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Impact of Pole Pair Number on the Efficiency of an Induction Generator for a Mini Hydro Power Plant

Abstract*. The aim of this paper is to analyse the impact of pole pair number on the efficiency of an induction generator designed for a mini hydro power plant. Six induction generators with different number of poles were designed: 2, 3, 6, 10 and 14. The basic point of this study is Kaplan turbine, which considering its rotational speed can be directly connected to a 14-pole induction generator. All other induction generators need a speed reducer for appropriate operation with Kaplan turbine, but speed reduction decreases the efficiency of mechanical energy conversion into electrical energy. Consequently this paper presents the efficiencies of induction generators and the summary efficiencies of an induction generator and a speed reducer. At the design phase of the aforementioned induction generators the realization possibility of the prototypes was taken into account, including the mass of active components and used materials.*

Streszczenie. *W artykule przedstawiono analizę wpływu ilości par biegunów na sprawność generatora asynchronicznego w mini elektrowni wodnej. W badaniach wzięto pod uwagę 6 zaprojektowanych maszyn (2, 3, 6, 10 i 14 biegunów) połączonych z turbiną Kaplana. Do wszystkich, oprócz 14-biegunowej wykorzystano reduktor, który również został uwzględniony w analizie. (**Wpływ ilości par biegunów na sprawność generatora asynchronicznego w mini elektrowni wodnej**).*

Keywords: hydro power plant, induction generator, analytical calculation, efficiency
Słowa kluczowe: elektrownia wodna, generator asynchroniczny, obliczenia analityczne, sprawność.

Introduction

Mini hydro power plants are used for producing hydroelectric power on a scale appropriate for serving a small community or a small industrial plant. The definition of a mini hydro power plant varies, but a generating electrical power of up to 1000 kilowatts (kW) is generally taken as the upper limit of what can be termed mini hydro. A subclass of mini hydro power plants are micro hydro power plants, usually defined as less than 100 kW. Micro hydro is usually the production of hydroelectric power sized for small number of people or small enterprises.

Ordinarily mini hydro plants can be connected to electric distribution networks as a source of low-cost renewable energy. Alternatively, mini hydro power plant projects may be built in separated areas without the national electric distribution network. Since mini hydro projects usually have minimal water reservoirs, their impact on the environment is lower in comparison with large hydro power plants. Hydroelectric power is electric power generated from the movement of water (water energy). In a typical installation, water is fed from a reservoir through a classical channel or a pipe into a turbine [1,2]. Water power is the product of water flow and height difference which cause the shaft of the turbine to rotate. The rotating shaft of the turbine is mechanically connected to an electrical generator (induction or synchronous) which converts mechanical energy of the shaft into electrical energy [3,4].

Induction generators for mini hydro power plant

Which type of electrical generator is used in a mini hydro power plant mainly depends on the speed of the turbine. Different types of turbines can be used in mini hydro power plants, for example Kaplan turbine (big water flow, small head and lower shaft speed) or Pelton turbine (small water flow, big head and higher shaft speed). In the case of Kaplan turbine the nominal shaft speed is normally around 430 rpm, which coincides with a fourteen pole induction generator. This paper discusses the design of an induction generator with nominal power of 450 kW in combination with Kaplan turbine with 430 rpm nominal shaft speed. In this study six different generators were designed: generators with two, four, six, ten and fourteen poles. Only the fourteen-pole induction generator can be directly connected to the turbine (Fig. 1a). In cases of two-, four-, six- and ten-pole induction generators the speed reducer must be used between the turbine and the generator shaft (Fig. 1b). In the case of a speed reducer the efficiency of water power conversion to the generator shaft is decreased. But on the other hand the efficiency of the induction generator is higher in the case of a smaller number of poles. With an increasing number of poles the magnetic field must cross the air gap more times. This causes a higher magnetizing current and a lower power factor of the induction generator.

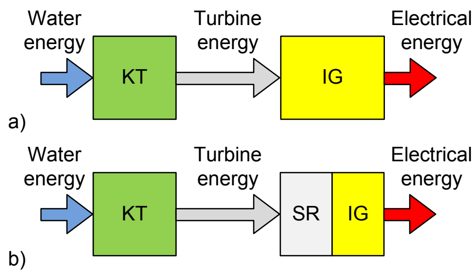

Fig.1. Schematic presentation: a) 14 pole induction generator directly coupled to Kaplan turbine, b) 2, 4, 6 and 10 poles induction generators coupled via speed reducer to Kaplan turbine

Design of two-, four-, six-, ten- and fourteen-pole induction generators with nominal power 450kW

To make the comparison and to choose the optimal variant of induction generator five different stator and rotor laminations were used. For designing the two-, four- and six-pole induction generators the standard IEC laminations with axis-height 355 mm and outer diameter $D_o = 580$ mm were used. All three laminations are designed for different pole numbers, i.e. two, four and six and for the longest possible package length $l_{Fe} = 550$ mm for which a rotor squirrel-cage can still be aluminium pressure cast. For longer rotor package lengths usually copper bars are inserted into rotor slots.

Two additional variants were calculated for analysis and comparison in this study: a ten-pole and a fourteen-pole variant of induction generator. The latter does not require a rotational speed reducer and is driven directly by a water turbine with nominal speed of approximately 430 rpm. Both variants were carried out with a copper rotor squirrel-cage and trapezium-shaped cage bars. The ten-pole variant was carried out for axis height 400mm according to IEC and has a 1.91-times higher active iron mass in comparison with the four-pole variant. Fourteen-pole variant is even more disadvantageous in the material consumption; it is made for axis height 450mm according to IEC and has a 2.84-times higher mass of iron. All basic geometry (Fig. 2) and design data for all induction generators are presented in Table I. For further comparison two four-pole induction generators were designed. The difference between them is in squirrel-cage material; the squirrel-cage material for the induction generator with mark 4p is aluminium and for the induction generator with mark 4p* the material is copper.

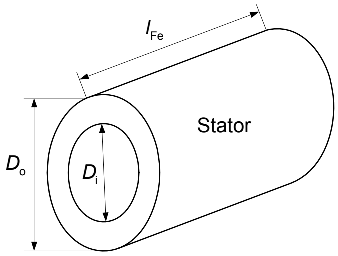

Fig.2. Stator geometry: outer and inner diameter, stator length

Results of calculations for two-, four-, six-, ten- and fourteen-pole induction generators

All characteristics of designed induction generators were calculated with software package emLook [5] and based on analytical calculation [5, 6]. For all induction generators the same quality of iron core lamination M600-50A including saturation effects was used [7,8]. Results in Table II show that the four-pole variation has the highest energy conversion efficiency, i.e. the lowest losses; in generator mode of operation and with the output electrical power of 450kW it has only 15.8KW of losses in case of an aluminium squirrel-cage (0.966 energy conversion efficiency) and 13.9KW of losses in case of a copper squirrel-cage (0.971 energy conversion efficiency). The two-pole variation has higher power losses that are 18.3kW, and the six-pole variation 18.7kW. Comparisons in Table II show that the package would have to be longer for the six-pole variation, because it has worse cooling and higher current density J_s in the stator winding. In comparison with the two-pole and the four-pole variants this consequently leads to greater heating. Longer package in the case of a six-pole generator is however not possible because of the longest possible length of the aluminium version of rotor squirrel-cage.

The ten-pole variant has a lower power factor in comparison with the four-pole variant. Fourteen-pole variant is even more disadvantageous; it has a power factor of only 0.55. According to the energy conversion efficiency of the rotational speed reducer (0.98) and the energy conversion efficiency of the four-pole generator (0.966) the total energy conversion efficiency is 0.947, which is only slightly less than the energy conversion efficiency of the fourteen-pole generator (0.955), but the power factor is significantly higher, and there is less need for compensation of the reactive component of the current. A comparison of calculated values for all generators is shown in Tables II and III. Figures 3-9 present different characteristics for all induction generators in dependency of turbine power (mechanical power on generator shaft). Figure 3 clearly shows that both four-pole induction generators achieve the highest efficiency. The lowest efficiency has the fourteen-pole generator, which is the only one that can be directly coupled with Kaplan turbine. When increasing the number of poles the power factor *PF* decreases (Fig. 4), which is disadvantageous for the generator and consequently means more costs for reactive power compensation.

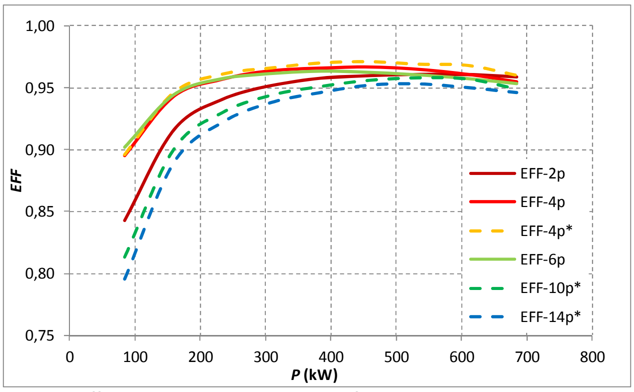

Fig.3. Efficiency characteristics of induction generators with different numbers of poles in dependency of turbine power

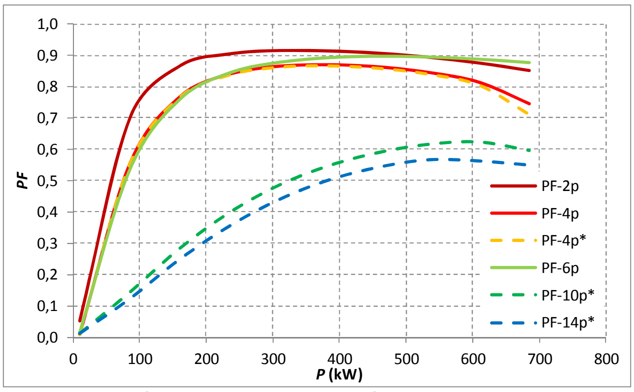

Fig.4. Power factor characteristics of induction generators with different numbers of poles in dependency of turbine power

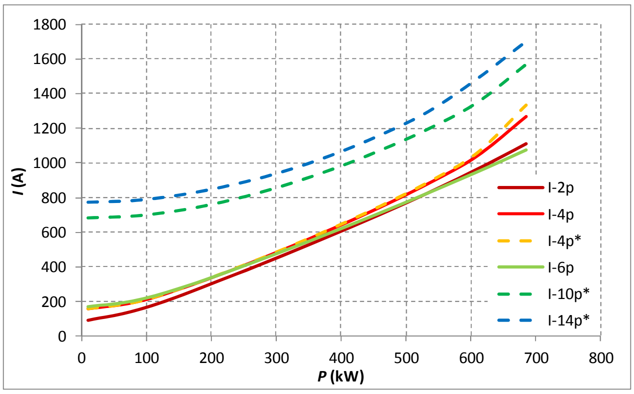

Fig.5. Current characteristics of induction generators with different numbers of poles in dependency of turbine power

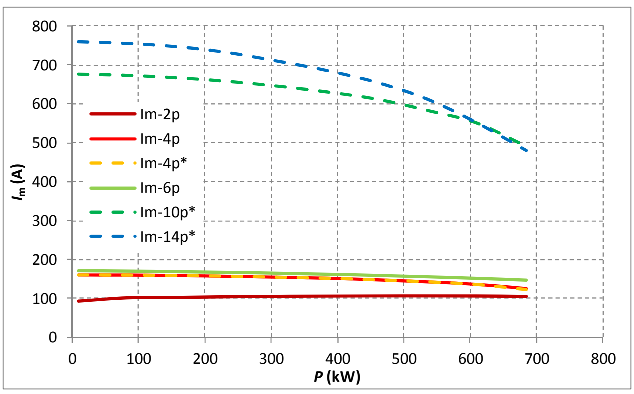

Fig.6. Magnetizing current characteristics of induction generators with different numbers of poles in dependency of turbine power

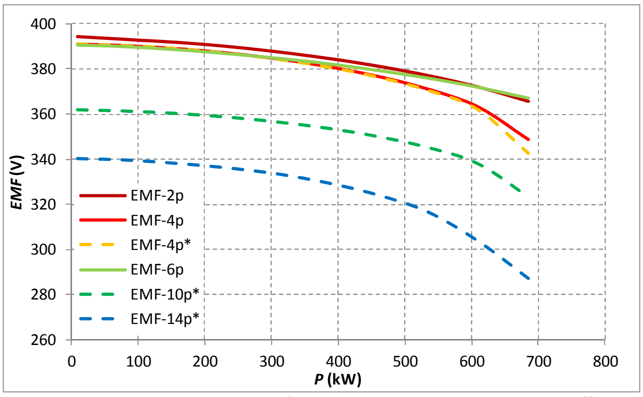

Fig.7. EMF characteristics of induction generators with different numbers of poles in dependency of turbine power

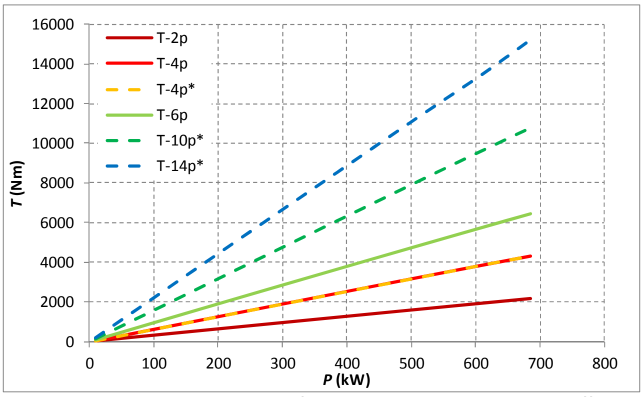

Fig.8. Torque characteristics of induction generators with different number of poles in dependency of turbine power

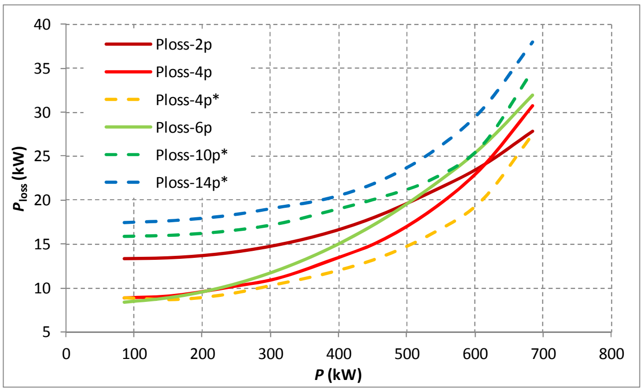

Fig.9. Power losses characteristics of induction generators with different number of poles in dependency of turbine power

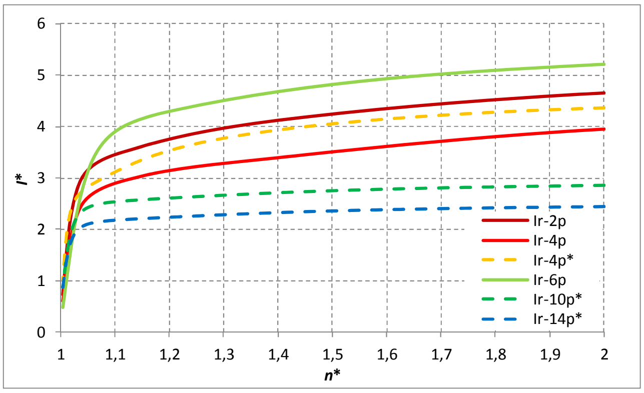

Fig.10. Relative current characteristics of induction generators with different numbers of poles in dependency of relative rotor speed

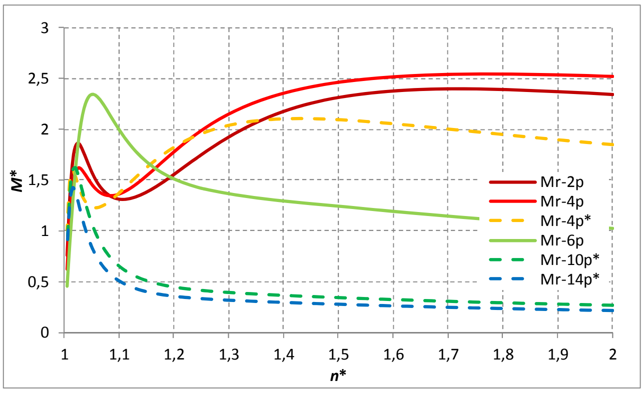

Fig.11. Relative torque characteristics of induction generators with different numbers of poles in dependency of relative rotor speed

In Figure 5 we can observe that ten-pole and fourteen-pole induction generators have the highest stator currents. Magnetizing currents [9] are also more than four-times higher than with two-, four-, and six-pole variations. Because of this ten-pole and fourteen-pole induction generators have lower EMF characteristics.

With the same electric power, torque characteristics are different in dependency of the synchronous speed of each generator shown in Figure 8 [10]. Power losses characteristics shown in Figure 9 confirm higher efficiency of both four-pole versions.

In Figures 10 and 11 the characteristics of relative current (I / I_N) and relative torque (T / T_N) in dependency of relative speed (n / n_N) are presented. Figure 11 shows the values of breakdown torques for each type of induction generator.

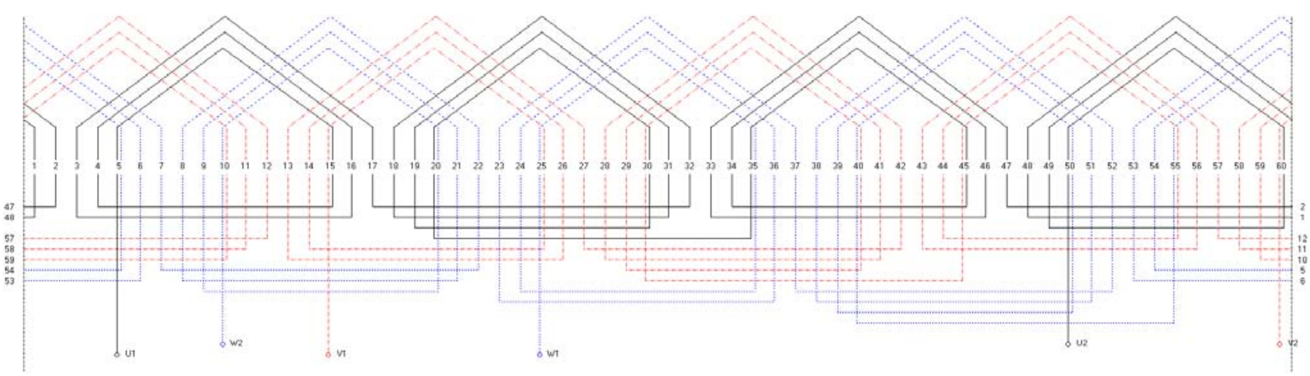

Fig.12. Three-phase combined concentric winding for four-pole induction generator, winding step 1-11,13,15

Table I. Basic geometry and design data of induction generators

Generator	Q_s	Q_r	D_o (mm)	D_i (mm)	δ (mm)	l_{Fe} (mm)	m_{Fes} (kg)	m_{Fer} (kg)	m_{Cu} (kg)	m_{Al} (kg)	m_{sum} (kg)
2p	48	40	580	325	2,0	550	613,0	220,0	132,9	38,0	1003,9
4p	60	48	580	375	1,5	550	467,7	293,7	136,9	44,5	942,8
4p*	60	48	580	375	1,5	550	467,7	293,7	136,9	146,4*	1044,7
6p	72	84	580	425	0,9	550	379,6	429,5	108,0	39,4	956,5
10p*	60	48	645	465	1,1	850	727,4	848,9	176,7	168,7*	1921,7
14p*	84	70	725	530	1,2	1000	1015,0	1262,0	252,1	295,7*	2824,8

Remark: * copper as the material for the rotor squirrel-cage

Table II. Electric and mechanical values of induction generators at nominal generated power P=450kW

Generator	U (V)	I (A)	PF	η	P_t (kW)	J_s (A/mm^2)	n (min^{-1})	T_N (Nm)	T_b / T_N
2p	D 400	717,3	0,906	0,960	468,71	3,64	3021	1482,1	2,34
4p	D 400	754,9	0,860	0,966	465,76	3,86	1513	2941,9	2,53
4p*	D 400	759,6	0,859	0,971	463,92	3,87	1507	2942,2	2,12
6p	D 400	723,5	0,898	0,961	468,31	5,02	1012	4422,0	2,34
10p*	D 400	1091,9	0,595	0,956	470,55	4,02	604	7452,4	1,64
14p*	D 400	1182,0	0,549	0,955	471,10	3,72	431	10450,2	1,42

Remark: * copper as the material for the rotor squirrel-cage

Selection of the best performance combination

In this part the best performance combination of an induction generator and a speed reducer is selected. As described above, two-, four-, six- and ten-pole induction generators necessarily need a speed reducer to achieve a speed appropriate for Kaplan turbine. Ordinarily in such drives a single-stage speed reducer is used. In this work a high efficiency class single-stage speed reducer with efficiency of $\eta_{sr} = 0{,}98$ and total mass of 309kg was incorporated. Table III presents the reduction ratio i and the summary efficiency η_{sum} of all six designed induction generators. In the last column the approximate summary mass of induction generator and speed reducer is presented. Mass of the induction generator is calculated considering that the total mass of the generator is 2.2-times higher than the mass of all active components. Considering the summary efficiency and total mass the four-pole combination with a copper squirrel-cage is proposed as best induction generator.

Table III. Summary efficiency of induction generators

Generator	i	η	η_{sr}	η_{sum}	m_{sum} (kg)
2p	7,0	0,960	0,98	0,941	2518
4p	3,5	0,966	0,98	0,947	2383
4p*	3,5	0,971	0,98	0,952	2607
6p	2,3	0,961	0,98	0,942	2413
10p*	1,4	0,956	0,98	0,937	4537
14p*	1,0	0,955	1	0,955	6215

Remark: * copper as the material for the rotor squirrel-cage

Conclusion

This paper presents the design and the characteristics of six induction generators with different number of pole pairs. This study focuses on a comparison of the efficiency of generators, as well as complete mini hydro power plant efficiency, including the turbine, speed reducer and induction generator. From the presented results it is possible to conclude that despite the higher summary efficiency of the fourteen-pole induction generator, in practice it is more useful to use the four-pole induction generator with copper squirrel-cage. The difference in the efficiency is small, only three thousandths, and the material costs and summary mass are more advantageous for the four-pole version.

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