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Designing of a Permanent Magnet and Directly Driven Synchronous Generator for Low Speed Turbines

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Introduction

Micro scale hydro electric power plants are being used in outside national residential areas [1]. Here in such plants, turbine and alternator are coupled to each other by contrivances such as belt pulley and gear mechanism; afterwards the system can produce electricity [2]. Increase at speed difference between turbine and generator which is being run by turbine raises cost and complicacy of system, diminishes feasibility and efficiency. Hence, producers recommend that turbine must be fastened directly [2, 3, 5]. Michell-Banki turbines which are mostly preferred for small rivers drive the generator via belt pulley till 100 *kW* power, for more than 100 *kW* power, the generator is driven by turbine via gear box [3].

In this study, a generator which is structured from permanent magnets and driven directly by a Banki turbine has been designed instead of external excited one. It can decrease the setup and operational costs since that the designed permanent magnet generator can eliminate coupling contrivances at contemporary systems.

Optimal selection of turbine type for any operational place is determined according to geographical features of venue, water fall and flow and specific speed values of the water. At small water falls (between 2–60 *meters* long) and big water flows, from 2 *kWs* up to 200000 *kWs*, Kaplan type turbines which specific speed is more than 450 *rpm* is being used [1, 6]. Francis type turbine has a speed range of 45–550 *rpm*, they are used at 2–600 *meters* long medium waterfalls and 2–600000 *kWs* power plants [1, 6].

Pelton type turbine has a speed range of 2–30 *rpm*; they are used at 60–1000 *meters* long big waterfalls and 2–100000 *kWs* power plants [6]. Banki type turbines are formed by cogwheel and water spreader mouth. The water comes from spreader mouth penetrates to cogwheel which is shaped as wings, it passes through interior space and it enters into wings from cogwheel's hoop and so on an occurred secondary force releases the turbine. It is used at up to 200 *meters* waterfalls and 9 m^3/s water flows and in small hydroelectric power plants [6]. In case of Banki type turbine might be used at small water flows, higher efficiency could be obtained.

In order to obtain low speed / high torque, permanent magnet motors are used in many industrial applications. That means that a permanent magnet synchronous machine can be used instead of an asynchronous machine system which is connected to a gear box at low speed drives. Because direct drive systems haven't got gear box costs, maintenance costs are inconsiderable, their efficiencies are high, noise emissions are low, and turning on system is lightweight [9, 13]. Despite the fact that connecting electric motors to the driven machining system without gear box decreases cost and the combined unit's volume which contains motor, gear box and others, it also redounds system reliability. In researches made recently, electric motors which produce high torques at low speed have been designed [3, 4, 7].

The Used Material and Method in Design

The losses in electrical machines are happened as ferrite and core losses at active magnetic parts and as Cu losses at electrical circuits of the machine [10, 11]. The occurrence of Neodmiyum–Iron–Boron (Nd–Fe–B) magnet quietly gives the added value to improvements of permanent magnet structured synchronous machines [8]. SmCo magnets follow the developments of NdFeB magnets [10]. The magnets which have naturally high energy extensive such as NdFeB affect machine performances relatively in a big ratio [5]. Hence, in this design, NdFeB and SmCo which have well magnetized characteristic and low cost have been chosen.

As design parameters, magnetic flux density is calculated from the Eq. 1 and the electro motor force (emf) at air gap is calculated from the (2):

$$B = \nabla \times A, \qquad (1)$$

$$E = N_{ph} \sum_{n=1}^{K_n} - \left[k_w \frac{\delta \emptyset_n}{\delta t} \right], \quad (2)$$

where A is magnetic vector potential; ∇, is the curl of flux density magnetic vector potential at air gap [15]; N_{ph} is number of serial winding per phase; k_w is winding distribution factor; K_n is number of total harmonics; ϕ_n is average flux per pole.

The induced voltage in a machine which has P pole number and is wound as serially is given in (3)

$$E = 4.44 f \emptyset_n N_{ph} \times k_w. \quad (3)$$

Machine output power proportionally to magnet volume is given in (4)

$$P_{max} = \frac{\pi^2}{2} \cdot \frac{\xi}{k_f . k_{ad} . (1+\varepsilon)} . f . B_r . H_c . V_M , \quad (4)$$

where k_f is magnetic flux density; k_{ad} is armature reaction constant; ε is relation of no–load electromagnetic force and voltage; f is frequency; B_r is permanent magnetic flux density; H_c is coercive force; V_{pm} is magnet volume; ξ is magnet usage constant.

Output power of electrical machine is seen in (5)

$$P_R = \eta \frac{m}{T} \int_0^T e(t) i(t) dt = \eta m K_p E_{PK} I_{PK}, \quad (5)$$

where $e(t)$ and E_{pk} are air gap phase EMF and its peak value; $i(t)$; I_{pk} are phase current and its peak value; η is efficiency, m is number of phase, and T is period.

The peak value of air gap phase EMF is given in Equation 6 for standard permanent magnet machines

$$E_{PK} = K_e . N_t . B_g . \frac{f}{p} \lambda_0 D_0 l_e, \quad (6)$$

where K_e is EMF factor, N_t number of turn per phase, B_g is air gap flux density, f is frequency, p is pole pair, D_o is outer diameter of machine, l_e is effective length of machine.

The peak value of phase current is given in (7)

$$I_{PK} = \frac{1}{1+K_\phi} K_i A \pi \lambda_o \frac{D_o}{2 m_1 N_t} \quad (7)$$

where; A is total electrical loading, K_f is ratio of rotor electrical loading to stator loading.

The output power of a standard permanent magnet machine is written as $D^2 l$ equation as shown in (8)

$$P_R = \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p \eta B_g A \frac{f}{p} \lambda_0^2 D_0^2 l_e \quad (8)$$

Designing of a Permanent Magnet Synchronous Generator

In this study, a generator considered for a low water fall turbine has been designed. First, the basic parameters like power, size, etc. have been obtained; then magneto static analyses have been done. [16]. 3D model of the designed generator can be seen in Fig. 1. Even symmetry boundary condition has been used for ease of analysis; afterwards, analyses have been obtained in a short time and in a sensible form.

The stator slots shown in Fig. 2 have been designed to be decreased rotor cogging torque as skewed. Angle of dip of stator slots has been calculated to be minimized cogging torque. Table 1 shows the parameters and values which were obtained from the analysis results.

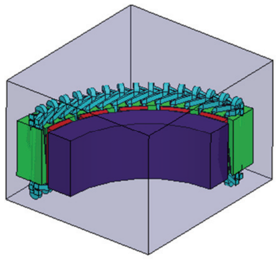


Fig. 1. 3D model of the design

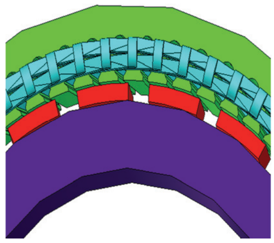


Fig. 2. View of magnets

Table 1. Analysis results

Cogging torque	6.14 *Nm*
Total weight	35.55 *kg*
Output power (P_o)	4016.6 *W*
Efficiency (η)	90.28 %
Load inductance (L_L)	0.055 *H*
RMS phase current	7.59 A
Armature current density	5.79 (A/mm^2)
Short circuit current	41.45 *A*
Load resistance (R_L)	23,232 *Ω*
Magnet weight	2.76 *kg*
Copper weight	5.26 *kg*
Synchronous speed	300 *rpm*

6 *Nm* cogging torque affects the rotor at *rpm*. It is inferred that the cogging torque is in the acceptable boundaries in the designed machine. Fig. 3 shows cogging torque curve of the machine. As seen from the Fig. 4, peak value of the cogging torque is limited to approximately 7 *Nm*.

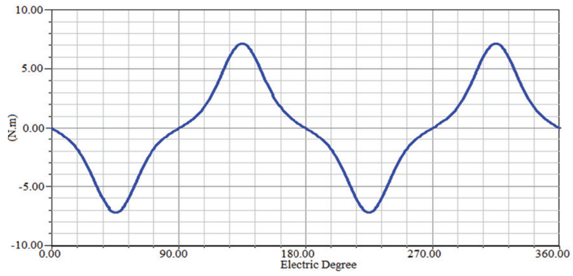


Fig. 3. View of cogging torque curve

The speed and output power change of the designed generator is seen in Fig. 4. The speed of generator is taken as a variable in simulations; the parameter to be calculated is entered as output power. When speed interval is changed between 0 and 550 *rpm*, it has been observed that output power is changed between 0 and 11 *kW*. 4 *kW* output power at 300 *rpm* is verified by the graphics shown in Fig. 5.

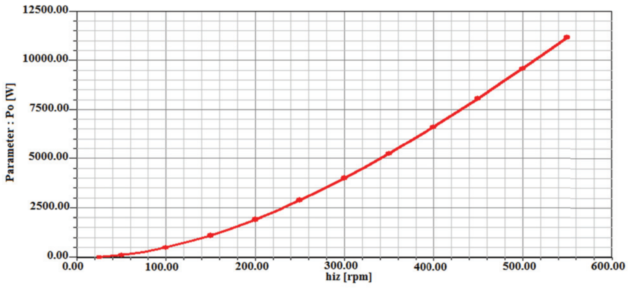


Fig. 4. Generator output power versus speed.

In this study, the designed permanent magnet generator has been analyzed by finite elements methods. Air gap flux density, its wave form, total magnetic flux and the induced *emf* value are calculated by finite elements methods. 3D finite elements analyses have been done, since that slot structure and magnetic saturation make calculations to complicate for air gap. The taken result which was drawn at air gap by contour line can be seen in Fig. 5–6. The peak value of magnetic flux density at air gap is about 1.0 *T* according to Fig. 5. From Fig. 6, it can be seen that the calculated air gap flux density is approximately 1.25 *T*. This peak value can be used for calculating voltages while the generator is analytically designing [14].

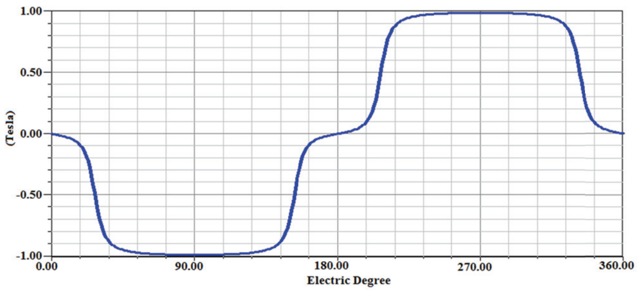


Fig. 5. Curve of flux density at air gap by Rmxrt

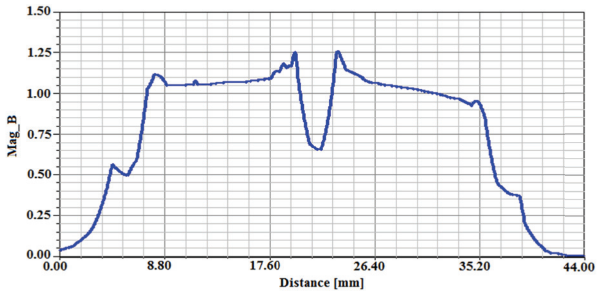
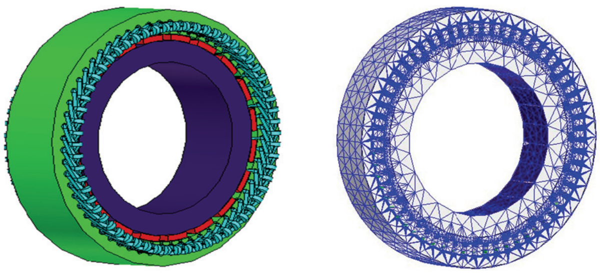


Fig. 6. Curve of air gap flux density

The flux density values at air gap must be known for calculating the induced generator voltages. Therefore several simulations have been done by Maxwell 3D and Rmxprt, the values found at air gap have been compared. It is inferred that the flux densities which were given in Fig. 5 and 6 are pretty closed values to each others. The designed generator has been transferred to 3D model for doing magneto static analysis. The generator structure and the meshed network for solving by finite elements are shown in Fig. 7.



a) b)

Fig. 7. 3D model and the meshed view of the design

The created model has been analyzed by finite elements methods. When it's being analyzed, the mesh compactness has been added for more sensitive solution. The entire model of generator and distribution of magnetic flux density can be shown in Fig. 8.

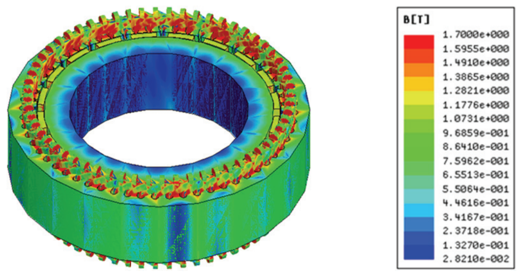


Fig. 8. Distribution of magnetic flux density in the entire generator model

It is seen that magnetic flux density is surpluses on the magnet and in the tightest parts of stator slots in this model (Fig. 9). The flux density is in the acceptable boundaries. The obtained maximum saturation is 1.7 *T* for the designed machine and this value is seen in the tightest parts of stator slots.

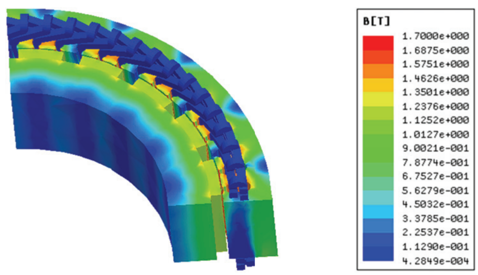


Fig. 9. Magnetic flux density of the obtained model by using even symmetry

From Fig. 10, the curve of the induced *emf* per phase can be seen for the radial flux permanent magnet generator.

As shown in Fig. 10, the induced voltage wave presents a stable magnitude for the generator which runs at 300 *rpm*. Fig. 11 shows the change of phase currents during the generator is running as stable at nominal speed. If the generator takes over load, the peak values of the phase currents are disordered.

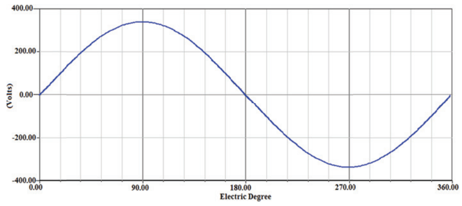


Fig. 10. The induced voltage per phase of the generator

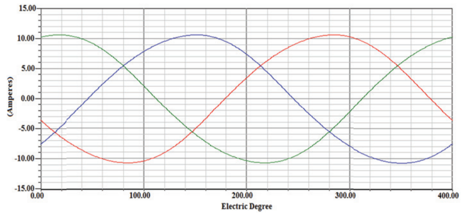


Fig. 11. Phase currents of the generator

Conclusions

In this study, a radial flux permanent magnet generator has been designed for low speed turbines by analytical and computer aided finite elements methods. The designed generator has been detailed by 3D magneto static analyses and it has been seen that it would be used as a directly driven machine for the low speed turbines. In this design, a certain value was supposed to be a constant speed and regarding to the obtained electromagnetic generator model, magnetic parameters have been calculated, these values have also been visualized.

In the analyses, it has been supposed to be connected the load given in Table 1 to be connected to the generator's terminals. The results obtained at this loading have been base for evaluations. It has been observed that the ratio of magnet step to pole step of the designed radial flux generator was affected over descending to cogging torque. Beyond the case, geometrical structure (length of the designed machine) and the efficiency are obtained surplus rather than normal generator.

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In this study, a radial flux generator which is driven directly for low speed turbines and structured by permanent magnets has been designed and analyzed by finite elements methods. The designed generator model has got the good results which show high performance characteristics of a permanent magnet generator. Both electrical and magnetic parameters of the designed generator have been calculated; the data obtained from the analyses have been commented. Maximum efficiency has been tried to get by interfering to structure of generator regarding to magnetic materials saturation. Comparison results made in the study have been demonstrated that the designed permanent magnet radial flux generator has superior performance rather than normal generator. Ill. 11, bibl. 16, tabl. 1 (in English; abstracts in English and Lithuanian).

I. Tarımer, E. O. Yuzer. Sistemos su nuolatiniu magnetu ir tiesiogiai sujungto generatoriaus su lėtaeige turbina projektavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 6(112). – P. 15–18.

Analizuojama suprojektuota sistema su nuolatiniu magnetu ir tiesiogiai sujungtas generatorius su lėtaeige turbina. Analizė atlikta taikant baigtinių elementų metodą. . Suprojektuotas generatoriaus modelis pasižymi dideliu našumo koeficientu. Aptarti apskaičiuotieji elektriniai ir magnetiniai generatoriaus parametrai. Keičiant magnetinių medžiagų savybes, buvo siekiama gauti maksimalų efektyvumą. Il. 11, bibl. 16, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).