Selecting the Best Permanent Magnet Synchronous Machine Design for Use in a Small Wind Turbine

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Abstract: The article describes the selection of a permanent magnet synchronous machine design that could be implemented in a small wind turbine designed by the GUST student organization together with researchers working at the Technical University of Lodz. Based on measurements of the characteristics of available machines, eight initial designs of machines with different rotor designs were proposed. The size of the stator, the number of pairs of poles, and the dimensions of the magnets were used as initial parameters of the designed machines. The analysis was carried out about the K-index, the so-called index of benefits. The idea was to make the selected design as efficient as possible while keeping production costs and manufacturing time low. This paper describes how to select the best design of a permanent magnet synchronous generator intended to work with a small wind turbine. All generator parameters were selected keeping in mind the competition requirements, as the designed generator will be used in the author’s wind turbine. Based on the determined characteristics of the generator variants and the value of the K-index, a generator with a latent magnet rotor was selected as the best solution. The aforementioned K-index is a proprietary concept developed for the selection of the most suitable generator design. This paper did not use optimization methods; the analysis was only supported by the K-index.

Keywords: permanent magnet; synchronous machines; small wind turbines

1. Introduction

This article refers to [1–3] and is related to the work on the design of a small wind turbine, which is the focus of a research group from the Technical University of Lodz: GUST (acronym for “Generative Urban Small Turbine”). The group is formed by students and young researchers from the university. The task of the authors of this paper was to design a generator to drive a small wind turbine, which was designed for a competition and according to the related requirements.

The GUST project concerns the development and construction of a small wind turbine (approximately 1 kW power) for sustainable energy delivery in urban and suburban conditions. The horizontal-axis rotor of 1.6 m diameter is intended to use three or four blades designed via an in-house aerodynamic algorithm. The wind turbine’s reliable performance at minimum maintenance is achieved through a robust power conversion system and straightforward mechanical design.

The GUST project is highly oriented toward meeting the UN Sustainability Goals. The designed machine supplies the end user with affordable and clean energy. Still, its process of manufacturing and recycling follows a responsible consumption and production path by favoring eco-friendly materials and design solutions. Compact size and dedicated design principles are making turbines such as the one designed by GUST an increasingly in-demand solution. The reason it is important to use small wind turbines is confirmed by the literature review shared below.

According to the Global Wind Energy Council’s 2023 report [4], the future of wind energy appears promising. The report highlights that 2022 was the third-best year ever for...
new capacity, with 78 GW added globally, bringing the total installed worldwide capacity to 906 GW. This represents a year-over-year growth of 9%. Over the following five years (2023–2027), the GWEC Market Intelligence forecasts 680 GW of new capacity, which represents an addition of 136 GW per year.

Designing wind turbines involves numerous technical challenges. Traditional design processes and approaches need to be reassessed, as modern turbine rotors operate through the entire atmospheric boundary layer. Traditional aerodynamics and aeroelastic modeling approaches are reaching their limits of applicability due to the size and flexibility of future architectures. Uncertainty in turbine wakes complicates both structural loading and energy production estimates [5]. Advancements in wind power-generation technologies are crucial for grid dispatching and energy distribution. Artificial intelligence techniques such as artificial neural networks (ANN) and support-vector machines (SVMs) have been widely used in wind energy forecasting [6,7]. The development of accurate and precise short-term wind power prediction models based on these advanced algorithms is necessary to accommodate large-scale wind power into the electricity grid. Furthermore, the implications of climate change on wind energy potential are being studied, which will also influence the future development of this branch of renewables [8].

1.1. Small Wind Energy

Small wind turbines (SWTs) are compact devices that generate electricity for small-scale (typically not more than 100 kW) use in residential, agricultural, or small commercial and industrial applications [9]. They are usually considered as a part of the prosumer energy concept, a model where consumers also become producers of energy, often using renewable energy sources. This model allows individuals or businesses to generate their own electricity, often feeding excess power back into the grid [10]. In [11], the authors pointed out the impact of SWTs on the Internet of Things scenarios. They overviewed a wide range of wind turbine types and applications, concluding that future development in this direction needs to include three factors: efficiency, durability, and practicality.

Small wind turbines and prosumer energy sources face a multitude of challenges themselves [12]. For small wind turbines, the key challenges include improving energy conversion through better design and control, especially in turbulent wind conditions. Predicting long-term turbine performance with limited resource measurements and proving reliability is another significant hurdle. Furthermore, improving the economic viability of small wind energy and facilitating the contribution of small wind turbines to the energy demand as well as and electrical system integration are also critical. Prosumer energy sources in general face challenges such as managing surplus energy, particularly in promoting energy storage technology and improving interconnections between different regions with varying energy production and consumption profiles [13]. Maintaining voltage quality, including voltage quantity and harmonics, is another significant point [14]. The use of renewable energy sources (wind and solar) can lead to voltage variations and unbalanced, unacceptable voltage rises in the network nodes and uncontrolled power flows in the network. Additionally, ensuring access to distribution and transmission networks and establishing transparent rules for contributing to the associated costs are also significant challenges [15]. Power conversion and control is thus one of the key issues in proper wind turbine design.

1.2. SWT Electricity Generation

The wind turbine generator design process must always be performed with the machine’s cooperation with the SWT rotor and the electric grid in mind. In [16], the authors performed numerical modelling of squirrel-cage and doubly-fed induction generators in wind turbines (albeit for 1.5 MW machines). Having studied a wide range of operating conditions, the authors noted the importance of ensuring proper cooperation of the generator and electric grid.
The authors of [17] compared experimental flux-reversal generators equipped with rare-earth (RE) and non-RE permanent magnets. Two designs of comparable efficiencies and relatively high overload capabilities were tested in no-load and on-load conditions. The authors concluded that the NRE design is a particularly attractive solution, as it was found to have lower demagnetization risk and lower torque ripple and density, with a cost similar to the RE counterpart. The study [18] extended the generator research from the SWT control point of view. The authors examined control techniques based on the adjustment of blade pitch and the generator field current of a 3 kW SWT under real wind conditions in Japan. They concluded that the combination of electric load and proper pitch may successfully replace the mechanical braking systems in case of strong winds.

SWTs as whole machines are often tested within a dedicated case study. The comprehensive design and analysis process of a horizontal-axis SWT was performed [19]. The author identified the main mechanical parameters vital for the generator design process: rated torque and rotational velocity, maximum cogging torque, and maximum temperatures (for overheating protection). Haridas and Parkhe [20] performed a case study of a 500 W horizontal-axis SWT for rural application in India. The authors used a 16-pole permanent magnet generator (PMG) as a relatively inexpensive and reliable power conversion device, which also ensured a low starting speed. A PMG was also proposed by Buaossa et al. in their design of an SWT for applications in Libya [21]. The system was designed for on-grid applications, equipped with off-grid energy storage possibility, e.g., in case of overproduction. The authors applauded the PMG’s low cost, wide range of wind speed operation, and ease of controlling. A PMG was also tested in the study [22], concentrated on increasing the magnetic flux with neodymium magnets. The authors underlined the generated current consequential rise, which may be challenging if the winding is not designed appropriately.

2. Permanent Magnet Synchronous Generator Design

Based on the literature research, the authors of the present study committed themselves to creating their own tailored PM generator for the specific needs of the GUST project.

2.1. Preliminary Requirements

The basic requirements for the designed generator were an active power output of approximately 1–1.2 kW at a rotational speed of 700–800 rpm and the highest possible efficiency. This specific speed assumption means that 8-pole machine designs (synchronous speed 750 rpm) were considered. An additional criterion adopted in the design was to obtain the lowest possible cost for the creation of a prototype machine. However, no cost optimization algorithms were used in the design, only in the additional initial assumptions. The design of the generator was based on available mass-produced induction motors, using their body, shaft, and stator and, if possible, also the winding (it was assumed that the machine would have a double-layer winding). The cost of sourcing these structural components was lower than making bespoke prototype solutions. Thus, the design process involved only the rotor and possibly the winding. An additional possibility to reduce the cost of building a prototype generator was considered: using available mass-produced permanent magnets. The geometrical dimensions of the permanent magnets were therefore an additional initial assumption. The last design assumption made was to keep the machine dimensions as small as possible. To clarify this assumption, it was assumed that the external diameter of the stator would be considered. The generator would operate with a resistive load. The most important pre-requirements of the designed generator are shown in Table 1.

2.2. Stator Choice

The design of the proposed generator was based on series-produced induction motors. Therefore, the selection of the stator (as well as the body and shaft) was based on available types. Table 2 shows the selected stators used in the base induction motors along with the basic parameters.
Table 1. Key prerequisites of the generator project.

<table>
<thead>
<tr>
<th>Order No.</th>
<th>Criteria</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Output power</td>
<td>1.2 kW</td>
</tr>
<tr>
<td>2</td>
<td>Speed</td>
<td>700–800 rpm</td>
</tr>
<tr>
<td>3</td>
<td>Rated speed/number of poles</td>
<td>750 rpm/8</td>
</tr>
<tr>
<td>4</td>
<td>Double-layer</td>
<td>Winding</td>
</tr>
<tr>
<td>5</td>
<td>Rotor core plate</td>
<td>M600-50A</td>
</tr>
<tr>
<td>6</td>
<td>Air gap</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>7</td>
<td>Load type</td>
<td>Resistive</td>
</tr>
<tr>
<td>8</td>
<td>Ambient temperature</td>
<td>40 °C</td>
</tr>
</tbody>
</table>

Table 2. Basic stator parameters of selected induction motor base designs.

<table>
<thead>
<tr>
<th>Order No.</th>
<th>Identification</th>
<th>Shaft Inclination (mm)</th>
<th>Stator Outer Diameter (mm)</th>
<th>Stator Inner Diameter (mm)</th>
<th>Number of Slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>90</td>
<td>135.4</td>
<td>86</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>132</td>
<td>208</td>
<td>140</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>G</td>
<td>100</td>
<td>155</td>
<td>94</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>H</td>
<td>132</td>
<td>208</td>
<td>151</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>I</td>
<td>100</td>
<td>155</td>
<td>85</td>
<td>24</td>
</tr>
<tr>
<td>6</td>
<td>J</td>
<td>112</td>
<td>182</td>
<td>130</td>
<td>48</td>
</tr>
<tr>
<td>7</td>
<td>K</td>
<td>90</td>
<td>128</td>
<td>84</td>
<td>36</td>
</tr>
</tbody>
</table>

2.3. Rotor Design

Of the many permanent magnet synchronous machine rotor shapes used and described in the literature [23–28], eight were selected for analysis. The selected variants have both surface-mounted magnets and latent magnets. The proposed designs are shown in Figures 1 and 2.

Figure 1. Rotor shapes with interior magnets selected for analysis: (a) IPM-01, (b) IPM-03, (c) IPM-12, and (d) S-02.

Figure 2. Rotor shapes with surface-mounted magnets selected for analysis: (a) SM-01, (b) SM-07, (c) SM-08, and (d) B-01.

The various electrical machines used in wind turbines in general are also reviewed [29,30]. Of the pre-selected rotor designs, the SM-01 and B-01 were abandoned due to the need for profile magnets, which are custom-manufactured and therefore more expensive. The S-02 was also abandoned due to its more complicated design, requiring a non-magnetic sleeve. Due to the lack of significant differences between SM-07 and SM-08, SM-08 was also
discontinued. Variants were therefore used for further analysis: IPM-01, IPM-03, IPM-12, and SM-07. Variants IPM-01, IPM-03, and IPM-12 are rotors with latent magnets, while SM-07 is a rotor with surface magnets.

2.4. Permanent Magnets

One of the design considerations was to use commercially available mass-produced permanent magnets in the rotor. The characteristics of permanent magnets, as quoted by manufacturers, do not always agree with the real ones. These differences result in the electromotive force at the terminals of permanent magnet synchronous machines being lower than those resulting from calculations. Figure 3 shows examples of the electromotive force waveforms obtained for synchronous motors in no-load generator operation [31], where “measured” corresponds to the measured voltage at the terminals of a motor operating as a generator (permanent magnet synchronous motor PMSM). The PMSM motor is a 4-pole motor with an electromagnetic torque of 1.1 Nm, a lead voltage of 200 V, a lead current of 7 A, and a rotational speed of 1500 rpm [31]; “calculated” refers to the FEM-calculated waveform, including rotor rotation (2D Opera, 2-dimensional, stratified model).

![Comparison of measured and calculated electromotive force waveforms in synchronous machines with different types of neodymium magnets in no-load generator operation: (a) 30 × 15 × 2 N38 magnet; (b) 42 × 20 × 5 N35H magnet [31].](image)

**Figure 3.** Comparison of measured and calculated electromotive force waveforms in synchronous machines with different types of neodymium magnets in no-load generator operation: (a) 30 × 15 × 2 N38 magnet; (b) 42 × 20 × 5 N35H magnet [31].

Based on the measurement results shown in Figure 3, adjustments were made to the magnets’ characteristics to obtain coincident electromotive force waveforms. The results of these corrections are shown in Figure 4.

![Correction of the characteristics of permanent magnets used in synchronous motors: (a) magnet 30 × 15 × 2 N38; (b) magnet 42 × 20 × 5 N35H.](image)

**Figure 4.** Correction of the characteristics of permanent magnets used in synchronous motors: (a) magnet 30 × 15 × 2 N38; (b) magnet 42 × 20 × 5 N35H.

The analysis shows that for a 30 × 15 × 2 N38 magnet, the actual remanence induction value is 0.847 T instead of 1.21 T, and for a 42 × 20 × 5 N35H magnet, it is 1.1 T instead of
1.21 T. The characteristics were therefore corrected by approximately 30% and 10%. There is a more significant deterioration in these characteristics for smaller-sized magnets. The above analysis was used to estimate the changes in the characteristics of the magnets used in the designed generators.

NdFeB permanent magnets were used in the designed generators, the parameters of which are shown in Table 3. The characteristics of these magnets were corrected. The actual characteristics are not known, and at the design stage, there are no ready-made prototype machines that could indirectly, by measuring electromotive forces, be used to correct them. Therefore, based on the results of the corrections for the above-discussed permanent magnets used in actual machines, the following estimated changes in characteristics were assumed—see Table 3.

### Table 3. Basic parameters of the magnets used in the designed generators.

<table>
<thead>
<tr>
<th>Order No.</th>
<th>Identification</th>
<th>Material Type</th>
<th>Size (mm)</th>
<th>Manufacturer's Br (T)</th>
<th>Adjusted Br (T)</th>
<th>Manufacturer's Hc (A/m)</th>
<th>Adjusted Hc (A/m)</th>
<th>Adjustment (%)</th>
<th>Max. Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25 x 10 x 5 N38</td>
<td>N38</td>
<td>25 x 10 x 5</td>
<td>1.21</td>
<td>0.79</td>
<td>-899,000</td>
<td>-584,350</td>
<td>35</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>40 x 20 x 10 N42</td>
<td>N42</td>
<td>40 x 20 x 10</td>
<td>1.29</td>
<td>1.16</td>
<td>-876,000</td>
<td>-788,400</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>25 x 15 x 10 N38</td>
<td>N38</td>
<td>25 x 15 x 10</td>
<td>1.25</td>
<td>0.91</td>
<td>-774,400</td>
<td>-674,250</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>42 x 20 x 5 N35H</td>
<td>N35</td>
<td>42 x 20 x 5</td>
<td>1.21</td>
<td>1.10</td>
<td>-900,000</td>
<td>-800,000</td>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>30 x 20 x 5 N38</td>
<td>N38</td>
<td>30 x 20 x 5</td>
<td>1.24</td>
<td>1.05</td>
<td>-937,400</td>
<td>-749,920</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>20 x 10 x 5 N38</td>
<td>N38</td>
<td>20 x 10 x 5</td>
<td>1.29</td>
<td>1.10</td>
<td>-876,000</td>
<td>-744,600</td>
<td>15</td>
<td>80</td>
</tr>
<tr>
<td>7</td>
<td>20 x 10 x 5 N38</td>
<td>N38</td>
<td>20 x 10 x 5</td>
<td>1.29</td>
<td>1.10</td>
<td>-876,000</td>
<td>-657,000</td>
<td>25</td>
<td>80</td>
</tr>
</tbody>
</table>

The permanent magnet characteristics obtained from the above analysis were adopted for the design calculations.

### 2.5. Calculations Methods

The d-q model of the generator created in MotorSolve (product of Simcenter – MotorSolve, ver. 2020.2) was used for the design calculations. The MotorSolve software provides parameterized models, which allow different variants of the designed machines to be created easily and quickly and calculation results to be obtained quickly.

During the design phase, thermal calculations were also made to determine the rated current of the generator and to check that the permissible operating temperature of the permanent magnets and windings was not exceeded. A three-dimensional calculation model and the finite-element method were used for these calculations. The model includes a section of the machine with all the components involved in heat transfer: the body, shaft, and bearings. A model of one variant of the designed machine is shown in Figure 5.

![Figure 5](image-url)
The final stage of the design was to analyze the operation of the designed generator cooperating with the proto bridge. The calculations necessary for this analysis were made using two-dimensional field-circuit models of the machine and the finite-element method. The Opera 2D software was used to create these models and calculations considering the rotor’s rotational movement and modeling the 6D rectifier bridge system with resistive load. The field-circuit models of the generator variants are shown in Figure 6.

![Figure 6](image)

**Figure 6.** Two-dimensional FEM electromagnetic model—geometry and mesh of two variants of generators: (a) H-SIPM-01, (b) H = SM-07, and (c) circuit model of the bridge.

### 3. Selecting the Best Design

Based on the selected four rotor variants (IPM-01, IPM-03, IPM-12, and SM-07—Figures 1 and 2) and seven stator variants (Table 2), twenty-eight generator variants were developed, and the basic characteristics were determined for them: \( U_f = f(P_2) \), \( I_f = f(P_2) \), and \( \eta = f(P_2) \), where \( U_f \) is the phase voltage, \( I_f \) is the phase current, \( \eta \) is the generator efficiency, and \( P_2 \) is the output power. The comparison of the characteristics allowed a preliminary selection and elimination of those designs that did not meet the basic requirements of achievable output power and efficiency and potentially acceptable phase current. As a result, twelve designs were obtained. For these machines, the current rating was determined based on thermal calculations and the characteristics determined previously. The current rating was assumed such that the temperature of the permanent magnets did not exceed the permissible temperature of 80 °C or 120 °C at an ambient temperature of 40 °C. In addition,
the permissible temperature for class H insulation of the windings was considered. To ensure that the permanent magnets did not operate in the temperature range close to the maximum temperatures (80 °C and 120 °C), temperatures of 60 °C for 80 °C magnets and 100 °C for 120 °C magnets were adopted as the temperature limit for determining the rated current.

As a result, five designs, designated as machine G IPM-12, machine H IPM-01, machine H IPM-12, machine H SM-07, and machine J SM-07, were selected, from among which the best one was chosen. The characteristics of the selected generators are shown in Figures 7 and 8.

![Figure 7. Generator variants characteristics: (a) phase voltage vs. output power; (b) phase current vs. output power.](image)

**Figure 7.** Generator variants characteristics: (a) phase voltage vs. output power; (b) phase current vs. output power.

![Figure 8. Generator variants characteristics: (a) efficiency vs. output power; (b) torque vs. phase current.](image)

**Figure 8.** Generator variants characteristics: (a) efficiency vs. output power; (b) torque vs. phase current.

The selection of the best design was based on the benefit K-index, which was determined by the following formula:

$$K = \frac{\eta^2 \cdot P_N^2 \cdot p}{U_N \cdot D \cdot l \cdot z_1 \cdot \delta U_0},$$  \hspace{1cm} (1)$$

where $\eta$ is the efficiency of the generator, $P_N$ is the rated active power, $p$ is the overload capacity, $U_N$ is the rated voltage, $D$ is the outer diameter of the stator, $l$ is the length of the package, and $z_1$ is the number of series windings. The K-index is a proprietary concept developed for the selection of the most suitable design. In Formula (1), the magnitudes in the denominator are to be as large as possible, while those in the numerator are to be as small as possible. In addition, the exponents of the powers are to increase the significance of the parameter.

The parameter appearing in Formula (1) is the voltage variation determined from the following relationship:
\[ \delta U\% = \frac{U_0 - U_N}{U_N} \cdot 100\%, \]

where \( U_0 \) is the voltage at the terminals of the non-loaded generator. The value of this K-index indicates which of the analyzed designs is the best: The higher it is, the better the design, from the point of view of the requirements.

The results of the K-index calculations are shown in Table 4.

<table>
<thead>
<tr>
<th>Construction</th>
<th>( I_N ) (A)</th>
<th>( U_0 ) (V)</th>
<th>( U_N ) (V)</th>
<th>( \eta ) (%)</th>
<th>( P_N ) (kW)</th>
<th>( p ) (-)</th>
<th>( \delta U% ) (%)</th>
<th>( z_1 ) (-)</th>
<th>( D ) (m)</th>
<th>( l ) (m)</th>
<th>( K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>G IPM-12</td>
<td>9</td>
<td>45.6</td>
<td>37.2</td>
<td>91.9</td>
<td>1</td>
<td>1.15</td>
<td>22.6</td>
<td>144</td>
<td>0.155</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>H IPM-01</td>
<td>4</td>
<td>124</td>
<td>123</td>
<td>94.9</td>
<td>1.48</td>
<td>3.48</td>
<td>0.8</td>
<td>192</td>
<td>0.208</td>
<td>0.1</td>
<td>172</td>
</tr>
<tr>
<td>H IPM-12</td>
<td>2</td>
<td>194</td>
<td>192</td>
<td>93.3</td>
<td>1.15</td>
<td>8.91</td>
<td>1.0</td>
<td>192</td>
<td>0.208</td>
<td>0.1</td>
<td>128</td>
</tr>
<tr>
<td>H SM-07</td>
<td>4.5</td>
<td>113</td>
<td>109</td>
<td>94.7</td>
<td>1.55</td>
<td>3.55</td>
<td>4.6</td>
<td>192</td>
<td>0.208</td>
<td>0.1</td>
<td>42</td>
</tr>
<tr>
<td>J SM-07</td>
<td>4</td>
<td>94.5</td>
<td>91.3</td>
<td>94.5</td>
<td>1.09</td>
<td>3.94</td>
<td>3.5</td>
<td>192</td>
<td>0.182</td>
<td>0.1</td>
<td>37</td>
</tr>
</tbody>
</table>

Based on the data presented in Table 4, it can be concluded that the best design is the H IPM-01 machine; the K-index value for this machine is 172 and is the highest. This machine is characterized by the highest efficiency at the rated current, with the active power of this machine being 0.38 kW higher than required. This machine also has the lowest voltage variation of 0.8% and an overload capacity of 3.48.

The second K-index value was achieved by machine H IPM-12, which is inferior to machine H IPM-01 mainly in terms of rated power, efficiency, and significantly higher voltage. However, it has the highest overload capacity of all the designs.

The third K-index value was achieved by the H SM-07 machine, which has a higher power rating than the H IPM-01 machine, slightly lower efficiency, similar overload capacity, and higher voltage variability, which is typical of machines with surface-mounted magnets.

The H IPM-01 machine and the H SM-07 machine were selected for further design calculations due to the simplest rotor design, which possibly allow lower rotor plate cutting costs.

4. Construction Calculations

Additional calculations related to the design of selected machine variants were also carried out. These were aimed at increasing the power output and improving the efficiency of the machines. The calculations were performed for different values of selected rotor plate dimensions (Figure 9a,b) as well as different numbers of coils. The effect of these dimensions on the value of the K-index was analyzed.

![Figure 9a](image1.png)

(a)

![Figure 9b](image2.png)

(b)

Figure 9. Modified rotor plate dimensions of the (a) H IPM-01 and (b) H SM-07 machines.

The results of this analysis are shown in the graphs below.
Figure 10a shows that for machine H IPM-01, the highest value of the K-index was achieved for a bridge thickness dimension equal to 2 mm and core gap width equal to 1 mm. For machine H SM-07 (Figure 10b), the highest K-index value was achieved for the dimension magnet inset depth equal to 4 mm and magnet gap width equal to 4 mm.

Figure 10. Influence of selected rotor dimensions on K-index value: (a) H IPM-01 and (b) H SM-07 machines.

The changes made to the selected dimensions did not significantly improve machine performance (Figure 11a). The increase in K-index values was mainly due to a marked reduction in voltage variation $\delta U$ (Figure 12a) and an increase in rated power $P_N$ (Figure 13a). The varying rotor dimensions, on the other hand, significantly affect the rated voltage value: The difference between the variant with the largest and smallest rated voltage value is about 30 V (Figure 14a). The best solution was obtained for a core gap width of 1 mm and a bridge thickness of 2 mm.

As a result, the differences between the K-index values are small (Figure 10b). In the case of the H SM-07 machine, the changed dimensions did not affect the efficiency, nor did the power rating (Figures 11b and 13b). A small effect of dimensions can be seen for some variants, such as in the case of voltage variation (Figure 14b). The solution with the highest K-index value was obtained for magnet gap width and magnet inset depth parameters equal to 4 mm.

Changing the number of winding coil windings did not improve the efficiency of the machines. Reducing the number of windings mainly reduced the value of the voltage variation $\delta U$, which increased the value of the K-index. Finally, 11 windings were selected for the H IPM-01 machine and 10 windings for the H SM-07 machine.

Figure 11. Influence of selected rotor dimensions on efficiency: (a) H IPM-01 and (b) H SM-07 machines.
Influence of selected rotor dimensions on voltage variation: (a) H IPM-01 and (b) H SM-07 machines.

Influence of selected rotor dimensions on active power rating: (a) H IPM-01 and (b) H SM-07 machines.

Influence of selected rotor dimensions on voltage rating: (a) H IPM-01 and (b) H SM-07 machines.

5. Calculation of Output Parameters of a Generator Cooperating with a Bridge Rectifier

The final stage of the project was to determine the voltage and current at the output of the rectifier bridge operating in a system with a generator under a single-phase resistive load. For this purpose, the circuit-field models shown in Figure 7 were used. Based on calculations performed with these models, the characteristics of both considered generator variants were determined. These characteristics were compared with the characteristics of the generators determined using the d-q model. The results of the calculations of these characteristics are presented in Figures 15 and 16.
Figure 15. Comparison of the characteristics of the IPM-01 generator calculated using the d-q model and the FEM model: (a) phase voltage, (b) current voltage, (c) efficiency and (d) torque.

Figure 16. Comparison of the characteristics of the SM-07 generator calculated using the d-q model and the FEM model: (a) phase voltage, (b) current voltage, (c) efficiency and (d) torque.
The calculations made by the two methods coincided. Some differences in the characteristic curves occurred in the range of the highest output power and for maximum power. For rated power, the characteristics overlapped.

6. Stress Analysis of the Rotors Package

Stress analysis of the rotor package was performed using 3D models and the finite-element method. This analysis was carried out to confirm the mechanical strength of the selected constructions. Models were made for both analyzed designs: IPM-01 and SM-07. Finite-element meshes were generated, containing 7365 hexahedral elements (36,765 nodes) for the IPM-01 rotor (Figure 17a) and 4848 hexahedral elements (23,219 nodes) for the SM-07 rotor (Figure 17b). The material mass density of the two packages was assumed to be 7750 kg/m³ and Young’s modulus 2.1·10⁵ MPa.

![Figure 17. Computational models of rotor packages: (a) IPM-01 and (b) SM-07.](image)

The twisting torque of 50 Nm and the rotational speed of 955 rpm were used as boundary conditions: values above the expected operating conditions of the generators. The results of the calculations are shown in Figures 18 and 19.

The performed calculations, although rough, confirm that the proposed generator design will sustain the predicted loads: the maximum observed displacement is equal to 49.2·10⁻⁵ mm for IPM-01 and 5.2·10⁻⁵ mm for SM-07, and the maximum predicted loads, 3.2 MPa for IPM-01 and 0.35 MPa, are 65.6·10³ and 60·10⁴ times higher, respectively, than the typical values observed for steel. The maximum predicted loads are lower than typical values of tensile strength observed for steel used for generators.

![Figure 18. Stress (a) displacement and (b) distributions for rotor’s core IPM-01.](image)
Figure 19. Stress (a) and displacement (b) distributions for rotor’s core SM-07.

7. Conclusions

This paper describes how to select the best design of a permanent magnet synchronous generator designed to work with a small wind turbine. Based on the determined characteristics of the generator variants and the value of the K-index, the generator with a rotor with latent magnets, designated as H IPM-01, was selected as the best solution. However, due to the anticipated lower costs and easier fabrication in workshop conditions, the best solution among the generators with a rotor with surface-mounted magnets, designated as H SM-07, was also retained. For both variants, simulations of operation in a system with a diode bridge rectifier and a resistive single-phase load were also performed. These calculations allow the determination of the output parameters: rectified voltage and current, necessary for the design of the voltage converter with which the turbine-generator unit will operate. Prototype tests of the designed generators and tests of the entire turbine and generator assembly, including the electronics, are also planned in such a system. Through strength analysis, the authors showed that the maximum predicted loads are lower than the typical tensile strength values observed for steel used in generators.

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