matemātiskais apraksts par procesiem un parametru noteikšanas metodēm atkarībā no pārveidotāja nominālās jaudas, kā arī minimālās slodzes strāvas, pie kuras induktora momentānā strāva ir nepārtraukta. Veikto datorsimulāciju rezultāti lielā mērā apliecina risinājuma iespējamo efektivitāti.

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TOWARDS A HOME ENERGY MANAGEMENT MODEL THROUGH A COORDINATOR OF SMART SOCKETS

F. Ulloa [1], L García-Santander [2], D. Carrizo [3], C. Hurtado [1]

[1] Metropolitan Technological University, Santiago, 7800002 CHILE,
[2] University of Concepción, Concepción, 4089100 CHILE,
[3] University of Atacama, Copiapó 1530000, CHILE,
e-mail: fulloa@utem.cl [1], churtado@utem.cl [1], luis.garcia@udec.cl [2],
dante.carrizo@uda.cl [3]

The efficient use of energy and its implementation in domestic automation systems is an essential requirement in Smart Cities. However, this requires appropriate measurement devices and an M2M control-communication alternative that offers real-time visualization of the information. This article proposes a prototype of the home electric power consumption management platform, as an advance in generating a model for future Smart Grid. Therefore, the research implements smart socket devices and a coordinator of the communication of a home area network between these measuring devices to have an intelligent control of electric power. As a result, real-time data of the defined electrical parameters have been obtained. This information has been stored in the Internet cloud, also allowing remotely programming and controlling these measurement devices. The present research contributes to generating a profile of total load consumption for residential users and allowing them to know and compare their real consumption with what was reported by the distributors.

***Keywords**: HEMS, smart metering, smart socket, smart grid, smart cities*

1. INTRODUCTION

What makes an electrical network to be an intelligent network (Smart Grid) is the ability to communicate with all its users, and these with the general control system of electric power distribution. This provides benefits at different scales, not only to energy suppliers and distributors, but also to the end user in terms of being able to measure their own consumption of household electrical appliances [1], [2]. Therefore, it must be guaranteed that the communications are robust, manageable and safe, so they must be based on standards that guarantee connectivity among the elements of the network and an adequate quality of service, including the information of alarms and connection-disconnection remote [3]. Each of the network layers:

Homes, Neighbourhoods and Urban Areas (Home Area Network HAN, Neighbourhood Network Area NAN and Wide Area Network WAN), must have its own communication standard and also be able to communicate and interoperate with each other [4], [5], [6].

In the present research, a basic electronic structure for a Home Energy Management System (HEMS) is proposed, based on a wireless network of sensors/actuators/agents, controlled by a coordinating device that makes the decisions. The coordinator is responsible for concentrating the data of the terminal devices that measure the electrical parameters of the demand in the home, and then present them through an application for Smartphone. To obtain the information, the coordinator connects wirelessly with the terminal devices (IEEE 802.15.4) that measure and calculate the electrical parameters in the nodes of the network (voltage, current, power, energy, etc.) and communicate the electrical variables of each device that is part of the electrical circuit of the home, in addition to controlling the power supply and recording its status [7], [8].

The proposed system allows effectively regulating the use of energy using measurement and communication terminal devices called Smart Socket and a Communication Coordinator system for automatic meter reading (AMR). The set of these elements forms an Advanced Measurement Infrastructure (AMI) to inform the user of its Response to Demand (DR) through the automation of advanced distribution and dynamic models of pricing [9], [10].

2. EXPERIMENTAL DEVELOPMENT

For the purpose of investigation, a prototype of Automatic Meter Reading (AMR) device has been developed, which measures the electrical parameters in each of the household appliances connected to the home network, with the aim of obtaining a residential consumption profile, for its later coordination to automatic measurement of readings and real-time sending to the Internet cloud. This device, called "Smart Socket Light" (SSL), fulfils the function of a single-phase socket and communicates the parameters measured through the M2M technology to IoT (Internet of Things), as shown in Fig. 1.

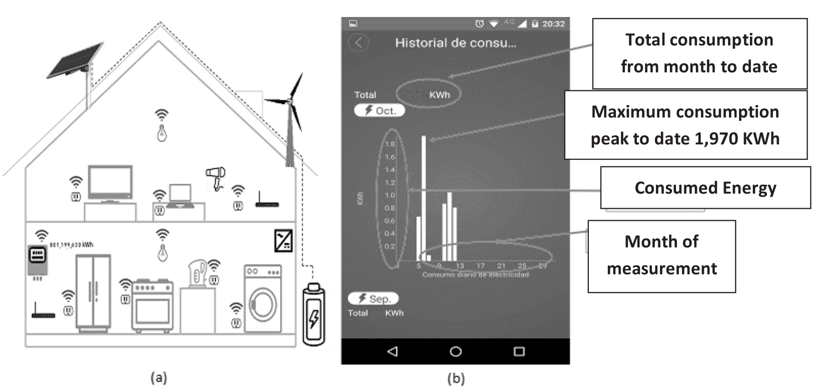

Fig. 1. (a) Communication systems HAN and intelligent measurement based on IoT, (b) History of energy consumption shown on a smartphone.

In this model, the SSL is communicated wirelessly to a receiving node and Gateway-Access Point coordinator. This agent fulfils the role of creating a bridge for the data and transmitting it through the Internet, allowing it to be viewed by the user on a smartphone or similar devices. This experimental prototype is a basic element to obtain a home energy management system. In this way, the behaviour of the users of a residence is recorded through their electrical consumption needs, such as: cooking, heating, food preservation, communication and recreation, as well as remote switching on and off.

The proposed architecture consists of a microcontroller unit and voltage-current sensors to measure the energy consumption, communication modules and power supply unit. This measurement can be visualized on a screen assembled with a smart connector and show the power consumption in a tablet device. The energy consumption data of the AMR is sent to the cloud, where the data is processed to make an appropriate decision based on the limitations of the available energy, the risks of overconsumption and different alarms. Figure 2 presents the topology of communication network and data storage platform.

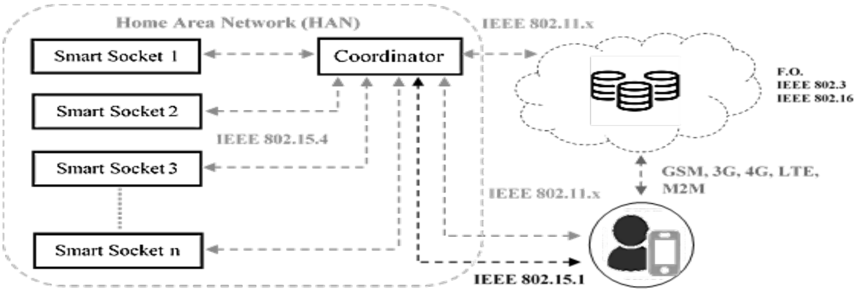

Fig. 2. Topology of communication network and data storage platform.

2.1. Automatic Meter Reading (AMR-SSL)

The SSL corresponds to an intelligent complement for a general electrical outlet; it has the capacity to measure the energy consumption in household appliances (up to 15 Amperes). If a particular device is consuming energy above a threshold value, the device orders for safety reasons its disconnection from the supply, as well as if an over current or short circuit is detected. The proposed model has the flexibility of the device portability to different sockets within the deployed coverage environment and is able to change the identity of the device in the user interface from a smartphone.

The SSL includes a communication interface, a current-voltage sensor, an MCU unit (Microcontroller Unit) and a switching circuit. The functionality of SSL is as follows:

- Measures the voltage and instantaneous current that are present in the device connected to it.
- Calculates the instantaneous power demanded by the device connected to it.

- Calculates the energy consumed by the device connected to it.
- Executes the communication request algorithm to inform the power and make the decision to turn on / off by the Smart Socket Coordinator.

As shown in Fig. 3, the consumption measurement is obtained through a current sensor and a voltage sensor, which measure the voltage and current values respectively, as well as obtain the difference between the zero crossings of these two signals and calculate correctly the powers required by the loads (Active, Reactive and Apparent). The current signal is obtained by a non-invasive sensor and the voltage signal is obtained through a potential transformer with a transformation ratio of 220V to 12V.

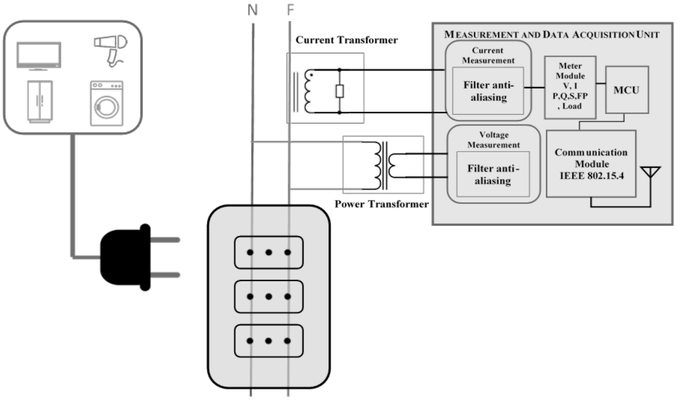

Fig. 3. Architecture of Smart Socket Light.

The SSL device has a unit of measurement of electrical parameters made by the microcontroller ADE7753, which supports the IEC 62053-22 standard, which regulates the electrical energy measurement equipment, more specifically to the "Active energy static counters". This microcontroller has ADCs and DSP patented for high accuracy in the face of large variations in environmental conditions and time.

The features and benefits of the proposed MAR – Smart Socket Light are as follows:

- High accuracy; compatible with IEC 60687/61036/61268 and IEC 62053-21 / 62053-22 / 62053-23.
- Digital on-chip integrator that allows for direct interface to current sensors with di / dt output.
- A PGA in the current channel allows for direct interface to inverters and current transformers.
- Active and reactive energy, sample waveforms, current and voltage rms.
- Less than 0.1 % error in active and reactive energy in a dynamic range of 1000: 1 at 25 ° C.
- Accumulation mode only of positive energy available.
- User-programmable on-chip threshold for line voltage and SAG peaks and PSU supervision.
- Digital calibration of power, phase and input offset.
- Temperature sensor on chip (± 3 °C typical).

- Serial interface compatible with peripheral interface serial interface (SPI).
- Pulse output with programmable frequency.
- Interrupt request (IRQ) pin and status record.

The ATMega328P microprocessor is used for data acquisition, configuration and calibration of the ADE7753, which is also connected by an I2C bus to a real time clock (DS3231).

2.2 Communication Technologies for the Proposed System

The data of current, voltage and power transmitted from the terminal devices represent a small amount of data, which makes a very high bandwidth unnecessary. Therefore, it is established that a speed of 250 kbps is sufficient to carry out transmissions at the HAN level, and this will be the maximum speed required by the data acquisition agents. The IEEE 802.15.4 wireless communication standard is the most convenient from the energy point of view, since it has the least consumption, so ZigBee has been chosen as the standard for communicating the Smart Sockets in the HAN (Table 1).

Table 1

Speed and Consumption of Technologies for Use in Measurement Agents

Technology	Data Rate	Consumption
Bluetooth	1 Mbps	100 mW
ZigBee	250 kbps	30 mW
WiFi	2–600 Mbps	667 mW
PLC	2–45 Mbps	Null

There are several ways to perform measurements of electrical parameters (voltage, current, power, energy, etc.), as well as various ways to communicate the data obtained from the devices. This paper presents the communication of the data, analysing the techniques that will be used to send the information in the standards that are intended to be used for this task IEEE 802.15.4 and IEEE 802.11, for each of the stages of transmission of the proposed platform architecture that is disclosed in the following points. ZigBee is used as an open source wireless protocol that provides benefits such as low cost, low power, low data rate and its compatibility with IEEE 802.15.4 mesh networks.

2.3 Communication to the Cloud

The required topology is based on deploying a network of mesh-type wireless sensors, which will provide multiple routes for sending data. This sensor network is composed of the coordinator, the router and the terminal devices. Through the Gateway incorporated in the Coordinator, it is possible to connect the sensors to the Internet, so that the user can see, through a web page, the status and consumption in real time of their devices, as well as all the electrical parameters of each household appliance as shown in Fig. 4.

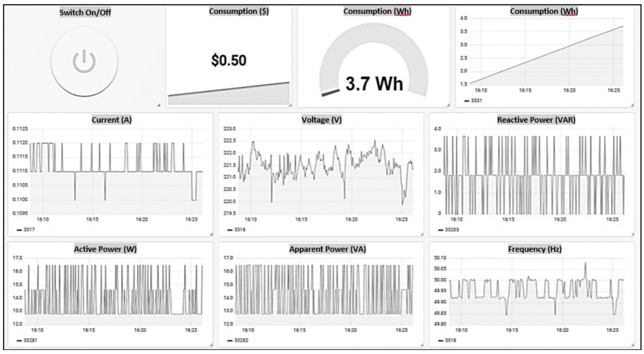

Fig. 4. Real-time AMR application (Radio communication Proposal UTEM-UDA-UdeC).

There must be a coordinator per Smart Socket network, since the network architecture requires having a Master-Slave that allows for the correct coordination of communication with all terminal devices. Its functions are to control the network and the paths that devices must follow to connect with each other, requires memory and calculation capacity. The GW Coordinator connects devices in the topology of the network, in addition to offering an application level for the execution of user code. The final device has the necessary functionality to communicate with its Master node (the Coordinator). In this way, this type of node can be asleep most of the time, increasing the average life of its batteries. A terminal device has minimal memory requirements and is therefore significantly cheaper.

The communication between Smart Socket and Gateway is done through the protocol (IEEE802.15.4), sending a String separated by commas, which has the structure shown in Table 2.

Table 2

Data Structure for IEEE 802.15.4 Protocol

Structure	“ID_Entity	ID_Attribute,	Value	Mark of time”	
Example	UID	UID	222.5	2018-04-09T15:10:09.000Z	
Size	16 B	5 B	10 B	24 B	Total = 55 B

The data frame currently used has a size of 55 bytes. According to the ZigBee protocol, the maximum per data frame is 127 bytes, but in practice using the network functionalities of the protocol it decreases to 100 bytes without encryption and to 82 bytes with encryption. The communication between the Gateway and the Data Centre will be done through the HTTP, MQTT and COAP protocols, sending a JSON object (JavaScript Object Notation). An object sent by the MQTT protocol will be analysed which has the structure that is represented in Fig. 5.

```
Object {    topic: 'entity/ID_Entidad/attr/ID_Atributo',
             payload: {
                   "id_entity":"ID_Entidad",
                   "id_attribute":"ID_Atributo",
                   "value":" 200.5",
                   "timestamp":"2018-04-09T15:10:09.000Z"
            },
            messageId: 'l7f5ZV9',
             qos: 0,
            retain: false }
```

Fig. 5. Communication structure between Gateway and Data Centre.

The data frame currently used has a size of 202 bytes, which determines the basic data load.

3. RESULTS AND DISCUSSION

The graphs of the electrical parameters are obtained in a measurement campaign of several electrical appliances: Refrigerator, Router, Electric Oven, Water Kettle, Smartphone Charger and a Notebook (laptop). From the measurements obtained through Smart Sockets, stored in the cloud, the power graphics are obtained instantaneously and in 24 hours of measurement. It should be noted that these measures only include the most important household appliances within a household and that lighting has been left out. For reasons of space, only the consumption profile of the washing machine is shown. In Fig. 6, washing, rinsing and centrifuging periods of the washing machine are displayed. Cycle 1 (2: 16: 20-2: 28: 51) of the washing machine carries out the filling of the tank by means of the filling pump, which is then followed by the washing by the motor movement connected to the tank. Cycle 2 corresponds to rinsing (2: 35: 09-2: 37: 09) and emptying the tank by means of the discharge pump. Cycle 3 (2: 45: 38-2: 49: 04) performs the same function described in Cycle 1 but with a shorter wash cycle. Cycles 4 and 5 of machine activity are identical to Cycles 2 and 3 (2: 55: 46-2: 58: 13 and 3: 07: 14-3: 09: 01). Cycle 6 (3: 16: 35-3: 21: 57), the most particular in all the operation, corresponds to the rinse with centrifugation, which can be clearly seen as low power due to the deactivation of the motor of the tank and stop with its own inertia.

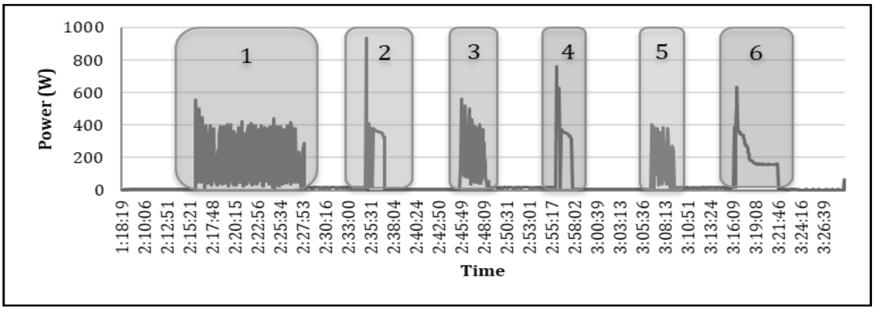

Fig. 6. Demand for washing machine power.

4. CONCLUSIONS

In this experimental research, a wireless AMR type Smart Socket design has been presented, which measures real-time electrical parameters such as Active, Reactive and Apparent Power; Power Factor; Active Energy Consumed by each device with a resolution of 4 seconds. This architecture allows obtaining the totality of the required electrical parameters and to be shown to the user through graphics in an application. The data are obtained in real time and collected in the central node of the Internet cloud, which can be stored and used to program and configure HEMS devices, together with this, to generate a profile of total load consumption for residential users. The data and the graphs of voltage and current may also be used to identify faults in the home electrical system and to record the behaviour of the distribution company and the supply in general, and failures of the electrical distribution system of the sector. The obtained capacity, to connect and disconnect remotely the home charges remotely, will allow consumption, alarms and emergencies to be avoided. In addition, it will generate energy savings and these appliances can be activated at more convenient times in case of having a flexible regulated tariff. This allows projecting a model of Remote Home Energy Management. As a future line of research for the Coordinator (HEMS), it is intended to incorporate the improvement of a power negotiating device capable of estimating the availability of renewable energy, which plays a crucial role in optimising consumption and assigning priority to an individual household appliance.

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MĀJAS ENERĢIJAS PĀRVALDĪBAS MODELIS, IZMANTOJOT VIEDO KONTAKTLIGZDU KOORDINATORU

F. Ulloa-Vaskes, L. Garsija-Santander, D. Karrizo, K. Urtado

Kopsavilkums

Viedo pilsētu pamatprasība ir efektīva enerģijas izmantošana un tās ieviešana iekšzemes automatizācijas sistēmās. Lai to panāktu, ir nepieciešamas atbilstošas mērierīces un M2M vadības komunikācijas alternatīva, kas piedāvā informācijas reāllaika vizualizāciju. Raksts piedāvā mājas elektroenerģijas patēriņa pārvaldības platformas prototipu, kas ir priekšnoteikums nākotnes viedā tīkla modelim. Pētījuma autori piedāvā viedās kontaktligzdas ierīces un mājas tīkla komunikācijas koordinatoru starp šīm mērierīcēm, lai nodrošinātu viedu elektroenerģijas kontroli. Rezultātā iegūti definēto elektrisko parametru reāllaika dati. Šī informācija tiek saglabāta interneta mākonī, ļaujot arī attālināti programmēt un kontrolēt šīs mērierīces. Pētījums veicina iedzīvotāju kopējā slodzes patēriņa profila radīšanu un ļauj patērētājiem uzzināt un salīdzināt viņu reālo patēriņu ar to, par kuru ziņo izplatītāji.

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THE DEVELOPMENT OF NANOTECHNOLOGIES AND ADVANCED MATERIALS INDUSTRY IN SCIENCE AND ENTREPRENEURSHIP: LEGAL INDICATORS. A CASE STUDY OF LATVIA (PART FOUR)

S. Geipele[1], E. Pudzis[1], J. Uzulens[1], I. Geipele[1], N. Zeltins[2]

[1]Institute of Civil Engineering and Real Estate Economics,
Faculty of Engineering Economics and Management,
Riga Technical University,
6-210 Kalnciema Str., LV-1048, Riga, LATVIA
E-mail: Sanda.Geipele@rtu.lv
[2]Institute of Physical Energetics,
11 Krīvu Str., LV-1006, Riga, LATVIA

The present scientific paper is the fourth part and continuation of the in-depth scientific study of the developed system of engineering economic indicators, where the authors obtain results from the scientific research presented in a series of works on the development of the nanotechnologies and advanced materials industry in science and entrepreneurship in Latvia. Part Four determines the essential legal indicators of the development of nano-field at the macro, micro, and meso development levels of the economic environment in Latvia. The paper provides the interaction of new identified indicators of nano-field in terms of further scientific and practical activities. Latvia is analysed in comparison with other countries in the world.

Keywords: *advanced materials, development of science, economic environment level, engineering economic indicator system, legal indicators, nanotechnologies*

1. INTRODUCTION

What does one need to find a job or to start a business, especially if that job or business is in the private sector? Many things are needed, but well-functioning markets – that are properly regulated so that distortions are minimised – are crucial. Governments play a pivotal role in establishing these well-functioning markets through regulation. A properly functioning tax system is also a key. Where the burden of tax administration is heavy – making it difficult to comply with tax obligations – firms will have an incentive to avoid paying all taxes due or may opt for informality, thereby eroding the tax base [1]. Leveraging the opportunities of the Fourth Industrial

Revolution will require not only businesses willing and able to innovate, but also sound institutions, both public and private; basic infrastructure, health, and education; macroeconomic stability; and well-functioning labour, financial, and human capital markets. Governments in emerging countries are facing tighter constraints as a result of lower revenues from commodity sectors, and still struggle with the burden of corruption and unfinished work on basic fundamentals of competitiveness such as pro-growth institutions and infrastructure [2].

Switzerland possesses one of the world's most fertile innovation ecosystems, combining a very conducive policy environment and infrastructure, academic excellence, an unmatched capacity to attract the best talent, and large multinationals that are often leaders in their sector. Singapore's public institutions (2nd behind Finland) are transparent and highly efficient (1st on public-sector performance). Finland can count on its first-class, efficient, and transparent institutions and its high-quality education system. Finland is also well positioned in terms of innovation, with its capacity to innovate supported by the excellent availability of scientists and engineers and a high degree of collaboration between universities and industry. Competitiveness of the UK economy has, up to now, rested on highly efficient goods and labour markets; business processes are highly sophisticated and supported by a high level of digital readiness by both businesses and consumers [2].

Businesses are organisations established by law that perform their activity in accordance with a large number of laws operating at the national and international level. The legal framework heavily impacts business activities and performance. The legal environment is closely connected even with the court activity [3]. Professor D. Acemoglu and Professor J. Robinson [4] conclusively show that it is man-made political and economic institutions that underlie economic success (or lack of it). Professors also point out that in successful economies the economic growth is beneficial to wider layers of society rather than just relatively small elite groups of influential people. The authors have identified "the successfully developed nations" in which political and economic institutions are "inclusive" and "the failed ones" in which they are "extractive".

Thus, it can be concluded that stable national economy, favourable political environment, competitive business, intensive cooperation between the academy and business, secure social environment and other factors are governed by the regulatory environment implemented by the state – the rule of law, which enables the government to promote, restrict and hinder the development of the national economy. The era of new technologies and digital revolution requires an appropriate, predictable, stable and well-regulated regulatory environment. Thus, the topicality of the theme is related to the identification, evaluation and comparison of legal indicators at macro, micro, and meso development levels in Latvia and other countries in order to reveal problems and find solutions to further development of the nano-field in Latvia from the perspective of the regulatory environment.

To evaluate the impact of legal indicators on the development of nanotechnologies and advanced materials industry in science and entrepreneurship and the efficiency of the regulatory environment in Latvia, the authors have identified and analysed the following indicators in Latvia and, for comparison purposes, in other countries, where data are available: Starting a Business: procedures, time, cost, paid

– in minimum capital; Legal Certainty Index; Index of Regulatory Quality; Duration of Patent Laundering; Administrative Burden in the Field of Patents; Intensity of Standard Implementation; Tax Rates; Length of the Proceedings and the Degree of Protection of Intellectual Property.

The **aim** of the research is to identify the legal indicators at the macro, micro, and meso development levels, evaluate them at the level of Latvia and compare them with the indicators of other countries if applicable to the nano-field in science and entrepreneurship.

To reach the aim of the research – to analyse the legal indicators characterising the level of development of the nano-field in quantitative terms in Latvia, the following research **methods** have been used: statistical, logical, data processing and comparative analysis, the study of the primary and secondary sources of the scientific literature, induction and deduction, scientific overview of theoretical aspects of the issue under consideration, as well as the study of a set of indicators.

The **results** of the research can be used to improve the efficiency of the regulatory environment and promote better regulation of practice development in Latvia, which directly affects the development of local business as well as the development of science in the nano-field.

2. RESULTS AND DISCUSSION

Assessment of the Legal Indicators

Continuing the study on the legal indicators included in the system of engineering economic indicators for the assessment of the development of nanotechnologies and advanced materials industries, the authors do not group legal indicators separately by macro, micro and meso development levels of the economic environment. Thus, the authors identify the most important legal indicators for the development and use of the nano-field, evaluate them at the Latvian level and compare them with the indicators of other countries, where possible, and assume that the proposed legal indicators, their scope and influence are applicable to all three levels: macro, micro and meso, substantiating these proposals in the subsequent sections of the paper.

In the group of legal indicators, the authors put forward indicators that characterise the legal environment – Starting a Business: procedures, time, cost, paid – in minimum capital; Legal Certainty Index and Index of Regulatory Quality, which characterise the effectiveness of the regulatory environment and their effects are implemented both globally and in the specific national economy – at the national level, and directly affect the business environment – micro level. These indicators are closely related to the political indicators – Sustainable Governance Indicators and the Level of Government Bureaucracy, which will be examined in the subsequent section of the present paper.

The World Bank's Doing Business survey (Regions: Europe & Central Asia, Middle East & North Africa, Latin America & Carribean, OECD high income, South Asia, Sub-Saharan Africa, East Asia & Pacific) ranked Latvia 21st among 190 countries in the category of Starting a Business by June 2017, while the neighbouring Estonia showed a much better performance (12th place) in this discipline. At the European level, Georgia (4th place), Ireland (8th place), Kosovo (10th place), Sweden (13th place), the UK (14th place), Belgium (16th place), Norway (19th place) and the Netherlands (20th place) showed better performance than Latvia. It is interesting to note that for starting a business, New Zealand has the smallest number of procedures required (1) and the shortest time to fulfil them (0.5 days). Slovenia has the lowest cost (0.0) and Australia, Colombia and 112 other economies have no paid-in minimum capital requirement. In turn, in the category of Ease of Doing Business, Latvia ranked 19th, indicating the ease of doing business, and over time the regulatory environment for local businesses had changed in the national economy. According to the Ease of Doing Business Rank, neighbouring Lithuania ranked 16th, while Estonia – 12th [5]. The results of this indicator in Latvia are closely related to the Tax Rate indicator, which perfectly reflects Latvia's performance in this discipline and the degree of rating in the subsequent sections of the present study. Despite the moderate performance of this rating, Latvia has the potential to create an attractive business environment, as in recent years, business regulatory reforms have been implemented in Latvia, provided that business regulatory framework will be easy-to-use, effective and more accessible. Government support and business-enhancing legal framework are important prerequisites for both the overall economic growth and the development of the nano-field in Latvia.

Legal certainty represents the qualitative value of a legal system resulting from demands "in terms of the quality of standards and the quality of the interpretation judges give them" [6]. Nowadays nobody would deny that legal certainty is a sine qua non condition for a democratic society or a state governed by the rule of law [7]. Legal certainty assumes the accessibility of the applicable law, its predictability due to the hierarchy of norms and predefined competencies of lawmakers and judges and reasonable stability over time and, lastly, a certain balance between economic interests and the parties concerned [8].

It is interesting to note that Estonia occupied 14th place among 113 countries in the World Justice Project Rule of Law Index last year. The index ranks countries based on a general score ranging from zero to one. Denmark scored the highest marks at 0.89 points. Estonia's score was 0.79, both Finland and Sweden scored 0.87, while Russia's score was 0.45. The index does not rank Latvia and Lithuania [9]. Taking into account the findings, the authors suggest that Latvia should also assess Legal Certainty and thus participate in the Rule of Law Index in the world ranking of countries, since it is based on the following important factors: Constraints of government powers, absence of corruption, open government, fundamental rights, order and security, regulatory enforcement, civil and criminal justice [10]. The Legal Certainty Index, therefore, points to the quality, certainty and security of the national legal environment, as well as the security of the investment environment. Its significance in the given study is also related to the economic function of the legal regulation – the fulfilment of economic activity, its performance and promotion.

As far as the Index of Regulatory Quality is concerned, in 2016, Latvia ranked 31st (1.08 points) among 193 countries, while neighbouring Estonia ranked 15th (1.70 points) and Lithuania – 29th (1.14 points). According to the methodology of this index, -2.5 corresponds to weak and 2.5 corresponds to strong [11]. The given indicator demonstrates the promotion and support of the development of the business sector, based on the government's ability to develop and implement a strong policy and a clear and understandable regulatory framework. Thus, this indicator is closely related to the previous indicators – Starting a Business and Legal Certainty, and all three indicators are attributable to macro, micro and meso development levels of the economic environment. If the state administration provides a legally stable, regulated and socially responsible environment to local and foreign businessmen as well as the society as a whole, Latvia's economic growth will be reflected in the economic indicators and the overall improvement of the welfare level of the society. In the situation in Latvia, the following weaknesses are observed: a variable fiscal policy, incomplete division of responsibilities in certain sectors (e.g., industry, construction and services) and incomplete legal system, in which there is a long legal process that is analysed in the subsequent sections of the paper, including in Latvia; shortcomings in the social legal field are also identified – there is a high level of shadow economy in several sectors, and the social responsibility of entrepreneurs has not reached a sufficient level of development yet.

For the assessment of the development of nanotechnologies and advanced materials industry, the authors have included the Duration of Patent Laundering as an indicator characterising the legal environment in the nano-field, which is an important indicator of any developed economy, as using directly patent shares, PCT patent applications and license and patent revenues from abroad it is possible to identify performance of a particular country in the advanced technology fields and the economic innovative output. Publication of an application for a patent after 18 months from the date of application is a globally recognised practice, which means that such a deadline has been established not only in Latvia but also in the European Patent Organisation (EPO) for European patent applications and Patent Cooperation Treaty (PCT) for international patent applications [12]–[14]. The same applies to the Lithuanian and Estonian patent systems [15], [16] as well as the Eurasian Patent Application [17]. Consequently, the disclosure of a patent application is a very important step in the procedure – the invention becomes known to the public. It should be noted that there is also the accelerated publication of a patent application – less than 18 months in accordance with the rules of the law; however, this practice is used in rare cases where, for example, an entrepreneur is willing to launch an invention product as soon as possible, to sell a patent or to sell a license, and all activities take place with the authorisation of professional patent offices to prevent unexpected losses. The time of the legalisation of a patent can be used for corrections and editing after a formal examination (for polishing the text), for the search of financing sources or a partner for international patenting or for launching the invention (the Latvian patent as any other patent has territorial protection, i.e., it operates only in the territory of Latvia), for decision-making whether to continue the patenting procedure, for example, after the additional ordered search results of patents. Figure 1 demonstrates the proportion of patents, designs, registration certificates and trademark registration certificates issued by the Patent Office of the Republic of Latvia in 1936 and 2016.

According to the information shown in Fig. 1, the proportion of patents (inventions) and certificates issued to industrial designs in 1936 is much higher than in

2016, which is related to the rapid development of the industry at that time, while the proportion of certificates issued today on trademarks compared to 1936 is greater [18].

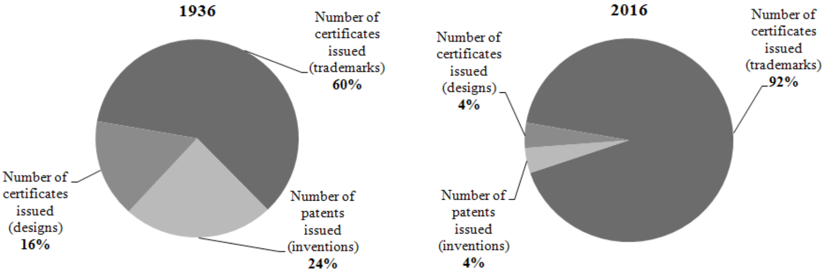

Fig. 1. Proportion of patents, design registration certificates and trademark registration certificates issued by the Patent Office of the Republic of Latvia in 1936 and 2016 [18].

The role of the patent system in business as well as in science means technological innovation, competition and investment, as well as dissemination of information, promotion of commercialisation and technology transfer. A factor to be improved in the future is better cooperation among patent offices, higher education and science institutions, thus promoting the importance of patents in Latvia as well as establishing more productive cooperation between science institutions and the private sector in order to promote and introduce commercialisation of inventions in the national economy.

It is also important to be aware of the administrative burden in the field of patents. The Latvian patent system can be assessed as simple because it operates according to the principle of the registration system [19], and it is associated with relatively low costs [20]. Nowadays, patenting abroad or in more than one country has become a good practice since the economy has become global. The choice of the patent procedure abroad is determined by the potential market for the patented invention, the "level of readiness" of the invention and the availability of finance. When patenting abroad, it is necessary to carefully examine the laws of a particular country, choose a representative from the respective country, and take into account that the patenting procedure takes place in the national language of the respective country. The legal consequences of a particular state's approval of a patent should also be known. The costs associated with patenting abroad and maintenance fees vary from country to country [21]. The patent procedure in Latvia takes place relatively quickly, without mandatory patent search, written opinion and patentability expertise – only formal and substantive examinations take place, which show that the administrative burden is not identified in the field of patents in Latvia.

According to the assessment of patents, both indicators identified relate to the global, national and entrepreneurial levels.

The development of the national economy in research and innovation also depends on indicators such as the intensity of standard implementation, tax rates, the length of proceedings and the degree of protection of intellectual property, the scope of which is attributed to the development of economic environment at macro, meso and micro levels. Consequently, the objective of national policy is to continuously and regularly analyse problems and obstacles in the legal environment, reduce them and provide as quickly as possible solutions to problems that affect the development of the business environment in the context of legal aspects of the high-technology and medium-high-tech industry and the development of the field of science in general by recognising examples of international and research-based good practice.

Standards provide individuals, businesses and all kinds of organisations with a common basis for mutual understanding. They are especially useful for communication, measurement, commerce and manufacturing. Standards make trade easier by ensuring compatibility and interoperability of components, products and services. They bring benefits to businesses and consumers in terms of reducing costs, enhancing performance and improving safety [22]. According to publicly available information, 99 % of all companies in Europe are small and medium-sized enterprises [23], which shows that while many company representatives are involved in standardisation activities, this is still insufficient, since in many cases there is a lack of awareness of the impact of standards on the business and the benefits of involvement in standardisation processes at the national, European and international levels. European Standardisation Organisations such as CEN and CENELEC in cooperation with the Small Business Standards have developed an interactive e-learning tool that will help entrepreneurs, representatives of small and medium-sized enterprises and stakeholders gain a wider understanding of standards and standardisation [24], as well as the European Standardisation Strategy up to 2020 [25] has been developed. The authors note that the standard is a document that is based on a combination of scientific and production experience and the promotion of the overall public good. Thus, in order to promote the development of nanotechnologies and advanced materials industry in terms of legal indicators, standard implementation means international experience, involvement of all multi-actors, focus on innovation and interdisciplinarity, such as, for example, the simplification and standardisation of contracts in the industrial, construction and service sectors as much as possible – standard contracts with a narrow interpretation, which would improve the indicator of the length of proceedings.

According to the Global Competitiveness Report 2014–2015, bureaucracy, tax regulations and limited access to finance impede Latvian businesses [26]; these findings were revealed using a survey, in which, from a list of 16 factors, Latvian business leaders selected the three most problematic ones for doing business. In turn, in the Global Competitiveness Report 2016–2017, respondents indicated the three most problematic factors for doing business: tax rates, inefficient government bureaucracy and tax regulations. According to the report, Latvia ranked 64th in the pillar "Institutions" among 138 countries in the world, where the lowest indicator in this pillar was achieved in the effectiveness of the legal framework (116th place), favouritism in decisions of government officials – the 99th place, public trust in politicians – the 95th place. For comparison purposes, neighbouring Lithuania in the pillar "Institutions" ranked 51st and Estonia – 23rd [2]. Consequently, it can be concluded that Latvia's performance, in the pillar of this report and its sub-indicators, is low and this is still a major issue that negatively affects competitiveness and overall economic growth.

According to the European Commission Staff Working Document "Country Report Latvia 2017" [27] on fiscal policy and taxation, investment is affected by uncertainty and the temporary trough in EU funding. The investment environment is weakened by uncertainty stemming from both the external situation and domestic economic policies. Inequality remains high and affects the labour market. The tax-benefit system in Latvia is less effective at reducing inequality than in other EU countries. The high tax wedge on low wages discourages formal employment. Weaknesses in providing public services affect the quality of the workforce in terms of education, skills and health. The tax and benefit system remains less effective in reducing income inequalities than the EU average. Taxes and benefits bring income inequalities down by 14 points of the Gini coefficient in Latvia against 21 points in the EU average. This situation is due to both the very limited progressivity of the tax system and the limited social protection system. The shadow economy is a structural constraint on the development of the Latvian economy. It is estimated to be as high as 21 % of GDP [28]. Underreported business income, unregistered companies and envelope wages are widespread practices. They directly affect the development potential and borrowing capacity of such companies and households. Since tax rates are an important indicator for both the private and public person in order to achieve sustainable development of entrepreneurship, research and the economy as a whole, as well as for any member of society, the authors conclude that, in light of the issue identified, the Latvian government should set a tax regulating – stimulating function (positive impact of economic processes, activities, demand and supply, price formation, setting differentiated tax rates and incentives, as well as reviewing tax collection and distribution processes), rather than the fiscal function of the tax, a charging function, as it is known by the theory of economics and management science.

As far as the indicator of length of proceedings is concerned, it should be noted that, according to the European Commission, among the countries of the European Union Latvia ranks 11th to 13th, thus taking a place in the middle of the ranking. The shortest duration of proceedings is demonstrated in Denmark – one case takes an average of 15 days. In Latvia, this indicator is 180 days, while in Portugal – 810 days [29]. In its turn, the Global Competitiveness Report 2016–2017 puts Latvia's efficiency of legal framework in settling disputes at 116th out of 138 countries [2]. The authors note that the length of proceedings in Latvia is one of the negative factors in business, the reason for which is due to the fact that legal disputes are unreasonable – one of the parties to the dispute retains control over the resources which, by their nature, should be passed on to the other party for the services or work fulfilled. Another problem is a lack of specialists in the courts who understand the specifics of different sectors, which means that often disputes are not resolved by nature, but only by reference to existing legislation. Consequently, experts are invited to the courts for specific dispute issues. Unfortunately, the authors do not have access to public information on statistics on the proportion of expertise in courts. Expertise is known to be a means of proof, but often it merely confirms the arguments of one party, which is considered to be evidence, and in this way, the role of expertise is in fact unnecessary and superfluous, which greatly prolongs the process of proceedings, makes it more expensive and does not produce any new effects in the proceedings.

In the decision-making process on potential investments, investors and entrepreneurs need to be aware of the potential risks of litigation, such as commercial disputes, labour disputes, tax disputes, insolvency disputes, disputes relating to government procurement and patent infringement etc. Consequently, the efficiency of the legal system in relation to litigation is very important, since, if the length of proceedings exceeds the originally planned time-line, it may cause damage to business. In Latvia, the legal system could be improved not only by the above-mentioned improvements in professionalism, but also by promoting a procedure such as mediation implementation in the system.

As a result, it should be concluded that the future challenges in Latvia are related to the improvement of tax collection and management process, implementation of standardised and standard contracts in various sectors of the economy (industry, construction and services), as well as the establishment of sectoral courts with appropriate experts.

As the last indicator of the identified indicator group, the authors have included the Degree of Protection of Intellectual Property, which is identifiable by the Global Competitiveness Report 2016–2017, according to the pillar "Institutions" within the sub-indicator of Intellectual Property Protection Latvia ranked 63th among 138 countries. The indicator shows to what extent the intellectual property is protected in a particular country. For comparison purposes, in the sub-indicator of Intellectual Property Protection, neighbouring Lithuania ranked 51st and Estonia – 26th [2]. The above-mentioned position of Latvia in the international rating is confirmed by the identified key issues of protection of intellectual property in line with the Guidelines for the Protection and Enforcement of Intellectual Property Rights 2015–2020 [30] in the following areas:

a. Improvement of the national regulatory framework for the protection and management of intellectual property rights;
b. Shortcomings in the sphere of education and information of society and entrepreneurs;
c. Deficiencies in the field of invention promotion;
d. Lack of research on intellectual property rights;
e. Deficiencies in the fight against piracy on the Internet.

In conclusion, the authors have summarised the essential legal indicators of the development of the nano-field. Figure 2 shows the link among legal indicators, their scope and economic environment development levels.

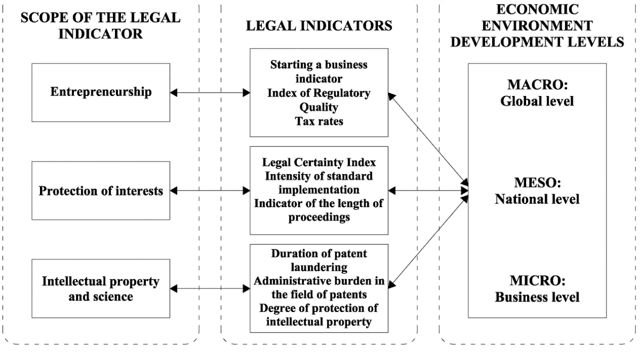

Fig. 2. Link among legal indicators, their scope and economic environment development levels [made by the authors].

The legal and administrative system, which simultaneously involves businesses, governments and other stakeholders, determines the efficiency of national public authorities, affecting both competitiveness and overall economic growth. Thus, a structured dialogue between the public and private sectors, especially for Latvia, which does not depend on political cycles and short-term interests of individual parties, is particularly important in order to identify developed countries' experience and promote real growth programmes.

3. CONCLUSION

1. In the framework of the development of the engineering economic indicator system, the legal indicators have been identified and evaluated at the macro, micro, and meso development levels of economic environment; they have been compared at the national and international levels if applicable in the nano-field in science and entrepreneurship.
2. The efficiency of the regulatory environment in the field of nanotechnologies and nanoscience can be assessed using the following indicators: Starting a Business Indicator; Legal Certainty Index; Index of Regulatory Quality; Duration of Patent Laundering; Administrative Burden in the Field of Patents; Intensity of Standard Implementation; Tax Rates; Length of the Proceedings and the Degree of Protection of Intellectual Property, the scope, impact and effects of which are simultaneously fulfilled at the macro, micro, and meso development levels of the economic environment in a particular economy. When assessing these indicators and comparing them with the indicators of other countries, it can be concluded that in the regulatory environment of Latvia there are many problems, which as a consequence manifest themselves in the factors hindering development of entrepreneurship, efficiency of public institutions, failure to formulate a dialogue between the public and private sectors, as well as economic growth in general.
3. The importance and efficiency of standards in Latvia are not entirely clear, but their development and implementation in accordance with a particular business sector would solve many issues of the legal environment analysed in the present study.
4. It is essential to stabilise the tax system in Latvia and be able to determine its changes for a period of at least five years in order to promote investment protection and safety of investment attraction, increase competitiveness and productivity, promote innovation development, support commercialisation and technology transfer.
5. The length of proceedings in Latvia is one of the negative factors in business, the reason for which is due to the fact that legal disputes are unreasonable – one of the parties to the dispute retains control over the resources which, by their nature, should be passed on to the other party for the services or work fulfilled. Another problem is a lack of specialists in the courts who understand the specifics of different sectors, which means

that often disputes are not resolved by nature, but only by reference to existing legislation.

6. An important factor in the future development of the state administration system is the long-term thinking and decision-making that will have a positive impact on the development of various sectors and a legally responsible and stable regulatory environment.

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NANOTEHNOLOĢIJU UN VIEDO MATERIĀLU INDUSTRIJAS ATTĪSTĪBA ZINĀTNES UN UZŅĒMĒJDARBĪBAS JOMĀS: TIESISKIE RĀDĪTĀJI. LATVIJAS PIEREDZE (CETURTĀ DAĻA)

S. Geipele, E. Pudzis, J. Uzulēns, I. Geipele, N. Zeltiņš

Kopsavilkums

Dotais zinātniskais pētījums ir turpinājums jau trijiem nopublicētajiem pētījumiem par inženierekonomisko rādītāju sistēmas grupu izpēti, šajā daļā veltot uzmanību tiesisko rādītāju izpētei nanotehnoloģiju un viedo materiālu industrijas attīstības līmeņa noteikšanai un paaugstināšanai zinātnē un uzņēmējdarbības jomā Latvijā.

Stabilas valsts tautsaimniecības, labvēlīgas politiskās vides, konkurētspējīgas uzņēmējdarbības, intensīvas sadarbības starp akadēmiskās un biznesa vides, drošas sociālās vides u.c. faktoru pamatā būtiska ir valsts realizētā normatīvā vide – tiesiskums, ar kuras instrumentiem valdība var veicināt, ierobežot un kavēt valsts tautsaimniecības attīstību. Jauno tehnoloģiju un digitalizācijas revolūcijas laikmetā ir nepieciešama atbilstoša, prognozējama, stabila un sakārtota normatīvā vide.

Dotajā pētījumā tiesiskie rādītāji novērtēti gan Latvijas līmenī, gan salīdzināti ar citu valstu rādītājiem, kur tas iespējams, un attiecināti uz makro, mezo un mikro ekonomiskās vides attīstības līmeņiem vienlaicīgi, atšķirībā no iepriekšējām pētījumu daļām, pamatojot izvirzīto tiesisko rādītāju darbības jomu un ietekmi. Pētījuma rezultāti liecina par identificēto un novērtēto tiesisko rādītāju aktualitāti un potenciālu, ja tiks rasti risinājumi izpētītajām problēmām turpmākai nano jomas attīstībai Latvijā no normatīvas vides darbības efektivitātes viedokļa.

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IDENTIFICATION OF MARITIME TECHNOLOGY DEVELOPMENT MECHANISMS IN THE CONTEXT OF LATVIAN SMART SPECIALISATION AND BLUE GROWTH

E. Pudzis[1], A. Adlers[1], I. Pukite[1], S. Geipele[1], N. Zeltins[2]

[1] Riga Technical University,
Institute of Civil Engineering and Real Estate Economics,
6-210 Kalnciema Str., Riga, LV-1048, LATVIA
E-mail: edgars.pudzis@rtu.lv
[2] Institute of Physical Energetics
11 Krivu Str., Riga, LV-1006, LATVIA

Recognising the fact that economic realities change the world faster than global politics, in 2010 the European Commission approved the strategy for smart, sustainable and inclusive growth, called EUROPE 2020, in order to promote greater economic independence and achieve a more sustainable future. The strategy puts forward three mutually reinforcing priorities: (P1) Smart Growth: developing an economy based on knowledge and innovation; (P2) Sustainable Growth: Promoting a more resource efficient, greener and more competitive economy; (P3) Inclusive Growth: Promoting a high-employment economy delivering social and territorial cohesion.

In the context of EUROPE 2020, the Smart Specialisation Strategy in Latvia (RIS3) has been set up and introduced as a strategic document for the development of support mechanisms of high value-added economic growth, including the maritime technology sector.

The present study explores the mechanisms for the introduction of Blue Growth and RIS3 Strategies, which should be used to develop the maritime technology industry by assessing the efficiency of these mechanisms. Thus, the study addresses the issues of the implementation of modern technologies in the coastal municipalities and planning regions of Latvia.

Keywords: *Blue Growth, maritime technologies, Smart Specialisation*

1. INTRODUCTION

European governments have developed different development strategies in compliance with the European cohesion policy reformed by the European Commission and the overall sustainable development of the European Union (EU) in the medium and long term in order to become part of the world of technological advances, use renewable resources efficiently, create additional added value, promote the development of interdisciplinary areas and support social innovation.

Global economy has started to show signs of recovery and yet policymakers and business leaders are concerned about the prospects for future economic growth. Governments, businesses and individuals are experiencing high levels of uncertainty as technology and geopolitical forces reshape the economic and political order that has underpinned international relations and economic policy for the past 25 years. At the same time, the perception that current economic approaches do not serve people and societies well enough is gaining ground, prompting calls for new models of human-centric economic progress [1]. Consequently, relatively new economies, such as the Latvian economy, should adapt to the common global and European trends in order to maintain their competitiveness on the international scene.

The aim of the research is to examine the available information on the implementation mechanisms of the marine technology industry intended for the use of marine and coastal resources in Latvia for the efficient implementation of RIS3 in the context of Blue Growth. To achieve the set aim, the following tasks are put forward: to study the concept of blue growth, its role in political documents and the impact on economic and environmental development, as well as identify the growth opportunities of the maritime technology industry in Latvia.

The methodology of the research: within the framework of the research, qualitative research methods have been used – the analysis and synthesis, induction and deduction, logically constructive, historical approach methods, information analysis and compilation, comparison, expert interviews and focus group method. The research is based on the information collected after a detailed analysis of documents (EU level planning documents, national planning and policy documents, regional and local planning policy documents) and information obtained in interviews and focus groups with national, regional and local experts.

The goal of the Smart Specialisation Strategy (RIS3) in Latvia is to increase the capacity for innovation as well as create an innovation system that promotes and supports technological progress in the national economy. Consequently, the choice of a national economic transformation strategy is closely related to the overall level of economic development and the competitive advantages (existing and potential) both at the national and regional levels [2].

The National/Regional Science and Innovation Strategies for Smart Specialisation (RIS3) are integrated, place-based basic transformation documents, with five distinctive elements:

1. Strategies focus on policy support for national investment priorities, challenges and knowledge-based development needs, including ICT activities;
2. Strategies are developed for strong and competitive national strengths and national excellence potential;
3. Strategies support technological and practical innovation and promote investment in the private sector;
4. Strategies provide full stakeholder involvement and encourage innovation and experimentation;
5. Strategies are evidence-based and include monitoring and evaluation systems.

In 2013, Latvia approved the Guidelines for the Development of Science, Technology and Innovation for 2014–2020 that comply with the objectives of EUROPA 2020 Strategy for the development of a national/regional science and innovation strategy for smart specialisation and the objectives of the National Development Plan (NAP) for science, technology and innovation development policy.

In Latvia, there is also a national industrial policy "The Guidelines for the National Industrial Policy for 2014–2020", which envisages stimulating structural changes in the economy in favour of the production of goods and services with higher profitability, including increasing the role of industry, modernising industry and services, and diversifying the export basket.

The following areas of smart specialisation are identified in Latvia:

1. Knowledge-intensive bioeconomy;
2. Biomedicine, medical technology, biopharmacy and biotechnology;
3. Smart materials and engineering technologies;
4. Smart energy;
5. Information and communication technologies [3].

In the following sections, the authors of the study will assess EU-level policies and the strategic vision of Latvian regions (including municipalities) in coastal economic and technological development, as well as identify available funding sources for promoting economic activity.

2. THE ANALYSIS OF BLUE GROWTH IN PLANNING DOCUMENTS

Behind the new growth theory there is an idea that each country or region should look for its technological development path. It is necessary to achieve technological progress appropriate for a specific level of environment, nature and human resource knowledge, since the adaptation of technologies in other regions means the repetition of old, already used ideas. New growth theory is based on a knowledge-based economy, in which the main resource is a person who is well trained, ready to learn new knowledge, as well as expresses his own initiative and is ready to share innovative ideas [4]. Blue Growth is one of the EU policies promoting the use of the above-mentioned human resources, technologies and knowledge-efficient use in coastal areas. This policy is an integrated approach to stimulate the marine economy, which, like the Smart Specialisation concept, pays significant attention to innovation, the formation of new companies, the bottom-up approach and the development of value chains. Creating the so-called blue value networks requires:

1. Development of networking between suppliers and promoters;
2. Infrastructure sharing;
3. Promotion of blue clusters and networks.

The stimulation of the above-mentioned activities should be initiated by the private sector. The following activities are expected from the public sector:

1. Competence development and knowledge sharing;
2. Use of marine clusters to promote Smart Specialisation;
3. Promotion of cross-border cooperation and

4. Promotion of Collaborative Laboratories.

The concept of Blue Growth has been developed by the European Commission (DG Mare) with the aim to exploit Europe's oceans and coastal areas for job creation and economic growth. It is a way to innovate the development of marine activities that are often dependent on each other, which in turn relies on shared knowledge and infrastructure sharing. The introduction of the concept is an essential innovation in the context of all sectors and cannot be implemented in the context of individual sectors.

In total, six Blue Growth functions are identified:

1. Maritime transport and shipbuilding;
2. Food, nutrition, health and ecosystem services;
3. Energy and raw materials;
4. Recreation, work and living;
5. Coastal protection;
6. Maritime monitoring and surveillance [5].

In 2014, the European Commission developed the Sustainable Blue Growth Agenda for the Baltic Sea Region, which provides a strategic approach to the use of existing marine and coastal resources based on the following pillars:

1. Consistent approach to innovation to increase sustainability;
2. Knowledge and skills, the development of clusters;
3. Financial access to maritime sectors [5].

By examining political documents and the rationale behind their development, it can be concluded that the sustainable use of the economic potential of the seas and oceans is one of the key elements of the European Union's maritime policy, which recognises ocean energy as one of the five areas for the development of the marine economy that could contribute to job creation in the coastal area.

In turn, according to the long-term thematic planning of Latvia for the development of the Baltic Sea coastal public infrastructure, developed in 2016, the coastline is described as a unique, diverse, sustainable and economically active space with clean water, air, beach, less-changeable landscapes and a quality living environment [6].

At present, humankind is facing the problem of a shortage of resources and a worsening environment. Thus, there has been a rapidly growing interest in the analysis and modelling of biological systems [7].

The authors of the present research maintain that the main areas of economic activity in the Baltic Sea coast of the planning region of Riga are the following:

1. Tourism and recreation, including health resort;
2. Port activities, including the reception and maintenance of yachts, as well as the construction of ships and the related equipment;
3. Fisheries, fish processing, in particular its traditional forms;
4. Use of renewable energy resources (wind, water, waves, biomass, etc.).

Thus, it can be concluded that in Latvia and in the planning region of Riga, maritime technologies are the most capable ones in promoting the renewable energy sector.

When one thinks of renewable energy, generally wind, solar or hydro power comes to mind. But forward thinkers, especially those within the livestock industry, have made remarkable strides by developing ways to use feedlot waste. Home-grown energy, as it is sometimes called, is making some farmers energy self-sufficient by using cow manure or household waste to produce biogas to generate heat or electricity [8].

The production of renewable biological resources can bring various benefits. Those are:

1. Energy: Biogas contains mainly CH4 (60 %–70 %), which is the same energy carrier as in natural gas. Thus, biogas and natural gas can be used for the same application. Methane can be burnt for cooking or lighting the house. It can also be used to power combustion engines, drive a mechanical motor or generate electricity [8];
2. Economy: energy savings, new product offerings, adoption of a certain market niche;
3. Carbon credit: Methane captured from anaerobic digestion of livestock manure may be qualified to receive carbon credit if it is collected and prevented from discharging into the atmosphere. According to the Second Assessment Report (1996) of the Intergovernmental Panel on Climate Change (IPCC), the Global Warming Potential of methane is equivalent to 21 times that of carbon dioxide. This means that in terms of global-warming potential, reducing one metric ton of methane gas emissions has the same impact as reducing 21 metric tons of carbon dioxide emissions [8].
4. Agriculture: In a biogas plant cow dung and other organic waste are converted to liquid slurry. The liquid slurry can be easily brought to places that need organic fertilizers. The most important benefit is that the slurry is a very effective fertilizer that can improve the growth of the crops. Nitrogen is one of the major nutrients required for plant growth [9].
5. Health: The process involves the killing of various types of bacteria, resulting in the improved hygiene environment and reduced health risks;
6. Environment: Reducing environmental pollution by chemicals.

To understand the feasibility of the implementation of the Blue Growth Policy in Latvia, the subsequent sections describe the development planning documents, which, in the course of implementation, could promote coastal economic development, as well as determine the financing possibilities for such initiatives.

3. RESEARCH ON THE ECONOMIC AREAS OF BLUE GROWTH AND LATVIA'S RIS3 IN PLANNING DOCUMENTS

In the largest region of Latvia – in the planning region of Riga – smart development is defined as flexible – knowledge-based and ready for change. The strategic goal is also defined as a knowledge-based "green" innovative economy, and two priorities are set:

1. Globally competitive industries (specialisation, knowledge, research, technology and continuity);
2. Smart development (education, cooperation, information, sustainable energy systems) [10].

In the planning region of Riga, the Blue Growth potential in RIS3 areas is based on the points of contact between the various planning documents and the aided economic areas mentioned therein. The synergy between RIS3 areas and maritime resource-related economic sector with great potential for development mentioned in the Baltic Sea planning documents is demonstrated in Fig. 1.

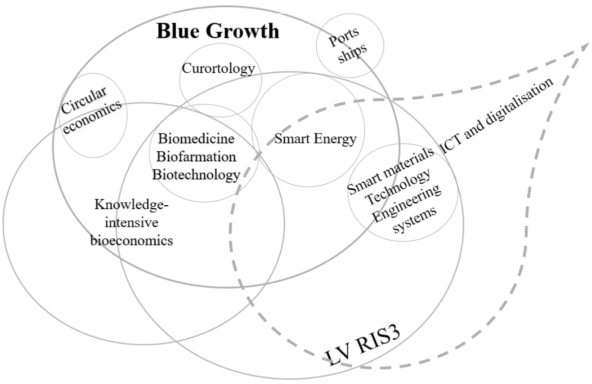

Fig. 1. Synergy between RIS3 and the Blue Growth area [made by the authors].

According to Fig. 1, it can be stated that in Riga Planning Region, in RIS3 context, the areas of Blue Growth are knowledge-intensive bioeconomy (also known as the blue bioeconomy), biomedicine, biopharmacy, resort development and active tourism, smart energy and materials, as well as new technologies.

As there is no Blue Growth Strategy in RIS3 context in Riga Planning Region, such a concept should be implemented on the basis of international, national and local planning documents, whose hierarchy and thematic link are developed and demonstrated in Fig. 2.

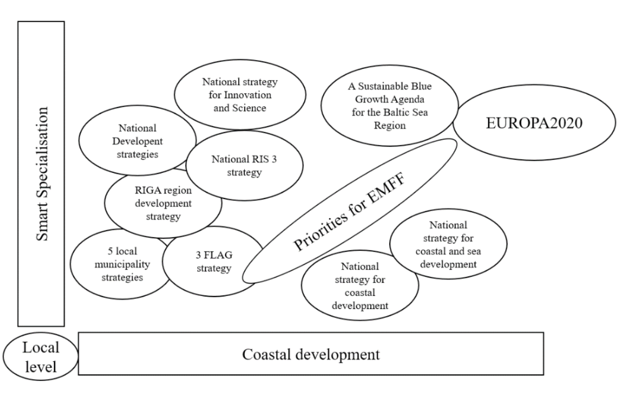

Fig. 2. Two-dimensional scheme of Smart Specialisation and Coastal Development Documents [made by the authors].

According to the two-dimensional scheme of the Smart Specialisation and the Coastal Development Documents developed by the authors (see Fig. 2), it is evident that the highest planning document is EUROPE 2020, the basic principles of which are further integrated into Latvian policy planning documents, according to which each local government integrates these directions and priorities into its municipal planning documents of local significance.

It is also important to note that in the city of Riga by smart specialisation one understands Riga's striving to become a "Smart City", which envisages transparent planning, sustainable mobility, zero-residual technology, ICT, circular economy and energy efficiency measures.

Exploring the development strategies of other coastal municipalities in Latvia, for example, in Kurzeme planning region, the following development priorities should be noted:

1. Developing a city/village as a resort, supporting micro, small and medium-sized businesses, as well as their diversification and tourism development in the area;
2. Developing seafront port services and shipping;
3. Developing communications systems;
4. Developing waste management, with particular attention being paid to waste collection and disposal;
5. Developing interest-related education in the field of natural sciences;
6. Developing an economically active environment;
7. Providing creative and professional growth opportunities in the field of production, which, inter alia, envisage lifelong learning, focusing resources on the development of the industry;
8. Creating new value, introducing innovative solutions and more efficient use of local resources;
9. Promoting the development of coastal business;
10. Promoting the use of local natural resources in business;
11. Developing a new or significantly improved service or activity and the application of new methods, processes or solutions to the production or commercialisation of products or services.

Taking into account that at present there is available financing by the EU Structural Funds, the authors have selected and summarised Smart Specialisation (RIS3) and Blue Growth implementation measures supported by the EU Structural Funds in Latvia, which may be used for the development of the Marine Technology Sector (see Table 1).

According to the information provided in Table 1, it can be concluded that efficiently working with planning documents, exploring the areas to be supported and drawing up high quality project applications, there are ample opportunities to achieve the goals set in the development of the field of marine technology, including the implementation of innovative solutions. Support is available for research and production development, as well as for the training of stakeholders, the restoration and development of objects that, in a broader context, will ensure the growth and sustainable development of Latvian economic areas, increasing the competitiveness of the country, the commercial return of scientific achievements and scientific excellence, promoting cooperation between entrepreneurship and public sector, developing staff competence and promoting job creation, as well as ensuring an interdisciplinary approach to decision making.

Table 1

RIS3 and Blue Growth Implementation Measures Supported by the EU Structural Funds in Latvia [selected and compiled by the authors on the basis of publicly available data on project selection www.esfondi.lv]

1	Postdoctoral research support
2	Development of R&D infrastructure in Smart Specialisation areas and institutional capacity building of scientific institutions
3	Support for the development of new products and technologies within the competence centres
4	Support for the improvement of the technology transfer system and innovation vouchers for SMEs
5	Support for the introduction of new products in manufacturing
6	Support for training of employees
7	Innovation motivation programme
8	Support for ICT and non-technological training as well as training to promote investor attraction
9	Promoting the establishment and development of SMEs, in particular, in processing industry and RIS3 priority sectors
10	Promoting international competitiveness
11	Cluster programme
12	Promoting energy efficiency in public and residential buildings
13	In compliance with the integrated development programmes of the municipality, promoting energy efficiency and use of renewable energy resources in municipal buildings
14	Promoting energy efficiency and the use of local RES in district heating
15	Preserving, protecting and developing a significant cultural and natural heritage, as well as developing related services
16	Developing the natural object protection and sightseeing infrastructure, habitat restoration
17	Promoting the reuse, recycling and recovery of different types of waste

The Smart Specialisation Strategy developed by the European Commission is a strategic approach to economic development, which envisages support for research and innovation. The Smart Specialisation Strategy envisages the development of a vision, the availability of competitive advantages, the choice of strategic priorities and the choice of a policy that maximises the knowledge-based development potential of the region. EU Structural Funds for research and innovation by 2020 will be invested in Latvia in compliance with Latvia's RIS3.

4. DISCUSSION AND RESULTS

In the course of the study, the authors organised focus groups to find out the views of industry experts on coastal growth. Expert interviews were also conducted. Overall, during the study, opinions of representatives of ministries and municipalities as well as industry-leading researchers were heard. The opinions of experts from 25 different institutions were summarised.

Summing up expert opinions on coastal growth in the context of Smart Specialisation, the authors made a summary of interviews.

As a result of the interviews, summarising the information provided by the leading employees of ministries, it can be concluded that coastal growth is considered in the context of implementation support of Latvia's RIS3 provided under the thematic objective "Strengthening of Scientific Research, Technological Development and Innovations" of the Operational Programme "Growth and Employment". Criteria of all measures of the thematic objective include the provision that investment complies with the areas of the Smart Specialisation Strategy. The monitoring system of the Smart Specialisation Strategy has been developed for monitoring the implementation of Latvia's RIS3.

Coastal growth is planned on the basis of planning documents, in which the Baltic Sea coast is defined as a space of national interest in the Latvian sustainable development strategy "Latvia 2030". The Baltic Sea coast is one of the regional policy target areas defined in the Regional Policy Guidelines for 2013–2019, as well as the coastal spatial development policy (refers to Riga Planning Region and Kurzeme Planning Region) is defined in the Coastal Spatial Development Policy Guidelines.

The focus is placed on the implementation of Specific Support Objectives related to the implementation of support for innovation. In this context, support is provided to Competence Centres with a total funding of 64.3 million EUR, as a result of investment eight competence centres will be established in all areas defined in RIS3 Strategy, Technology Transfer and Innovation Vouchers with a funding of 40.5 million EUR, the production of new products with funding of 60 million EUR and other programmes (motivation programmes, support for training of employees).

The aim of the ministries is to ensure that the financing is invested wisely, reasonably and has the economic impact. The funding of 200 million EUR is also intended for small businesses, which could create companies with high value added products. Representatives of the ministries also rely on the targeted research activities of the National Research Program for conducting research useful for the national economy. At the same time, the Investment and Development Agency of Latvia (LIAA) is developing a knowledge base to become a mediator between science and business. The development of people's skills is also essential; therefore, the ICT training carried out by the Latvian Information and Communication Technology Association is essential. It should not be forgotten about training that develops management skills, improves marketing knowledge etc. Thus, it is also intended to train LIAA staff that could help develop skills for attracting investors, as well as provide the necessary training for labour force.

Apart from specific training, a motivation programme is also important, such as "Idea Cup" (implemented by the Ministry of Environmental Protection and Regional Development), "Business Express", various networking seminars, mentoring, "Become an Entrepreneur in Five Days", etc.

However, the responsible national agency indicates that Horizon 2020 programme includes the following priorities: addressing societal challenges, including sustainable agriculture, marine and maritime and inland water research, bioeconomy, secure, clean and efficient energy, smart, green and integrated transport, climate change, resource efficiency and raw materials as well as inclusive, innovative and secure societies, leadership in enabling and industrial technologies, innovation in small and medium-sized enterprises (SMEs). The opportunities for SMEs in Horizon 2020 envisage participation in all forms of research, development and innovation focused on the application and commercialisation of results. The participation of SMEs is envisioned in joint research, development and innovation projects, SME Facility, Innovations for Young Entrepreneurs – Eurostars and other events. The program has three phases: Phase 1 – Concept Development, Phase 2 – Innovation, R&D Activities, and Phase 3 – Commercialisation.

Industry-leading researchers point out that a model has been developed to help create high added value for renewable bio-resources, but it is unclear how in the national way it would be implemented in life. Institutions, actively operating in several projects related to the use of marine resources and the promotion of the national economy, have the opportunity to actively participate in the integration of new innovative approaches in Latvia, including the implementation of good practices of Blue Growth.

Evaluating the views of representatives of local governments, the information has been obtained that in Riga large potential in knowledge-intensive economy and technology is created by universities and research institutes located in Riga, but stimulation of commercialisation of discoveries is weakly influenced. In Riga, it is planned to build business clusters, industrial clusters.

In the districts that are far from the capital and the local economy is related to the sea and marine resources, the development of knowledge-intensive economy and technology has not had visible impact and significance so far; however, various conferences and discussions focus on the use of existing but under-utilised resources. For example, it has been discussed that seaweed is used in cosmetics and medicine, and even in souvenir production and related technologies.

From other marine resources, fish stocks are decreasing, the coast itself is not used due to the Northern Vidzeme Biosphere Reserve and the 300-metre restricted area. These are the reasons why tourism is not feasible, for example, the infrastructure construction process. Traditionally, in districts, it is difficult to deal with private property issues, as well as the desire of the people to live in peace and tranquility. In the district, there is a positive view of the activities planned for the commercialisation of knowledge in the period of 2014–2020, but the representatives of the districts admit that there is currently no information on this issue.

Speaking of the Blue Growth concept, it is recognised that the concept is new and is still difficult to understand. It is believed that entrepreneurs who are informed and will identify profit opportunities will do so. All the innovations in the area would be perfect for everyone, so it is also possible to apply for support for fisheries and coastal development projects from the European Maritime and Fisheries Fund, but at present only the tourism industry is developing in the traditional sense.

As the tools to be used, it is worth mentioning programmes that support business incubators, community initiative projects.

The members of the focus group believe that, at present, the essential conditions hindering the development of Smart Specialisation in the area are the lack of research and awareness. There is no understanding of what can and should be done at sea (related to nature conservation). To activate the processes, it is necessary to maintain close cooperation and exchange of information with stakeholders at all levels, which could take place, for example, through the Union of Local Governments.

5. CONCLUSIONS

Under the influence of global processes and competition, the growth and competitiveness of enterprises are increasingly dependent on the ability to apply new knowledge, organisation and working methods, as well as the capacity to engage in the commercialisation of research projects in order to develop new products, services or processes. Companies should strive to seize the opportunities and competitive advantages that innovation can make.

Priority is given to promoting the balanced development of territories, which envisages the identification and specialisation of the resources located in the territories, setting out the opportunities and areas of economic development, including leading and perspective business areas in the municipality territories.

In the implementation of the national or regional RIS3 strategy, one-sided support for economic growth should be avoided – the economic environment promoting the economic activity and the development of human resources should be created; therefore, six business sectors that are important for coastal development are identified, but in the seacoast most opportunities for maritime technology development are identified in the area of renewable energy resources and intelligent materials, different areas of bioeconomy (e.g., biopharmacy) and information and communication technologies.

The development strategies of planning regions envisage the promotion of the merger of producers and service providers in terms of the territory, including within the industry, in order to strengthen international competitiveness. This is possible by creating clusters involving new actors, ensuring the development, production, distribution of products, thereby achieving territorial excellence and quality.

The central government and municipalities are open to knowledge-based and local marine resource-based economic development, not only by actually supporting entrepreneurs, but also by research projects, providing co-financing. However, it should be admitted that in the field of marine technology such projects have not been sufficiently implemented so far.

Taking into account that, from the persperctive of the country and the region, maritime technologies are only part of the country's technological development area, there is a reason to believe that currently available public funding from the EU Structural Funds could be used for the development of specific technologies. It should be emphasised that the support of the European Maritime and Fisheries Fund, in addition to direct support to fisheries, is also aimed at sustainable development of coastal areas.

To ensure the development of the Blue Growth approach in Latvia and more successful use of marine resources, as well as the introduction of a new development model, public authorities should cooperate with research institutes involving industry researchers, local authorities and, above all, business representatives in national-level discussions.

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JŪRAS TEHNOLOĢIJU NOZARES ATTĪSTĪBAS MEHĀNISMU IDENTIFICĒŠANA LATVIJAS VIEDĀS SPECIALIZĀCIJAS UN ZILĀS IZAUGSMES KONTEKSTĀ

E. Pudzis, A. Adlers, I. Puķīte, S. Geipele, N. Zeltiņš

K o p s a v i l k u m s

Eiropas valstu valdības ir izstrādājušas dažādas attīstību stratēģijas saskaņā ar Eiropas Komisijas reformēto Eiropas kohēzijas politiku un Eiropas Savienības kopējo ilgtspējīgo attīstību vidējā un ilgtermiņā, lai iekļautos pasaules tehnoloģiskā progresa laikmetā, efektīvi izmantotu atjaunojamos resursus, radītu papildus pievienotās vērtības, veicinātu starpdisciplināro jomu attīstību un atbalstot sociālās inovācijas. Salīdzinoši jaunām ekonomikām kā Latvija ir jāpielāgojas kopējām pasaules un Eiropas tendencēm, lai saglabātu savu konkurētspēju starptautiskā arēnā.

EUROPE 2020 kontekstā viedās specializācijas stratēģija Latvijā (RIS3) tiek noteikta un ieviesta kā stratēģisks dokuments augstas pievienotās vērtības tautsaimniecības izaugsmes atbalsta mehānismu izstrādei, tai skaitā jūras tehnoloģiju nozarei.

Pētījumā tiek pētīti zilās izaugsmes un RIS3 ieviešanas mehānismi, kas būtu izmantojami jūras tehnoloģiju nozares attīstībai, novērtējot šo mehānismu efektivitāti. Tādējādi pētījumā tiek aktualizēti mūsdienīgu tehnoloģiju jomas ieviešanas jautājumi Latvijas jūras piekrastes pašvaldībās un plānošanas reģionos.

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APPLIED PHYSICS

CALCULATION POSSIBILITIES OF 3D PARAMETERS FOR SURFACES WITH IRREGULAR ROUGHNESS

N.Bulaha, J.Rudzitis

Institute of Mechanical Engineering,
Riga Technical University,
36A Viskalu Str., LV-1006, Riga, LATVIA
E-mail: mti@rtu.lv

In the scientific research, calculations of roughness parameters are carried out, with the aim of comparing measured values of roughness parameters with the calculated ones by normal random field equations. First of all, roughness measurement experiments for surfaces with irregular roughness are carried out to determine the roughness parameters and the ordinate distribution histograms using modern measuring equipment Taylor Hobson Talysurf Intra 50. Using the obtained experimental data, Pearson criterion calculations are made in order to check the compliance of surface ordinate distribution function to normal Gaussian distribution law. The obtained results showed that for all investigated samples the surface ordinate distribution function complies with normal Gaussian distribution law. The next step is the calculation of several 3D roughness parameters (from the standard ISO 25178-2). According to the obtained results it is concluded that the calculated values of surface roughness parameters Sa, Sp, Spc, Sdq, Sdr are quite close to the values obtained by measuring equipment Taylor Hobson. The acquired formulas may be applicable for determination of 3D roughness parameters.

Keywords: distribution function, 3D roughness parameters, Pearson criterion, surface texture

1. INTRODUCTION

Nowadays, special attention is devoted to solution of engineering tasks – determination of wear, surface contact area, the coefficient of friction and surface contact deformations. Surface roughness parameters, which define surface quality and exploitation characteristics of components, play a considerable role in these types of tasks.

Today calculations of 3D surface roughness parameters have been little studied, and scientists rely on results obtained by measuring equipment. Everyone knows how the 3D surface roughness determination is implemented by profilometers, in turn, the equations used for texture parameter calculations by software are not specifically known. There are general formulas intended for integral calculating within the definition area. In turn, there are the theoretical formulas for calculation of 3D surface roughness parameters, which are suitable for surfaces, whose ordinates are distributed according to the normal Gaussian distribution law.

Particular attention is paid to surfaces treated with abrasive tools and electro-erosion, which are widely applied in the field of engineering and mechatronics. It is important to note that all of these types of surfaces are characterised by irregular distribution of microirregularities over the surface. For all such types of surfaces, roughness is often modelled by the normal Gaussian random field of two parameters *X, Y*, for which the following conditions are typical [1]:

- Symmetrical arrangement of random variable in relation to its average value. It means that roughness parameter *Ssk* – skewness of ordinate distribution function – has to be equal to “0”.
- Kurtosis of roughness ordinate distribution function, which is characterised by roughness parameter *Sku*, has to be equal to “3”.
- The probability that surface ordinate values will be grouped in interval from -3σ to $+3\sigma$ has to be equal to 99.7% , where σ is a root mean square deviation of distribution function.
- Correlation function and its derivatives are continuous.

In further research, the following activities will be performed:

1. Check of roughness ordinate distribution function compliance to the normal Gaussian distribution law.
2. Calculation of 3D roughness parameters, comparing the measured and calculated values of roughness parameters.

2. SURFACE ORDINATE DISTRIBUTION

In the present research, five different types of surfaces: flat grinded, cylindrically grinded, treated with sand blasting, electro-erosion and shot peening have been investigated. The measurement experiments have been carried out on a sample series “Rugotest”. Three surfaces have been measured for each sample. The obtained results of surface roughness measurements will be shown in the tables below.

Surface ordinate distribution compliance with the normal Gaussian distribution law as mentioned above is determined using the distribution function asymmetry indicator – *Ssk*, kurtosis *Sku* and Pearson criterion.

The parameter *Ssk* characterises the asymmetry of surface ordinate distribution function. Depending on the shape and location of roughness microirregularities in relation to the mean plane, this parameter can have either positive or negative values. The given parameter is described by the following equation [2]:

$$Ssk = \frac{1}{Sq^3}\left[\frac{1}{A}\iint_A z^3(x,y)dxdy\right], \quad (1)$$

where Sq – a root mean square height of the scale-limited surface, µm

A – a definition area, mm²

The parameter *Sku* characterises the curvature of surface ordinate distribution function. Depending on how densely the surface microirregularities are distributed over the surface, *Sku* values may be higher or lower than 3. The greater the distance between microirregularities is, the greater the values of parameter *Sku* will be. The given parameter is described by equation [2]:

$$Ssk = \frac{1}{Sq^4}\left[\frac{1}{A}\iint_A z^4(x,y)dxdy\right] \quad (2)$$

The present research analyses χ^2 distribution, which makes it possible to evaluate the compliance degree of theoretical and statistical distribution [3], [4]. There are special tables for χ^2 distribution, according to which the probability P can be determined for each χ^2 value at a certain number of degrees of freedom. Using the tabulated χ^2 values, it is possible to make the conclusions about probability, with which the hypothesis that a particular size *X* is divided by the normal Gaussian distribution law can be accepted.

Table 1

Conformity Assessment of Surface Ordinate Distribution to Normal Gaussian Distribution Law

Type of mechanical treatment	Ordinal No./ Surface No.	*Sa,* [µm]	Pearson criterion			Ssk	Sku
			Probability	$\chi^2_{critical}$	$\chi^2_{calculated}$		
1. Flat Grinding (Rugotest 104)	1 - No.2	0.042	0.95	8.67	0.675	-0.129	2.970
	2 - No.7	1.420			1.347	-0.277	3.000
	3 - No.8	3.120			4.819	-0.473	3.300
2. Cylindrical Grinding (Rugotest 105)	4 - No.2	0.044	0.95	8.67	0.427	-0.124	2.920
	5 - No.4	0.102			8.331	-0.746	4.660
	6 - No.7	1.140			1.239	-0.136	2.580
3. Electro-erosion (Rugotest 107)	7 - No.6	0.736	0.95	8.67	2.059	-0.328	2.930
	8 - No.7	1.200			0.644	-0.096	2.76
	9 - No.8	2.920			0.327	-0.073	2.900
4. Sand Blasting (Rugotest 3)	10 - No.6	0.500	0.95	8.67	2.003	-0.253	3.100
	11 - No.7	1.070			0.924	-0.213	3.18
	12 - No.8	2.3			4.560	-0.267	3.300
5. Shot Peening (Rugotest 3)	13 -No.6	0.487	0.95	8.67	0.275	-0.024	2.990
	14 -No.7	1.270			0.222	-0.021	2.910
	15 -No.8	3.460			1.280	-0.249	2.960

The calculated χ^2 values for surfaces with irregular roughness are shown in Table 1. For chosen probability $p = 0.95$, tabulated value of Pearson criterion χ^2 is 8.67. For all explored surfaces, the calculated values of Pearson criterion are lower than the tabulated ones.

The next step is to check the compliance of values of roughness parameters *Ssk* and *Sku* with standard values of Gauss distribution, where skewness of surface ordinate distribution function *Ssk*=0 and kurotsis *Sku*=3.

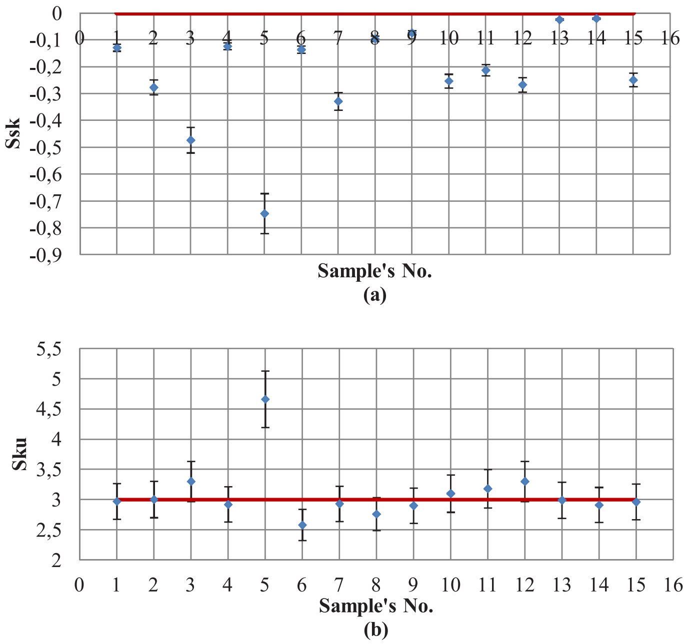

Fig. 1. Comparison of surface roughness parameters *Ssk* (a) and *Sku* (b) with standard values for the normal Gaussian distribution law.

The values of the given parameters are compared with standard values using graphical method, assuming that the values of measured parameters *Ssk* and *Sku* may vary within ±10 %. Figure 1 shows that the values of parameter *Sku* for several surfaces match with the standard values, while the value of parameter *Ssk* only for two surfaces matches with a standard value. *Ssk* and *Sku* values differ for cylindrically grinded surface No. 5, for which the calculated value of Pearson criterion is also greater than for all other surfaces.

Nevertheless, data from Table 1 shows that distribution function of surface ordinates correspond to the normal Gaussian distribution law with probability $p \geq 0.95$ for all investigated samples.

3. CALCULATION OF 3D SURFACE ROUGHNESS PARAMETERS

Solving engineering tasks, for example, wear, surface contact area, coefficient of friction, surface contact deformations, it is important to understand the connection between the modelled surface and the experimental data. Irregular surface roughness is very often modelled by the normal random field of two parameters *X, Y*. The present paragraph describes the compliance of parameters of normal random field with experimental results.

The first group of roughness parameters is amplitude parameters. As mentioned above, the surface roughness is mainly characterised by height parameter *Sa*, which is directly related to the root mean square deviation *Sq*. Knowing *Sq* value, parameter *Sa* can be calculated using the following equation [1]:

$$E\{Sa\} \approx Sq \cdot \sqrt{\frac{2}{\pi}} \tag{3}$$

where *Sa* – an arithmetical mean height of the scale limited surface, [µm];
Sq – a root mean square height of the scale-limited surface, [µm].

Table 2

Comparison of Calculated and Measured Values for Parameter *Sa*

Type of mechanical treatment	Ordinal No./ Surface No.	$Sa_{calculated}$, [µm]	$Sa_{measured}$, [µm]	ΔSa, %
1. Flat Grinding (Rugotest 104)	1 - No.2	0.042	0.042	0
	2 - No.7	1.420	1.42	0
	3 - No.8	3.176	3.12	1.79
2. Cylindrical Grinding (Rugotest 105)	4 - No.2	0.043	0.043	0
	5 - No.4	0.107	0.102	4.90
	6 - No.7	1.117	1.14	-2.01
3. Electroerosion (Rugotest 107)	7 - No.6	0.728	0.736	-1.08
	8 - No.7	1.180	1.200	-1.66
	9 - No.8	2.905	2.920	-0.51
4. Sand Blasting (Rugotest 3)	10 - No.6	0.501	0.500	0.20
	11 - No.7	1.085	1.070	1.40
	12 - No.8	2.330	2.300	1.30
5. Shot Peening (Rugotest 3)	13 - No.6	0.488	0.487	0.20
	14 - No.7	1.268	1.270	-0.15
	15 - No.8	3.455	3.460	-0.14

Table 2 shows that all calculated values of parameter *Sa* are very close to the measured ones and lie within the range ± 10 %. It can be concluded that deviations of surface ordinate distribution practically do not change the relationship between basic parameters *Sa* and *Sq*.

The next roughness parameter is *Sp* – the maximum peak height subtracted from the mean plane [5]. The parameter *Sp* may find application in sliding contact issues. The given parameter can be calculated by the following formula [1]:

$$E\{Sp\} \approx 2 \cdot Sq \cdot \sqrt{\ln\left[E\{N_{01}\} \cdot \sqrt{Str}\right]}\ , \qquad (4)$$

where $E\{N_{01}\}$ – the number of intersections with a mean line;
Str – a texture aspect ratio.

Consequently, to calculate this parameter it is necessary to know anisotropy coefficient and number of zeros. In [6], it is substantiated that anisotropy coefficient can be replaced by 3D roughness parameter *Str* – a texture aspect ratio. The number of zeros can be determined by profile diagrams. In this case, the number of zeros is calculated as the arithmetic mean of three profile diagrams.

Table 3

Comparison of the Calculated and Measured Values for Parameter *Sp*

Type of mechanical treatment	Ordinal No./ Surface No.	$Sp_{calculated}$, [μm]	$Sp_{measured}$, [μm]	ΔSp, %
1. Flat Grinding (Rugotest 104)	1 - No.2	0.147	0.154	-4.55
	2 - No.7	5.51	6.09	-9.52
	3 - No.8	11.97	12.9	-7.21
2. Cylindrical Grinding (Rugotest 105)	4 - No.2	0.165	0.178	-7.30
	5 - No.4	0.387	0.447	-13.42
	6 - No.7	4.23	4.18	1.20
3. Electroerosion (Rugotest 107)	7 - No.6	3.59	2.81	27.76
	8 - No.7	5.97	4.85	23.09
	9 - No.8	15.16	13.8	9.86
4. Sand Blasting (Rugotest 3)	10 - No.6	2.38	2.47	-3.64
	11 - No.7	4.89	4.99	-2.00
	12 - No.8	10.95	9.61	13.94
5. Shot Peening (Rugotest 3)	13 - No.6	2.29	2.44	-6.15
	14 - No.7	5.81	5.86	-0.85
	15 - No.8	15.17	13.8	9.93

From Table 3, it can be concluded that the values of parameter Sp obtained by Taylor Hobson are close to the calculated ones, only for four samples Sp values fall outside the acceptable ± 10 %.

The next group of 3D roughness parameters is feature parameters. This group includes arithmetic mean peak curvature Spc [5]. This parameter can be applicable to contacting surfaces working in friction and wear conditions. Spc can help determine microirregularity ability of deforming plastically or elastically under the load. The appropriate surface intersection level γ needs to be selected for Spc calculations. The researchers have determined that theoretical and measured values of peak number start to coincide at levels above $\gamma = 2$ [1], which is why in the given calculations values of Spc are checked at three levels: $\gamma = 2; 2{,}5; 3$. Calculation formula for parameter Spc is the following [1]:

$$E\{Spc\} \approx \frac{1}{2} \cdot \pi^2 \cdot Sq \cdot \left(\frac{2}{RSm_1} \right)^2 \cdot (1 + Str^2)\gamma, \tag{5}$$

where RSm_1 – the mean spacing of profile irregularities in direction perpendicular to processing traces, [mm]; *RSm1* is determined as an arithmetic mean of three profile diagrams.

γ – a relative surface height section, which is calculated by the formula (6):

$$\gamma = \frac{u}{\sigma}, \tag{6}$$

where u – the height subtracted from the mean plane; u=1σ, 2σ, 3σ eth.

σ – the root mean square height, [µm].

Table 4

Comparison of the Calculated and Measured Values for Parameter *Spc*

Type of mechanical treatment	Ordinal No./ Surface No.	$Spc_{calculated}$, for γ=2, [1/µm]	$Spc_{calculated}$, for γ=2,5, [1/µm]	$Spc_{calculated}$, for γ=3, [1/µm]	$Spc_{measured}$, [1/µm]	ΔSpc, %
1. Flat Grinding (Rugotest 104)	1 - No.2	0.00034	0.00042	0.00051	0.00024	41.67 (γ=2)
	2 - No.7	0.00343	0.00429	0.00515	0.00593	-8.09 (γ=3)
	3 - No.8	0.00342	0.00428	0.00514	0.00441	-2.95 (γ=2,5)
2.Cylindrical Grinding (Rugotest 105)	4 - No.2	0.00127	0.00159	0.00191	0.00310	-38.39 (γ=3)
	5 - No.4	0.00056	0.00070	0.00084	0.00061	-8.20 (γ=2)
	6 - No.7	0.00623	0.00779	0.00935	0.00472	31.99 (γ=2)
3.Electro-erosion (Rugotest 107)	7 - No.6	0.02067	0.02580	0.03100	0.02090	-1.10 (γ=2)
	8 - No.7	0.01725	0.02150	0.02580	0.01070	61.21 (γ=2)
	9 - No.8	0.00780	0.00980	0.01180	0.00830	-6.02 (γ=2)
4.Sand Blasting (Rugotest 3)	10 - No.6	0.00740	0.00930	0.01110	0.00620	19.35 (γ=2)
	11 - No.7	0.01030	001290	0.01550	0.01110	-7.21(γ=2)
	12 - No.8	0.01350	0.01690	0.02030	0.00920	46.74 (γ=2)
5. Shot Peening (Rugotest 3)	13 - No.6	0.00590	0.00740	0.00880	0.00600	-1.67 (γ=2)
	14 - No.7	0.00888	0.01111	0.01333	0.0108	2.87 (γ=2,5)
	15 - No.8	0.00627	0.00784	0.00940	0.00612	2.45 (γ=2)

Table 4 represents the values of parameter *Spc* at different levels γ. In the present research, the smallest value from three γ levels is determined for ΔSpc. From Table 4, it can be concluded that the measured *Spc* values mainly correspond to the calculated ones at level γ = 2.

The third group of roughness parameters is hybrid parameters, one of which is a parameter *Sdq* – a root mean square gradient. The given parameter can be applicable for evaluation of sealing, in theory of light and electromagnetic beam reflectance, as well as for determination of a surface wetting degree by various fluids.

The given parameter is calculated by the following formula [1]:

$$E\{Sdq\} \approx \frac{\pi}{2} \cdot Sq \cdot \frac{2}{RSm_1} \cdot \sqrt{\pi \cdot (1 + Str^2)} \cdot \quad (7)$$

Table 5

Comparison of the Calculated and Measured Values for Parameter *Sdq*

Type of mechanical treatment	Ordinal No./ Surface No.	$Sdq_{calculated}$, [μm/μm]	$Sdq_{measured}$, [μm/μm]	ΔSdq, %
1. Flat Grinding (Rugotest 104)	1 - No.2	0.0037	0.0035	5.71
	2 - No.7	0.0693	0.0964	-28.11
	3 - No.8	0.1034	0.132	-21.67
2.Cylindrical Grinding (Rugotest 105)	4 - No.2	0.0110	0.0107	2.80
	5 - No.4	0.0077	0.0085	-9.41
	6 - No.7	0.0827	0.0822	0.61
3.Electroerosion (Rugotest 107)	7 - No.6	0.1290	0.1420	-9.15
	8 - No.7	0.1420	0.1200	18.33
	9 - No.8	0.1501	0.1530	-1.90
4.Sand Blasting (Rugotest 3)	10 - No.6	0.0641	0.0681	-5.87
	11 - No.7	0.1120	0.1280	-12.50
	12 - No.8	0.1763	0.1700	3.71
5. Shot Peening (Rugotest 3)	13 - No.6	0.0538	0.0595	-9.58
	14 - No.7	0.1100	0.1270	-13.39
	15 - No.8	0.1460	0.1430	2.10

Data from Table 5 indicate that *Sdq* parameter values are very close to the calculated ones, and only for five samples this parameter values do not lie within ± 10 %.

The last parameter, which has been analysed in the present research, is the developed interfacial area ratio *Sdr* [5] that defines the relationship between the real and nominal surface area. Values of this parameter are important particularly in case of surface adhesion. The greater the developed surface area is, the greater the number of links is between the substrate and coating. *Sdr* parameter can be calculated using the following equation [1]:

$$E\{Sdr\} \approx \frac{\pi^2}{2} \cdot Sq^2 \cdot \left(\frac{2}{RSm_1}\right)^2 \cdot (1 + Str^2) * 100\% \cdot \quad (8)$$

Table 6

Comparison of the Calculated and Measured Values for Parameter *Sdr*

Type of mechanical treatment	Ordinal No./ Surface No.	$Sdr_{calculated}$, %	$Sdr_{measured}$, %	Δ*Sdr*, %
1. Flat Grinding (Rugotest 104)	1 - No.2	0.0009	0.0006	50.00
	2 - No.7	0.3059	0.4610	-33.64
	3 - No.8	0.6822	0.8570	-20.40
2. Cylindrical Grinding (Rugotest 105)	4 - No.2	0.0034	0.0057	-40.35
	5 - No.4	0.0038	0.0036	5.56
	6 - No.7	0.4364	0.3360	29.88
3. Electroerosion (Rugotest 107)	7 - No.6	0.9436	1.0100	-6.57
	8 - No.7	1.2855	0.7200	78.54
	9 - No.8	1.4350	1.1600	23.71
4. Sand Blasting (Rugotest 3)	10 - No.6	0.2338	0.2320	0.78
	11 - No.7	0.7427	0.8210	-9.54
	12 - No.8	1.9814	1.4300	38.56
5. Shot Peening (Rugotest 3)	13 - No.6	0.1810	0.1770	2.26
	14 - No.7	0.7266	0.8030	-9.51
	15 - No.8	1.3579	1.0100	34.45

According to the data from Table 6, it can be seen that only for six surfaces the measured values of *Sdr* fall within the range ± 10 %, which may be explained by the insufficient number of measurements.

4. CONCLUSIONS

In the present scientific research, the possibility of applicability of calculation formulas for 3D roughness parameters has been checked and compliance of roughness ordinate distribution function with the normal Gaussian distribution law has been determined. It has been established that values of roughness parameters *Sa, Sp, Sdq, Sdr, Spc* obtained by the measuring equipment Taylor Hobson are quite close to the calculated ones. Incomplete coincidence of the measured and calculated values can be explained by surface ordinate distribution, for which *Ssk* and *Sku* values for some investigated surfaces do not fall within the deviation zone ± 10 %, without taking into account that the Pearson criterion value with probability > 95 % indicates that the ordinate distribution function conforms to the normal Gaussian distribution law. In addition, these results may be affected by the limited number of experiments. It has been concluded that equations analysed in the research can be applied for calculation of 3D roughness parameters and solution of global engineering tasks.

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3D PARAMETRU APRĒĶINU IESPĒJAS VIRSMĀM AR NEREGULĀRU RAUPJUMU

N.Bulaha, J.Rudzitis

K o p s a v i l k u m s

Dotajā zinātniskajā darbā tika veikti raupjuma parametru aprēķini, ar mērķi salīdzināt ar mēraparātu iegūtas raupjuma parametru vērtības ar aprēķinātām. Pirmajām kārtam, tika veikti virsmas raupjuma mērīšanas eksperimenti virsmām ar neregulāru raupjumu: slīpētām, apstrādātām ar elektroeroziju, smilšstrūklu un apšaudītām ar skrotīm, lai noteiktu raupjuma parametrus un virsmas ordinātu histogrammas, izmantojot moderno mērīšanas tehniku Taylor Hobson Talysurf Intra 50. Izmantojot iegūtos eksperimentālos datus, tika veikti Pirsona kritērija eksperimenti, lai pārbaudītu virsmas ordinātu sadalījuma sakritību ar normālo Gausa sadalījuma likumu. Pēc aprēķiniem tika noteikts, ka normālais Gausa sadalījuma likums ir raksturīgs visām pētāmām virsmām; tas, galvenokārt, tika pamatots ar Pirsona kritēriju, kura aprēķinātas un tabulētas vērtības sakrīt pie varbūtības 95%. Nākamais solis bija dažādu 3D raupjuma parametru (pēc standarta ISO 25178-2) aprēķini, izmantojot normālā gadījuma lauka formulas, ar mērķi noteikt sakarības starp eksperimentāliem datiem un modelētas virsmas parametriem. Parametru Sa, Sp, Spc, Sdq un Sdr vērtības bija salīdzinātas ar nomērītām. Pēc iegūtiem rezultātiem tika secināts, ka virsmas raupjuma aprēķinātas vērtības ir ļoti tuvas eksperimentālām, iegūtām ar Taylor Hobson mērīšanas tehniku. Taču dažiem paraugiem starpība sastādīja vairāk par ±10%, kas varētu būt izskaidrojams ar limitēto eksperimentu skaitu vai iespējamiem virsmas defektiem. Neskatoties uz to, iegūtas formulas var pielietot 3D raupjuma parametru noteikšanai.

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