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Analysis of design solutions for rotors with permanent magnets for small hydropower plants (SHP)

Analiza wpływu rozwiązań konstrukcyjnych wirników z magnesami trwałymi w urządzeniach dla małych elektrowni wodnych

***Abstract**. The article presents an analysis of the influence design solutions of rotors with permanent magnets on the parameters and operating characteristics of a hydrogenerator designed for small hydropower plants (SHP). Internal Permanent Magnet (IPM) and Internal Permanent Magnet V-shaped rotor configurations were considered. The influence of the angle between permanent magnets on the value of the induced voltage and the final operating characteristics was analysed. The obtained results were compared with the rotor solution with magnets mounted on the surface, called Surface Permanent Magnet (SPM). Based on the analysis, the advantages and disadvantages of individual solutions designed for use in hydrogenerator of SHP were determined.*

***Streszczenie.** W artykule przedstawiono analizę wpływu rozwiązań konstrukcyjnych wirników z magnesami trwałymi na parametry i charakterystyki eksploatacyjne hydrogeneratora przeznaczonego do małych elektrowni wodnych (MEW). Rozważano konfiguracje wirnika typu ang. Internal Permanent Magnet (IPM) oraz Internal Permanent Magnet V-shaped. Dokonano analizy wpływu kąta pomiędzy magnesami trwałymi na wartość indukowanego napięcia oraz końcowe charakterystyki eksploatacyjne. Uzyskane wyniki porównano z rozwiązaniem wirnika z magnesami montowanymi na powierzchni ang. Surface Permanent Magnet (SPM). Na podstawie przeprowadzonej analizy określono wady i zalety poszczególnych rozwiązań przeznaczonych do zastosowania w hydrogeneratorze MEW.*

Keywords: hydrogenerator, rotor with permanent magnets, electromagnetic calculations
Słowa kluczowe: hydrogenerator, wirnik z magnesami trwałymi, obliczenia elektromagnetyczne

Introduction

In Poland, hydrological conditions for generating electricity from watercourses are not favorable compared to, for example, Norway or Sweden. However, there is great potential to develop unused infrastructure for the building of small hydropower plants, defined as objects with a total installed power up to 10 MW [1]. According to the inventory carried out in 2012 year by the National Water Management Authority, there are about 14000 objects with a water level of at least 0.7 m, of which only 4.5% is used to generate electricity [1,2]. Within of the European RESTOR Hydro project a map was developed defining over 50000 potential SHP locations in Europe, 8500 of which are located in Poland [3]. The report "Small hydropower plants in Poland" gives that there are 775 small hydropower plants in Poland, the vast majority of which are power plants with an installed power of less than 0.5 MW. The same report estimates that the technical potential in Poland for utilization in small hydropower plants amounts about 1500 MW of installed power. The current installed power of the SHP is 286 MW, which indicates about 20% utilization of the available national technical potential [1].

In Small Hydropower Plants (SHP) low-speed synchronous generators with permanent magnets are increasingly gaining popularity, mainly due to their higher energy efficiency, the possibility of eliminating the mechanical gearbox and higher controllability, allowing for better utilization of the available hydrological conditions of a given watercourse [2,4]. The design of the electromagnetic circuit of a permanent magnet generator rotor has a key influence on the obtained parameters and operational characteristics, the values of the induced voltage and the THD level of the phase and line-line voltage [5, 6, 7, 8]. This publication presents the results of calculations and numerical simulations carried out for various rotor design solutions for a permanent magnet synchronous generator with a target power of 100 kW and a rated rotational speed of 250 rpm, operating on a resistive load cosφ = 1. The analysis included a rotor with IPM-type recessed flat magnets, rotors with V-shaped recessed magnets with various values of the opening angles of permanent magnets, and an SPM-type rotor with magnets mounted on the yoke surface.

The aim of the simulations was to evaluate individual rotor design solutions in scope of the operational obtained parameters and to evaluate the general advantages and disadvantages of a given solution.

Calculation model

The calculation model of the generator was prepared in the ANSYS Electronics software and is shown in Figure 1.

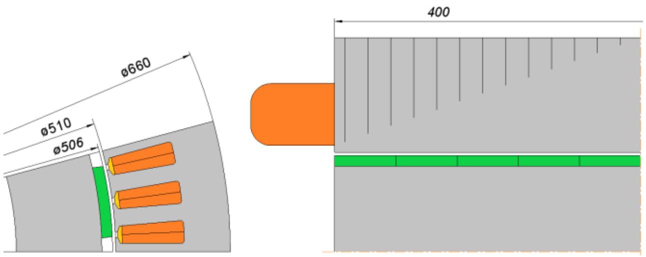
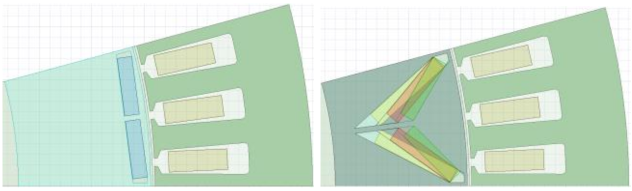


Fig. 1. Cross-section and longitudinal section of the generator's electromagnetic circuit and its geometric dimensions

The stator and winding data were identical for all analysed cases. In this publication, IPM (180), VPM (70), VPM (86), VPM (105) and SPM rotors were analyzed. The values given in brackets refer to the opening angle between the magnets. The basic parameters of the generator are presented in Table 1, while Figures 2-3 present models of the analysed rotors.

Table 1. Basic generator parameters for all analysed cases

Parameter	Value
Rated speed, n [rpm]	250
Frequency, f [Hz]	50
Number of poles, 2p [-]	24
Number of stator slots, Q_s [-]	72
Stator skew, β [°]	5



a) b)

Fig. 2. Cross-section of the electromagnetic circuit of generator with a rotor a) IPM (180), b) VPM (70 yellow, 86 red, 105 green)

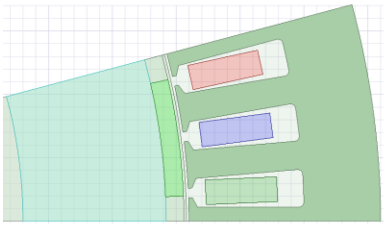


Fig. 3. Cross section of the electromagnetic circuit of generator with SPM-type rotor

Table 2 presents basic data characterizing individual rotor solutions. Particular attention was paid to the used volume of permanent magnets, because it significantly affects the cost of production the rotor. It can be seen that the volume of the SPM rotor magnets is approximately 40% smaller than the volume of the magnets in the VPM (70) rotor.

Table 2. Basic data of the analysed rotor design solutions

Parameter	Angle between magnets in one pole [°]	Magnet width [mm]	Pole Area [mm^2]	Volume of all magnets [cm^3]	Electric angle [°]
IPM (180)	180	27.4	383	3678	156.8
VPM (105)	105	31.2	437	4193	153.5
VPM (86)	86	35	490	4704	150
VPM (70)	70	40.5	567	5445	146.7
SPM	-	46.3	324	3116	126

Operating characteristics

For the calculation model presented in Figure 1, numerical simulations were carried out to determine the basic characteristics of the generator for various rotor design solutions. Figure 4 shows the waveforms of phase back EMF at no-load for different rotor solutions. The SPM-type rotor and the VPM-type rotor (70) have the highest value of induced back EMF at no-load, while the VPM-type rotor (180) has the lowest value. Figure 5-6 shows the calculated operating characteristics of the generator. The first one is the external characteristic, showing the value of the phase-to-phase voltage V_{LL} at the generator terminals as a function of the electrical power P_{el}. The second characteristic is the efficiency η as a function of the electrical power P_{el}. The characteristics were determined at a load of *cos*φ = 1, without taking into account the control.

Table 3 shows the calculated values of the basic generator parameters assuming a load of cosφ =1. Due to the identical design and winding data of the armature, in all analyzed cases the comparison was made for a load current of 280 A, treated as the rated load.

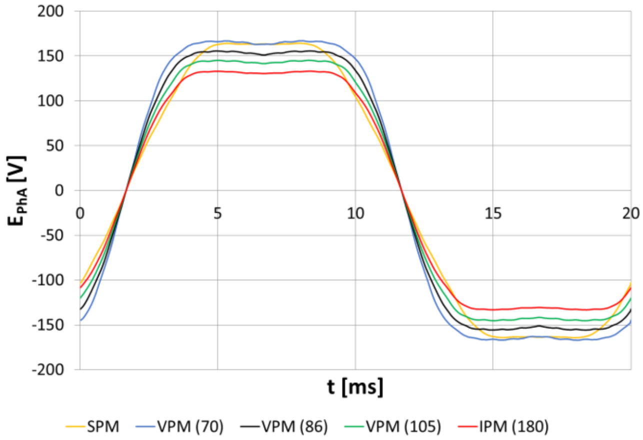


Fig. 4. Waveforms of phase back EMF at no-load for different rotor solutions

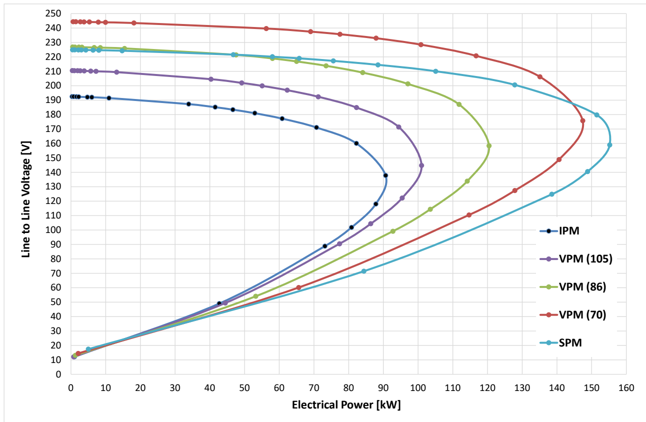


Fig. 5. Characteristics V_{LL} = f(P_{el}) for the analysed rotor variants at load cosφ = 1

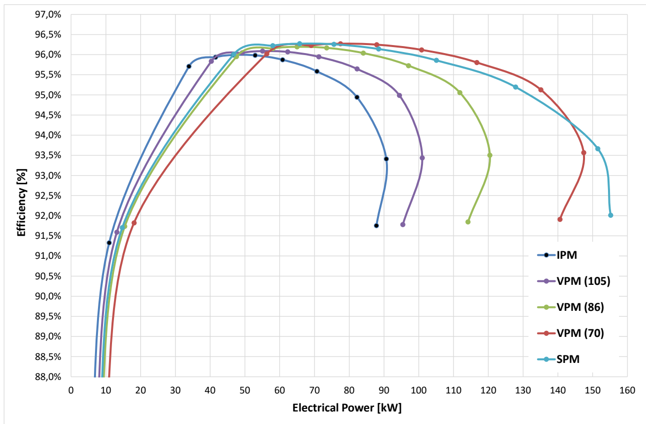


Fig. 6. Characteristics η = f(P_{el}) for the analyzed rotor variants at load cosφ = 1

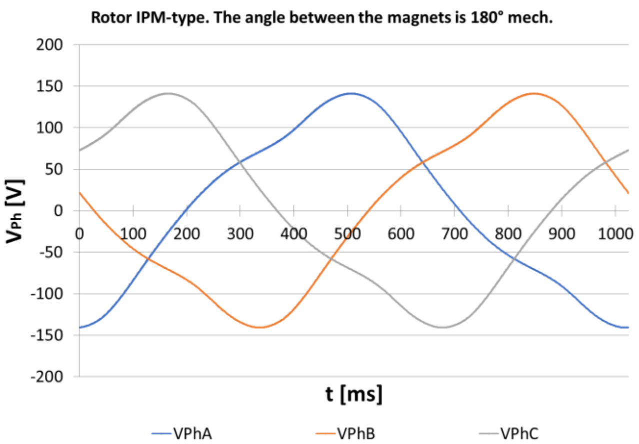
Table 3. Calculated parameters of the generator for individual rotor solutions with permanent magnets

Parameter	IPM (180)	VPM (105)	VPM (86)	VPM (70)	SPM
I_N [A_{RMS}]	280	280	280	280	280
E_{0LL} [V_{RMS}]	192	210	227	244	225
V_N [V_{RMS}]	165	180	203	227	212
ΔV [%]	16.4	16.7	11.8	7.5	6.1
P_N [kW]	77	85	94	106	98
P_{max} [kW]	90	101	120	147	155
$P_{max.}$ / P_N	1.17	1.19	1.28	1.39	1.58
η_N [%]	95.3	95.5	95.7	96.1	96.0

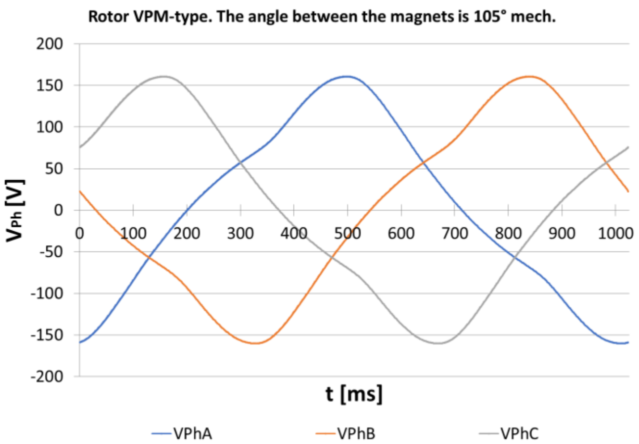
where:
I_N – rated current,
E_{0LL} – line to line back EMF at no-load,
V_N – rated line to line voltage,
ΔV – percentage voltage drop,
P_N – rated electrical power,
P_{max} – max. electrical power,
η_N – rated efficiency.

Voltage THD factor

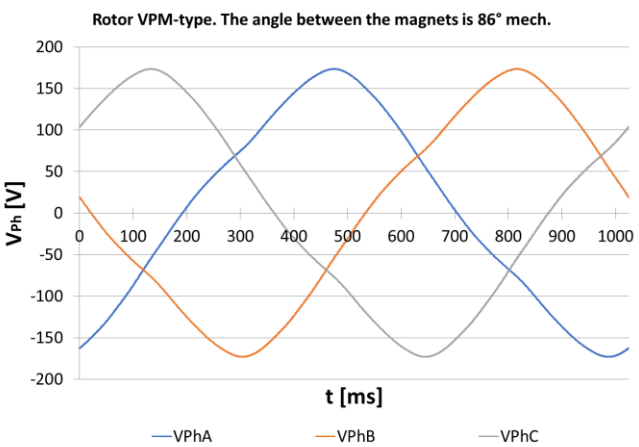
One of the main parameters of the generator is the voltage THD factor, which informs about the content of harmonics [9]. Figure 7 shows the phase voltage V_{ph} waveforms at a rated load I_{ph} = 280 A and $cos\varphi$ = 1 for different rotor design solutions. The calculated THD values are presented in Table 4.



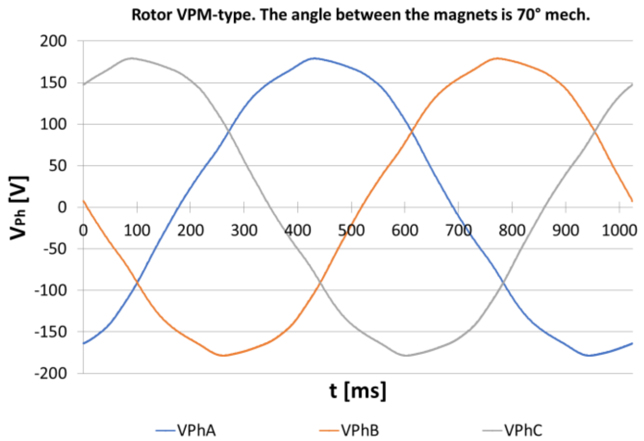
a)



b)



c)



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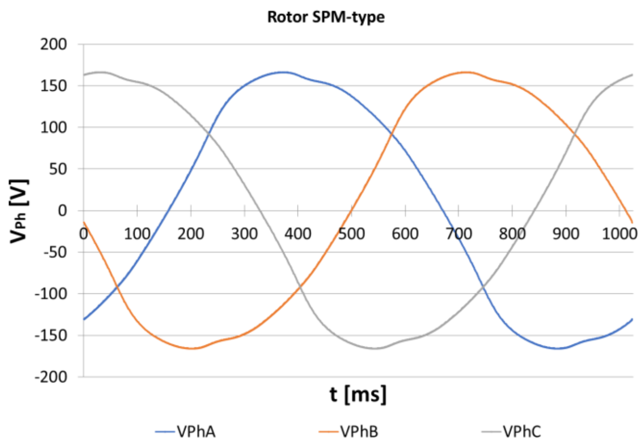

e)

Fig. 7. Output waveforms of phase voltages V_{ph} at rated load I_{ph} = 280 A and $cos\varphi$ = 1 for different rotor solutions: a) IPM (180); b) VPM (105); c) VPM (86); d) VPM (70); e) SPM

Table 4. THD values of phase voltage.

Rotor type	THD Phase A [%]	THD Phase B [%]	THD Phase C [%]
IPM (180)	13.96	13.96	13.97
IPM (105)	14.34	14.34	14.34
IPM (86)	9.11	9.11	9.11
IPM (70)	3.19	3.19	3.20
SPM	7.47	7.47	7.46

The highest content of harmonics is characteristic of the IPM (105) and IPM (180) rotor. The THD factor of the phase voltage under load for them is about 14%, while for the IPM (70) solution it is 3.2%. Of course, one should strive for as sinusoidal voltage waveforms as possible, but in the case of cooperation of a permanent magnet generator with the power grid, the power electronics converter is responsible for the correct shaping of the output voltage with an appropriately low THD factor.

Table 5 presents the determined amplitude values of individual harmonics. Apart from the first harmonic, the third harmonic has the largest amplitude for all rotor design solutions and it is this that mainly shapes the course of the obtained voltages.

Figure 8 present the amplitude of the main harmonic and higher harmonics of one phase of different rotors can be compared.

Table 5. Amplitude values of harmonic contents of phase voltage for different rotor type

	Phase A, B, C					
Harmonic, [V]	*1*	*3*	*5*	*7*	*11*	*13*
IPM (180)	127.0	17.5	2.4	0.5	0.0	0.0
IPM (105)	140.5	19.9	3.0	0.6	0.2	0.1
IPM (86)	158.0	14.2	2.1	0.5	0.2	0.0
IPM (70)	179.8	4.3	2.9	1.8	0.3	0.1
SPM	171.0	12.3	2.9	0.8	0.4	0.1

Table 6. Percentage ratio of higher harmonic contents to the first harmonic of phase voltage for different rotor type.

	Phase A, B, C					
Harmonic, [%]	*1*	*3*	*5*	*7*	*11*	*13*
IPM (180)	100	13.8	1.9	0.4	0.0	0.0
IPM (105)	100	14.2	2.1	0.5	0.2	0.1
IPM (86)	100	9.0	1.4	0.3	0.1	0.1
IPM (70)	100	2.4	1.6	1.0	0.2	0.1
SPM	100	7.2	1.7	0.5	0.2	0.1

Summary

The analysis shows that the most favorable parameters are characterized by the generator with the VPM (70) and SPM rotors. For these rotor variants, the highest value of rated and maximum power, the highest efficiency, the lowest voltage drop and the highest overload capacity are obtained. The advantage of the VPM (70) design solution is that permanent magnets are naturally protected against mechanical damage by being placed in appropriate slots. In the case of SPM rotors, it is necessary to use additional forms of protection, for example by banding. The disadvantage of the VPM solution (70) in comparison to the SPM rotor is the much larger volume of permanent magnets, about 75% larger, which significantly increases the cost of production the rotor.

The magnets embedded deeper in the radial dimension of rotor (VPM) generally exhibit greater demagnetization resistance, and such electric machines are the most promising designs overall in terms of demagnetization resistance. However, it should be noted that the volume and mass of magnets typically increase as magnets are buried deeper. [10, 12]

The IPM topology presents the smallest losses through hysteresis, followed by SPM and VPM. These differences are due to the magnetic saturation and harmonics characteristic of each particular topology. For all topologies currents cause the rotor temperature to rise, affecting the efficiency and performance of the machine. [11]

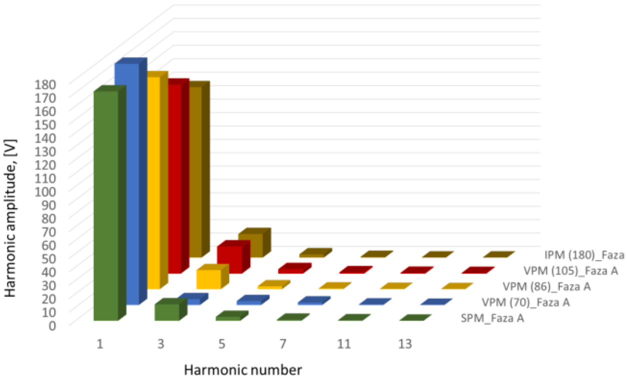

Fig. 8. Main and higher harmonic components of phase A for all rotor design solutions

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