Analysis of the Influence of NdFeB Permanent Magnet's Type and Volume on the Characteristics of a PM Claw-pole Alternator

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***Abstract*—This paper proposes an analytical method to calculate the magnetic flux in the air gap of a claw-pole alternator, created by a NdFeB permanent magnet in the rotor. The proposed method can also be used to calculate the dimensions and the volume of a permanent magnet that will create a desired voltage in the machine. The possibility to obtain a certain value of the machine voltage with lower volume of rare earth material will lead to a decrease in the cost of the final product. The need for such a method is grounded on the complex geometry of this type of electrical machines, which would require a time consuming 3D modelling with FEM analysis software. Knowing the air-gap magnetic flux of the machine permits the right choice of permanent magnet type and volume, which facilitates the designing phase of the alternator. The influence of the permanent magnet's cross section and length on the magnetic flux in the air-gap of the alternator is analyzed. A comparison between the electromotive forces created by a permanent magnets with different grades is made and presented.**

Keywords*—*claw-pole alternator, equivalent magnetic circuit, NdFeB permanent magnet.

I. Introduction

The claw-pole alternator is a type of a synchronous generator that is used in the automotive industry, as a source of power supply, for the vehicle's electrical needs. A particularity of this type of electrical machines is the form of its rotor, whose poles have a claw-like shape – thus its name. This machine uses a single excitation winding that creates the rotor magnetic field. This technical particularity feature makes the claw-pole alternators exceptionally competitive from an economic point of view, because they can be manufactured relatively easy and fast, compared to other types of electrical machines, and their components are relatively cheap.

A drawback of this type of electrical machines is their reduced efficiency – around 50-60% [1]. This is due to the fact that the small electrical machines naturally have lower efficiency. Another reason for this drawback is the rotor's shape, which augments the leakage losses, compared to other types of synchronous generators. To cover these superior leakage losses, the excitation current must be increased, which also increases the total losses in the alternator.

To combat the increased excitation losses, the field winding can be replaced with a permanent magnet [2], [3], [4]. By doing so, the electrical energy, that was used to create the magnetic field in the machine (most frequently this energy is produced by the alternator itself), can be used to supply the load. The replacement of the field winding with a permanent magnet also removes the need of brushes and contact rings in the rotor, which further reduces the mechanical losses and improves the machine's durability by reducing the need of maintenance. The improving qualities of rare earth permanent magnets in recent years makes them a suitable option for the replacement of the field winding in a claw-pole alternator [5].

However, the unstable prices of the neodymium which have skyrocketed since the summer of 2020 [6], call for ways to find the lowest and cheapest volume of rare earth material, for the permanent magnets in the alternator's rotor. The 3D FEM analysis permits this, but the required software is relatively expensive and the computations are time and resource consuming. The aim of this work is to propose a methodology for a comparatively fast and easy way to calculate the magnetic characteristic of a PM claw-pole alternator and its stator electromotive force, using different permanent magnet configurations in the rotor. The results of the proposed method ease the selection of an appropriately sized magnet, regarding its price and its potential to create the required magnetic flux in the alternator.

II. Proposed Methodology

This work proposes a method for the calculation of the magnetic flux, in the air-gap, created by the permanent magnet in the machine's rotor. By varying the permanent magnet dimensions one can calculate the required volume of rare earth material that can produce the required voltage at the alternator's terminals.

The proposed method is based on a model of the equivalent magnetic circuit of the machine [7], [8], [9]. The equivalent magnetic circuit used in this study is for one pole

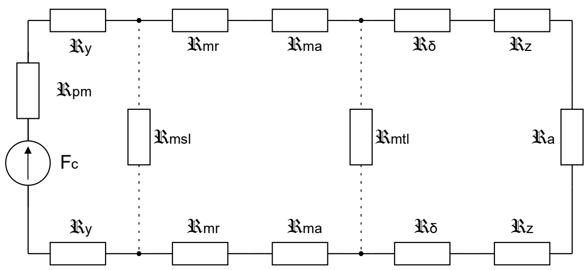

Fig. 1 Proposed equivalent magnetic circuit, for one pole-pair of a claw-pole alternator [7].

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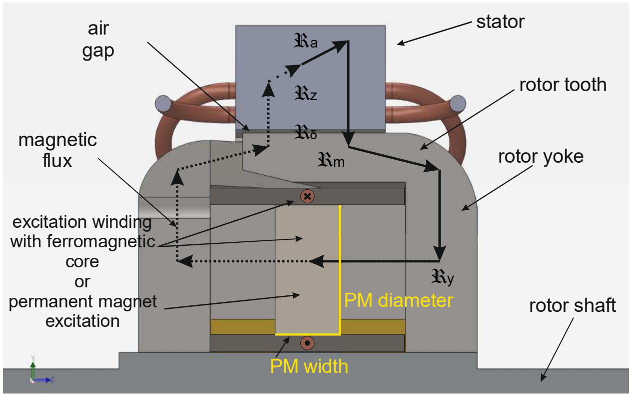


Fig. 2 Visualization of the reluctances in the alternator [12].

pair and is shown in Fig. 1. The path of the magnetic flux in the alternator, as well as a visualization of the reluctances and their location in the machine are presented in Fig. 2. The reluctances in the alternator are as follows: $\mathfrak{R}_\delta$ – air gap; $\mathfrak{R}_z$ – stator teeth; $\mathfrak{R}_a$ - stator yoke; $\mathfrak{R}_y$ - rotor yoke; $\mathfrak{R}_{mr}$ and $\mathfrak{R}_{mt}$ are the reluctances in the radial and tangential direction of the rotor pole, which for simplicity have been calculated as a single rotor pole reluctance $\mathfrak{R}_m$, and $\mathfrak{R}_{pm}$ is the reluctance of the permanent magnet, which is not used in the calculations of the external magnetic circuit. The leakage reluctances $\mathfrak{R}_{msl}$ (leakage reluctance between the two sides of the rotor yoke) and $\mathfrak{R}_{mtl}$ (tangential leakage flux between rotor poles) are neglected, due to their complex determination, which is shown in the figure with a dashed line. However, to calculate the leakage flux in the machine, magnetic leakage factors are used. According to [11], the magnetic leakage factor σ in the claw-pole alternators varies between 1.3 and 1.5. Here a magnetic leakage factor of σ=1.3 has been used. For easier determination of the reluctances of the different sections of the magnetic circuit, the geometry of some of the elements (such as the rotor poles) is simplified.

The proposed method is applied to an alternator of type G221, manufactured by "Dynamo – Sliven", Bulgaria. The alternator has an outer rotor diameter of 89 mm, 0.5 mm air-gap, 12 poles and 3 phases with 7 stator winding turns per pole and phase and 15 A rated phase current. The rotor length is 52 mm and the stator length is 23 mm, with 2.5 mm stator slot width, 10 mm stator slot height and 36 stator teeth.

The permanent magnet used in the study is ring-shaped, with a fixed internal diameter of 30mm (due to the rotor shaft diameter) and the outer diameter varies from 35mm up to 75mm in 5mm steps, thus varying the magnet's dimensions. In addition, the effects of varying the permanent magnet's width from 4mm to 10mm are studied. The constraints on the permanent magnet's dimensions are purely due to the geometry of the modelled machine and are not obligatory.

The magnetic characteristic of the alternator is obtained according to a classical methodology, proposed in [9], that is modified for the claw-pole alternator with permanent magnet excitation, and is calculated for a single pole pair. The main sections of the proposed magnetic circuit are the air-gap, the stator teeth and stator yoke, the rotor yoke and the claw-poles.

To describe the proposed magnetic circuit the following equation is used:

$$2H_\delta \delta + 2H_z h_z + 2H_a L_a + 2H_m h_m + 2H_y L_y = F \qquad (1)$$

Here H_δ, H_z, H_a, H_m, H_y, are the air gap, stator teeth, stator yoke, rotor pole and rotor yoke magnetic field strengths, δ is the air gap length, h_z is the height of the stator teeth, L_a is the length of the stator yoke, h_m is the height of the rotor pole, L_y is the length of the rotor yoke. This equation can be simplified for a single pole as:

$$F_\delta + F_z + \frac{F_a}{2} + F_m + F_y = F \qquad (2)$$

Here F_δ, F_z, F_a, F_m, F_y are the magnetomotive forces of the air gap, stator teeth, stator yoke, rotor poles and rotor yoke, and F is the total magnetomotive force in the equivalent magnetic circuit, created by the permanent magnet in the rotor F_{pm} and the armature current reaction F_{ad}.

$$F = F_{pm} \pm F_{ad} \qquad (3)$$

The worst possible case for the armature current reaction is the demagnetizing reaction at full load, which is calculated by:

$$F_{ad} = \frac{m\sqrt{2}}{\pi}\frac{wk_w}{p} I_d \qquad (4)$$

where m is the number of phases, w is the number of stator winding turns, k_w is the winding coefficient, p is the pole-pairs number and I_d is the stator current in the direct axis.

It has to be noted that the alternators usually operate with a built-in diode rectifier, which have a capacitive power factor of 0.85-0.9. This type of load produces a magnetizing armature current reaction in the alternator.

The operating temperature has great impact on the operational point of the permanent magnet in the rotor. The rotor of a claw-pole alternator can easily reach temperatures greater than 100ºC [10], which calls for the use of high-temperature grades of neodymium magnets such as NM (100°C), NH (120°C), NSH (150°C), NUH (180°C), NEH (200°C). For this study, the characteristics of three different grades of NdFeB magnets at a temperature of 80°C are used – N30SH, N38SH and N45SH [13].

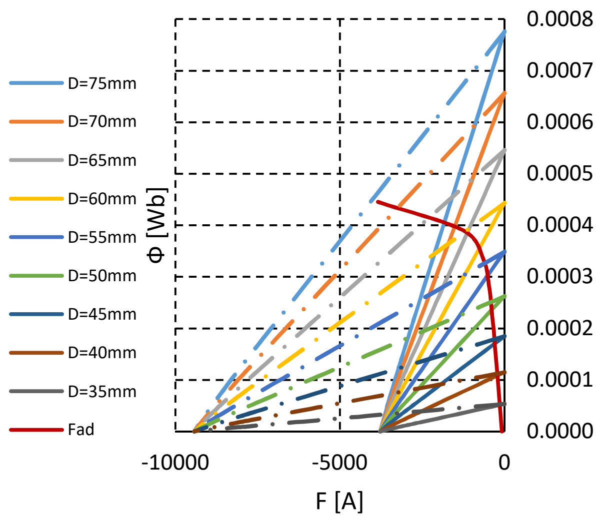


Fig. 3 Calculated characteristics of a N45SH NdFeB magnet in the rotor, with 10 mm (dashed line) and **4 mm (solid line) magnet length and different outer diameters D** and calculated characteristic of the external equivalent magnetic circuit of the alternator. The air-gap flux Φ_δ is determined graphically by the crossing of both characteristics and is used to calculate the alternator's electromotive force.

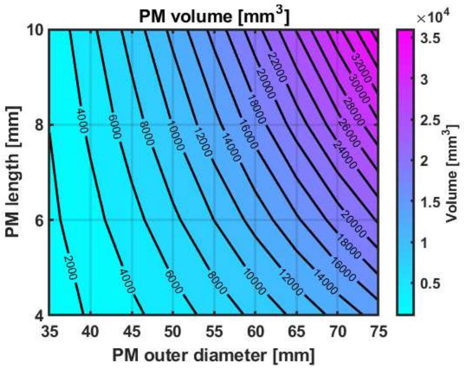


Fig. 4 Calculated volume of the ring shaped permanent magnet in the rotor (in mm^3) depending on the PM length and PM outer diameter.

in one phase winding of the alternator, k_w is the winding coefficient, which for the studied machine equals 1.

The presented equations are used to calculate the voltages of the studied alternator, using different grades and dimensions of the rare earth magnets in the rotor for a variety of rotational speeds.

III. Computational Results

Using the presented method, an analysis of the influence of the permanent magnet's dimensions and type on the claw-pole alternator's electromotive force has been conducted. The magnetic characteristic of the alternator using a permanent magnet with varying length (4mm, 6mm, 8mm and 10mm) and outer diameter (from 35mm to 75mm with 5mm step) has

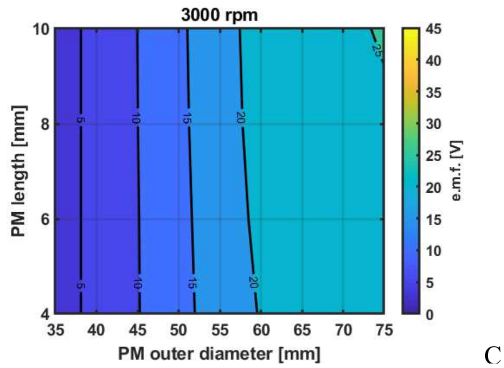
TABLE I. Cross section of the permanent magnet in the rotor, depending on its outer diameter

Outer diameter D (mm)	35	40	45	50	54.2	55	58.7	60	65	70	75
Cross section (mm^2)	255.25	549.78	883.57	1256.64	1600	1668.97	2000	2120.58	2611.45	3141.59	3711.01

After calculating the total magnetomotive force in the external equivalent magnetic circuit, the characteristic of the alternator is plotted against the characteristic of the permanent magnet in the rotor – Fig. 3. The magnetic flux in the air gap Φ_δ is determined by the crossing of the two characteristics. Using this magnetic flux, the electromotive force of the alternator for different rotational speeds is calculated:

$$E=\pi\sqrt{2} f w_c k_w \Phi_\delta \qquad (5)$$

where E is the no-load electromotive force, f is the frequency of the induced electromotive force, w_c is the number of turns



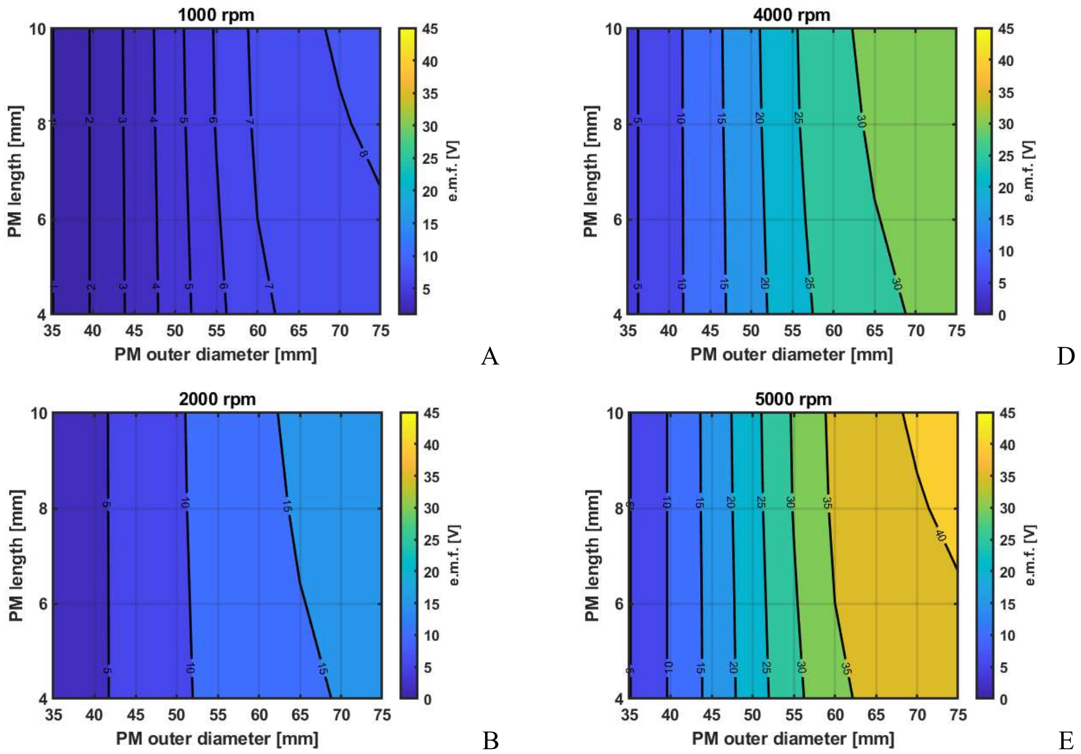


Fig. 5 Calculated electromotive forces with demagnetizing armature current reaction taken into account, depending on PM length and PM outer diameter for rotational speeds of (A) 1000 rpm, (B) 2000 rpm, (C) 3000 rpm, (D) 4000 rpm and (E) 5000 rpm and a N45SH permanent magnet at 80ºC.

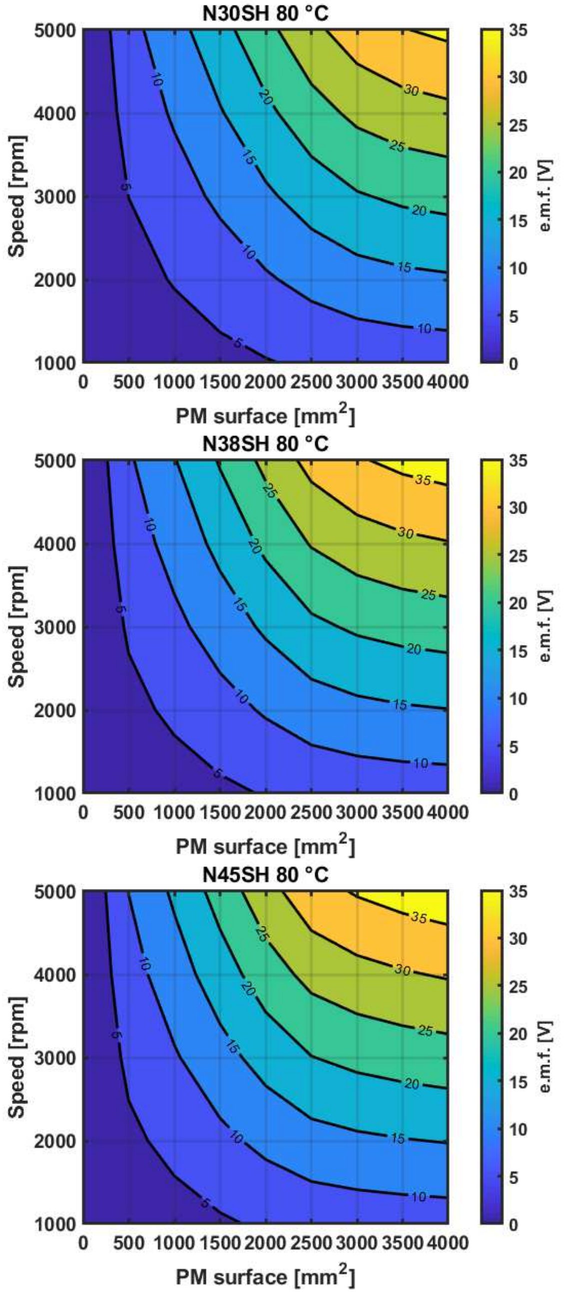


Fig. 6 Calculated terminal voltage of the PM alternators for N30SH (**top**), N38SH (**middle**) and N45SH (**bottom**) NdFeB magnets at 80ºC for a permanent magnet with 4 mm length and different PM cross sections and rotational speeds of the machine.

been calculated and the magnetic flux in the air gap has been determined as shown in Fig. 3. The volume of the permanent magnet in dependence of its length and outer diameter is presented on Fig. 4. The calculated electromotive forces of the alternator with the maximal possible demagnetizing armature current reaction, depending on PM length and PM outer diameter for different rotational speeds are shown in Fig. 5. This way the correlation between the desired voltage and the volume of the permanent magnet in the rotor can be made. The desired voltage for a given rotational speed can be determined from Fig. 5 and then by plotting the isoline of this value on Fig. 4 the volume needed to attain it can be determined. The results show, that a permanent magnet with 4 mm length produces enough magnetic flux in the air-gap to reach adequate e.m.f. of the alternator, while severely reducing the volume of rare earth material.

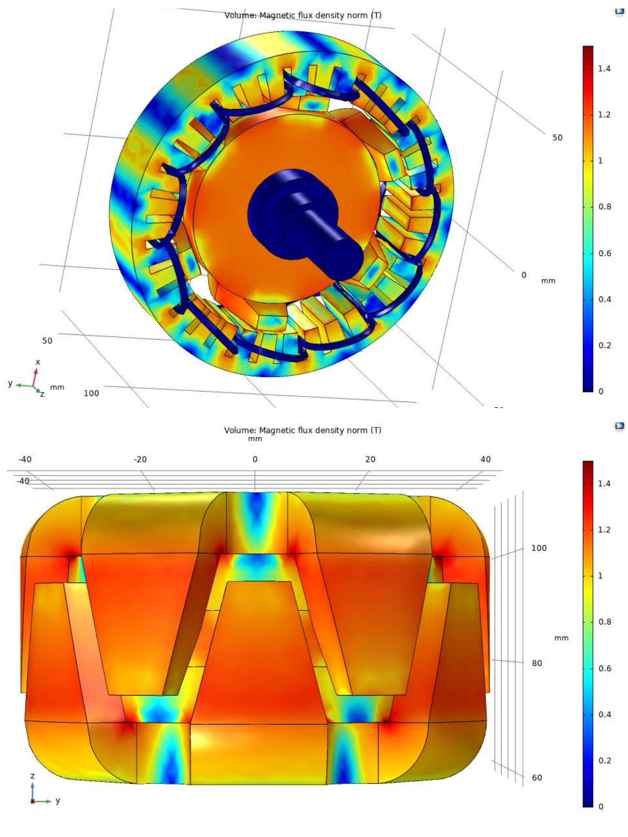


Fig. 7 Magnetic flux density in the alternator with N45SH ring shaped permanent magnet (D=70mm, d=30mm, L=10mm), obtained from the performed 3D FEM analysis.

The obtained results show that a permanent magnet length of 4 mm provides a sufficient output e.m.f. for the studied claw-pole alternator, while severely reducing the volume of the rare earth material, thus reducing the price of the machine. After the magnetic flux in the air gap for the N30SH, N38SH and N45SH permanent magnets with 4mm length and different outer diameters has been determined, the e.m.f. of the alternator has been calculated for different rotational speeds. Changing the outer diameter the cross section of the magnet and therefore its magnetic flux are varied. Table I

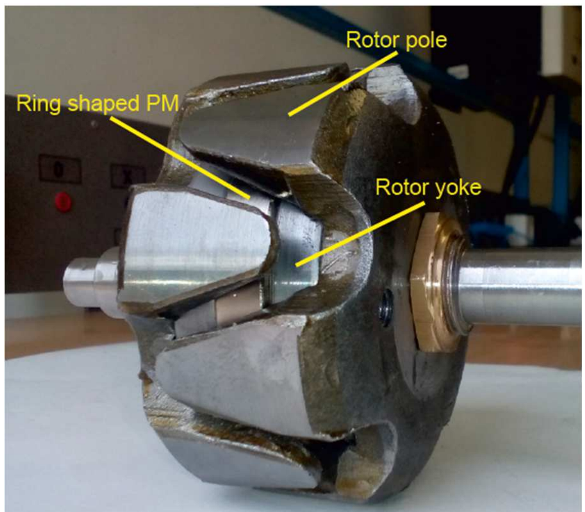


Fig. 8 Modified rotor of the created permanent magnet alternator.

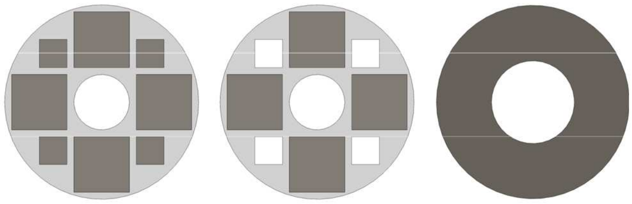


Fig. 9 Different configurations of the permanent magnets used in the rotors of the created alternators. From left to right: 8 magnets with total cross section 2000mm^2 (corresponding to PM outer diameter 58.7mm); 4 magnets with total cross section 1600mm^2 (corresponding to PM outer diameter 54.2mm), ring shaped magnet with cross section 3141mm^2. All of the magnets are with 10mm length.

presents the calculated cross section of the magnet for the different outer diameters. The calculated electromotive forces are presented in Fig. 6. In this calculation, the maximal possible demagnetizing armature current reaction taken into account, to study the worst possible case for the machine. There the alternator's e.m.f. is presented in dependence of the rotational speed and the permanent magnet's cross section. From these results the desired PM surface for the required terminal voltage of the machine can be determined. It has to be noted that removing the excitation winding of the alternator eliminates the possibility to regulate the terminal voltage. Most of these machines are used in the automotive industry as DC generators, where they operate along with a diode rectifier, to supply a relatively constant voltage to the vehicle's battery. To tackle this issue, a DC-DC converter (such as non-inverting buck-boost, SEPIC, Čuk) which has the ability to increase or decrease their input voltage to a desired value must be used.

IV. Experimental Validation

To prove the proposed methodology, 3D FEM analysis of the alternator has been conducted – Fig. 7, and a laboratory model of the proposed permanent magnet alternator is created. The modified rotor with a ring shaped magnet is shown in Fig.

TABLE II. Difference between the calculated and measured e.m.f.

S (mm^2)	3D FEM (%)	Proposed method (%)
1600	0.43	-6.89
2000	-0.02	-5.12
3141	1.86	7.39

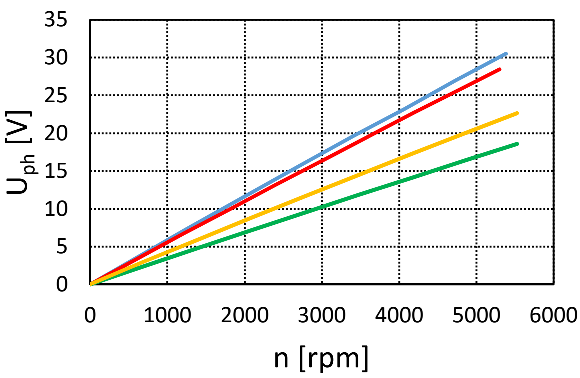


Fig. 11 No-load phase voltage, depending on the rotational speed of the alternators with different types of excitation. Red line – excitation winding with excitation current 3.3A; blue line – permanent magnet with area 3144mm^2; yellow line – permanent magnet with area 2000mm^2; green line – permanent magnet with area 1600mm^2. The lengths of the permanent magnets in the created alternators are 10 mm.

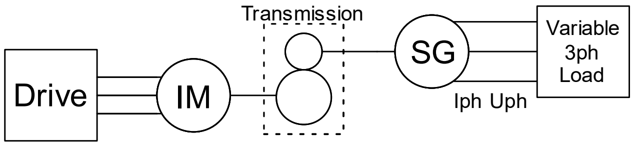


Fig. 10 Block-scheme of the experimental test bench. The alternator (SG) is driven by an induction motor (IM) through a transmission. The speed of the IM is varied by a 3ph inverter (Drive). The alternator is loaded by a 3ph variable active load and its phase voltage (U_{ph}) and phase current (I_{ph}) are measured.

8. The created alternator uses three different permanent magnet configurations, shown in Fig. 9. Not all of the used magnets are ring magnets, due to the availability of NdFeB magnets on the market. However, this comes as an advantage in the experimental phase, because the developed configurations permit the relatively easy use of different cross sections of permanent magnets in the rotor by varying the number of magnets and respectively their flux. All of the magnets are with 10 mm length, again due to the available magnets. The permanent magnet alternator is driven by an induction motor and is studied as an AC generator without the use of the in-built diode rectifier. The block-scheme of the experimental test bench is presented in Fig. 10. Some of the alternator's characteristics are presented at the figures below. The no-load phase voltage of the tested alternators in function of the rotational speed is shown at Fig. 11. There, a comparison is made between the voltages of the three created alternators with permanent magnet excitation and the original alternator with an excitation winding, supplied by its maximum excitation current. From these results it is clearly visible, that the electromotive force of the alternator depends on the surface of the permanent magnets used in the rotor.

A comparison between the calculated and measured e.m.f. of the alternator for a rotational speed of 3600 rpm is presented at Fig. 12. Eq. (5) is used for calculation of the e.m.f.. The comparison is made between the 3D FEM obtained results, the proposed method and the experimentally measured voltages of the created alternators. The difference between these values is presented in Table II. It can be seen that the results from the 3D FEM analysis correspond very well with the experimentally obtained results. On the other hand the difference between the electromotive force, calculated by the

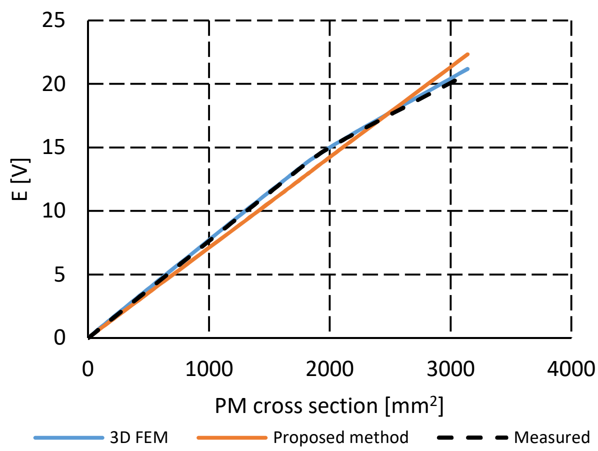


Fig. 12 Comparison between the measured (dashed line) and calculated electromotive force of the alternator for a rotational speed of 3600 rpm.

proposed method and the experimental results reaches up to 7,4%. This can be explained with the simplification of the geometry of some of the elements in the magnetic circuit of the alternator, as well as the used method of interpolation of the BH curves of the stator and rotor steel. However, the difference between the results of the proposed method and the measured voltages of the alternators is in acceptable limits (below 10%). Having in mind this, as well as the difficulty to create a 3D model of the rotor, the relatively high price of the 3D FEM analysis software and the fact that this type of analysis can be extremely time consuming and requires great computational times, the proposed method can be used at the beginning of the design phase of claw-pole alternators to save time and give acceptable results with relatively low effort. After having used the proposed method, one can decide on the dimensions and type of the permanent magnet used and proceed with a 3D FEM analysis and the creation of the claw-pole alternator.

V. Conclusion

An analytical method to calculate the air-gap magnetic flux in a claw-pole alternator has been proposed. By knowing the air-gap magnetic flux, this method permits the calculation of the e.m.f. of the claw-pole alternator, created by a permanent magnet with a certain length and cross section. On the other hand, the method permits to calculate the dimensions and the volume of a permanent magnet that will create a desired voltage in a certain interval. The possibility to obtain a particular value of the machine voltage with a lower volume of rare earth material will lead to a decrease in the cost of the final product. The fast and easy calculation of these parameters in the early stage of the design phase of the machine permits the optimization of the required volume of rare earth material in the alternator's rotor, imposed by the growing prices of Neodymium. The proposed method uses an equivalent magnetic circuit of the claw-pole alternator, which significantly facilitates the design and reduces the computational times, compared to the 3D FEM analysis with specialized software, while in the same time the loss in precision is acceptable.

The proposed method is applied for a claw-pole alternator with permanent magnet excitation and it permits the selection of the required permanent magnet cross section and length, for a certain desired value of the output voltage of the machine for a given rotational speed. A laboratory model of the permanent magnet claw-pole alternator has been created and the values for the terminal phase voltage of the machine, obtained with the proposed method are compared to the experimentally obtained voltages, with an acceptable accuracy.

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