Mohammadali ABBASIAN[1], Arash H. ISFAHANI[2], Saeideh SHAHGHASEMI[1], Farid SHEIKHOLESLAM[3]

[1]Islamic Azad University, Khorasgan Branch, Isfahan, Iran, [2]Islamic Azad University, Khomeinishahr Branch, Isfahan, Iran
[3]Isfahan University of Technology, Isfahan, Iran

Effects of Permanent Magnet Synchronous Generator and Wind Turbine Parameters on the Performance of a Small-Scale Wind Power Generation System

***Abstract**. Permanent magnet synchronous generators are widely used in small-scale wind power generation systems. Appropriate design of the generator and turbine parameters improves the performance of the wind power generation systems. This paper analyzes the effect of different design parameters of a surface-mounted permanent magnet synchronous generator and the turbine on the annual energy output and also on the cost of a small-scale wind power generation system. The analytical model of the generator and wind turbine is used along with cost models for different parts of the system. The power losses in power electronics devices are also taken into account.*

***Streszczenie.** Generatory synchroniczne z magnesami trwałymi są powszechnie używane w energetyce wiatrowej. W artykule analizuje się możliwości projektowe generatora i turbiny oraz ich wpływ na parametry małego systemu energetyki wiatrowej. (**Wpływ parametrów generatora synchronicznego i turbiny na właściwości małego systemu energetyki wiatrowej**)*

Keywords: wind power generation system, surface-mounted permanent magnet synchronous generator, small-scale, annual energy output, cost, design.
Słowa kluczowe: energetyka wiatrowa, generator synchroniczny.

Introduction

Future energy challenge and environment pollution crisis forces societies to use more renewable energy resources. Nowadays, wind is the most economical renewable energy forms which is widely used in different scales from stand-alone small-scales to wind farm megawatt scales. Superior performance of the permanent magnet synchronous generators (PMSG) makes them as proper candidates for small-scale wind power generation systems [1-2]. PMSGs benefit from high efficiency and power factor in a wide range of operation speeds, high torque density reducing its size and weight, low rotor losses resulting in a lower rotor temperature and simplified cooling system [3]. However, the suitable performance of wind power generation systems chiefly depends on the appropriate design of the generator and the turbine parameters.

In this paper the effects of different design parameters of a surface-mounted PMSG and a three blade wind turbine on the performance and total cost of a small-scale wind power generation system are investigated. For this purpose an analytical model of the PMSG and wind turbine are used and the costs of different parts of system are taken into account. Two main characteristic of a wind power generator i.e. the annual energy production and the total cost are then calculated and effects of different design parameters are investigated. This study provides useful guidelines for the optimal design and selection of the PMSG and the turbine of small-scale wind power generation systems.

Analytical model of PMSG

The schematic view of wind power generation system is depicted in Fig. 1. The system consist of a PMSG, a turbine, power electronics convertors and control system.

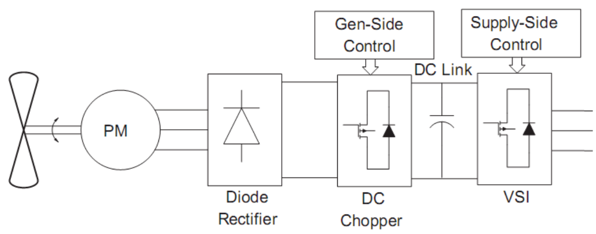

Fig. 1. Schematic view of a wind power generation system [4].

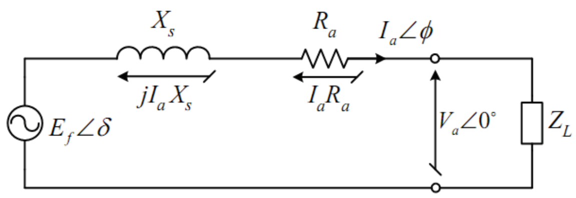

Fig. 2. Equivalent electrical circuit of a surface-mounted PMSG [5].

The equivalent electrical circuit of a surface-mounted PMSG is depicted in Fig. 2. The rms value of fundamental component of phase excitation voltage in a PMSG is given by [6]:

$$E_f = 4.44 f N_{ph} k_{w1} \varphi_{PM} \tag{1}$$

where *f*, N_{ph}, and k_{w1} are the electrical frequency of motor supply, the number of winding turns per phase and the fundamental harmonic winding factor respectively. Also φ_{PM} stands for the flux per pole due to the magnet first harmonic flux density which is obtained from magnetic equivalent circuit of the machine. The synchronous inductance and the stator resistance of the machine are also given by [5]:

$$X_s = \frac{6\mu_0 L D f k_{w1}^2 N_{ph}^2}{p^2\left(k_C l_g + l_m / \mu_r\right)} + X_l \tag{2}$$

$$R_a = \frac{l_{ph}}{a.\sigma_{cu}.A_{cond}} \tag{3}$$

where *L*, *D*, *p*, l_{ph}, A_{cond}, X_l, k_C, l_g and l_m are the stack length of the generator, the air gap diameter, the number of pole pairs, the length of phase winding, the cross area of conductors, the leakage inductance, Carter factor, the air gap length and the magnet height respectively.

Annual Energy Output

Assuming the vector control scheme is used for the generator, the maximum torque per ampere of the stator current is achieved if i_d is maintained to be zero [5]. Therefore, the machine current is obtained as:

(4) $$i_q = \frac{\rho_{air}\pi R^3}{3p\lambda_{pm}} C_T U^2$$

where ρ_{air}, R, U, C_T and λ_{pm} are the air density, the blade radius, the wind speed, the turbine power coefficient and the magnet flux linkage respectively.
Generator losses are then calculated as discussed in [6]. Therefore, assuming the annual energy output can be calculated as [7]:

(5) $$AEO = \sum_{i=1}^{n} P(U_i) H(U_i)$$

where $P(U_i)$ is the output power of wind generation system including the power losses in the turbine, the generator and the power convertors at the speed of U_i. Also $H(U_i)$ is the total number of hours per year in which the wind speed is U_i which can be calculated from probabilistic function of wind [7]. It is notable that the
The cost of the system is composed of the generator cost, the turbine cost and the power electronics cost, the control system cost and the installation cost as:

(8) $$C_t = (C_{PM} + C_{lam} + C_{cu})k_m + C_{tur} + C_p + C_i$$

where C_{PM}, C_{lam}, C_{cu}, k_m, C_{tur}, C_p and C_i are the cost of permanent magnet materials, the cost of laminations, the cost of copper windings, the manufacturing cost coefficient containing the cost of frame and other parts of machine, the cost of turbine, the cost of power electronic convertors and control system and the cost of installation respectively.
Only the cost of generator is assumed to be variable which depends on the volume of the consumed and the cost of other parts is kept constant during analyses.

Parameters Study

The effect of the number of pole paris on the annual energy output and the total cost of the system are depicted in Fig. 3 and 4 respectively. It is seen that, an increase in the number of poles enhances both the annual energy output and the total cost of the system. Therefore, the number of poles should be selected as high as possible. However, mechanical restrictions in tooth and slot width, limit the generator poles number. The effects of number of slots per pole per phase on the annual energy output and the total cost of the system are depicted in Figs. 5 and 6 respectively. It is seen that, increasing the number of slots per pole per phase deteriorates both the annual energy output and the total cost of the system.

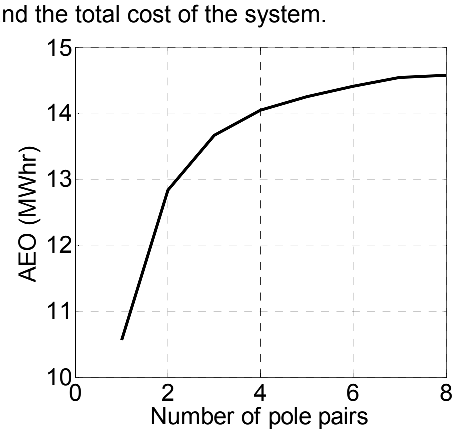

Fig. 3. The effect of the number of pole pairs on the annual energy output

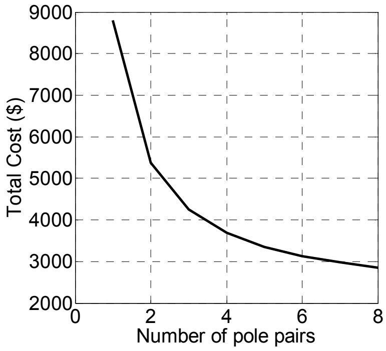

Fig. 4. The effect of the number of pole pairs on the total cost of the system

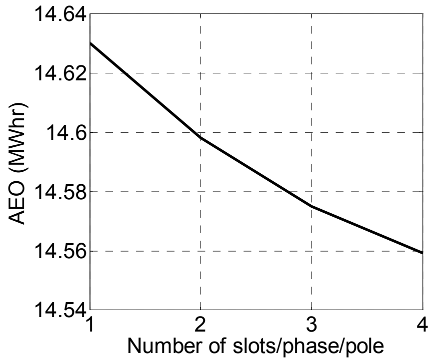

Fig. 5. The effect of the number of slots per pole per phase on the annual energy output

Therefore, it is desirable to keep it as small as possible. There is an optimal value for stack length to air gap diameter to have the maximum annual energy output as shown in Fig. 7. However, an increase in this ratio increases the total cost of the system as it is depicted in Fig. 8.

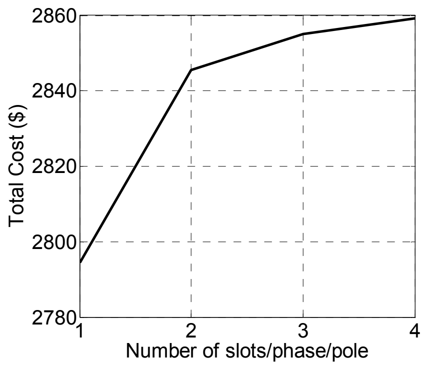

Fig. 6. The effect of the number of slots per pole per phase on the total cost of the system

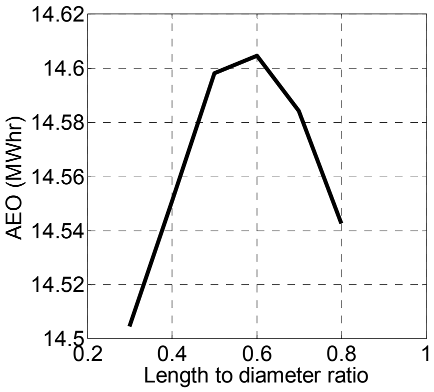

Fig. 7. The effect of the length to diameter ratio on the annual energy output

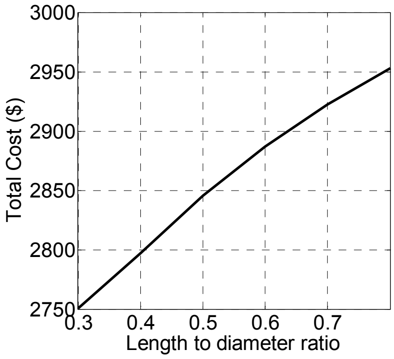

Fig. 8. The effect of the length to diameter ratio on the total cost of the system

The variation of the annual energy output and the total cost of the system versus the specific electrical loading are depicted in Fig. 9 and 10 respectively. It is observed that, a higher specific electrical loading reduces the annual energy output due to a reduction in the generator efficiency. However, it decreases the total cost of the system significantly due to lower permanent magnet consumption. Therefore, to have a suitable choice, the annual energy output per cost is calculated and illustrated in Fig. 11.

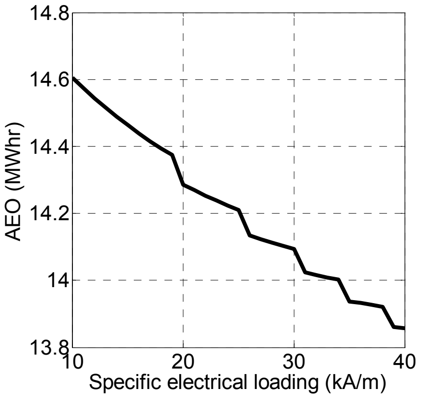

Fig. 9. The effect of specific electrical loading on the annual energy output

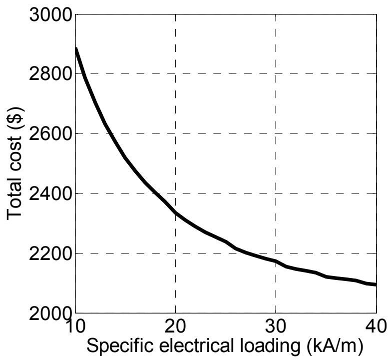

Fig. 10. The effect of the specific electrical loading on the total cost of the system

It is seen that, the higher specific electrical loading increases this ratio. However, a kind of saturation occurs for the specific electrical loadings more than 30 kA/m. Therefore, the specific electrical loading should be selected around this value. Finally, the effects nominal generator speed, in which the generator produces its nominal power, on the annual energy output and the total cost of the system are shown in Figs. 12 and 13 respectively. It is observed that, the lower nominal speed reduces both the annual energy output and the total cost of the system. Therefore, to find an optimum nominal generator speed, the variation of the annual energy output per total cost of the system is calculated and depicted in Fig. 14. It is seen that, the optimum value of the nominal generator speed is around 6 m/s for this case.

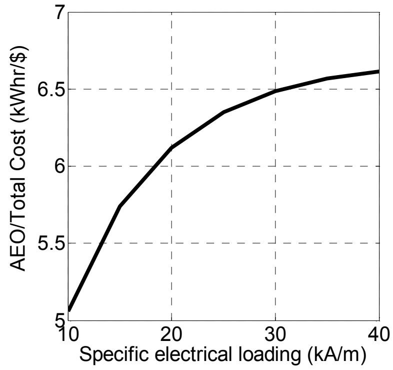

Fig. 11. The effect of the specific electrical loading on the annual energy output per total cost of the system

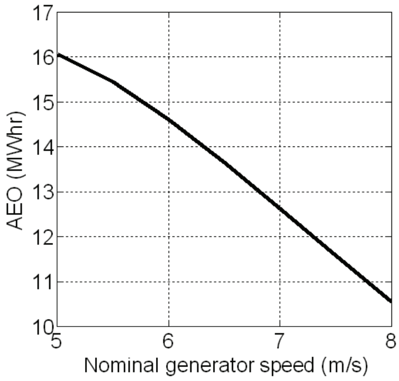

Fig. 12. The effect of the nominal generator speed on the annual energy output

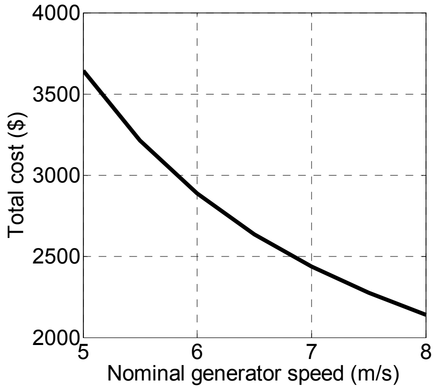

Fig. 13. The effect the nominal generator speed on the total cost of the system

Conclusion

This paper presents an analysis on the effects of the generator and the turbine parameters on the performance of a small-scale wind power generation system. Some design parameters of a surface-mounted permanent magnet synchronous generator and a three blade horizontal turbine are chosen and the effects of their variations on the total cost of the system and the annual energy output are investigated. It is shown that, a higher value of the number of poles and a lower value of the number of slots per pole per phase enhance the performance of the system. An increase, in the specific electrical loading till 30 kA/m significantly enhances the performance of the system but the higher the electrical specific loading has a little contribution in performance enhancement. Also there are optimum values for the stack length to the air gap diameter ratio and the nominal generator speed. This study provides useful guidelines for the optimal design and parameters selection of permanent magnet generators and turbines for small scale wind power generation systems.

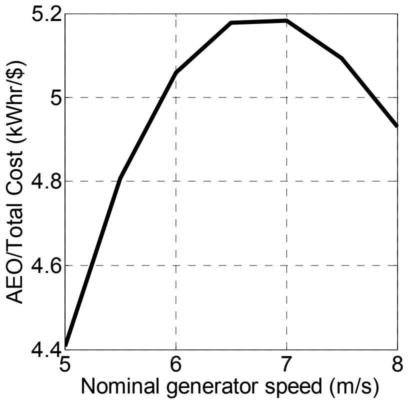

Fig. 14. The effect of the nominal generator speed on the annual energy output per total cost of the system

Acknowledgment

Authors wish to thank Islamic Azad University, Khorasgan Branch for supporting this work.

REFERENCES

[1] E. Spooner, A. C. Williamson, "Direct coupled, permanent-magnet generators for wind turbine applications," IEE Proc. B, Electr. Power Appl. , Vol. 143, pp. 1-8, Jan. 1996.

[2] B. J. Chalmers, E. Spooner, "An Axial-flux Permanent-magnet Generator for a Gearless Wind Energy System," PEDES 96, New Delhi, India, pp. 610-616, Jan. 1996.

[3] Y. Chen, P. Pillay, M. A. Khan, "PM wind generator topologies", IEEE Trans. Industry Applications, Vol. 41, No. 6, pp. 1619 – 1626, Nov. -Dec. 2005.

[4] G. A. Baroudi, V. Dinavahi, M. A. Knight, " A review of power converter topologies for wind generators," Renewable energy, vol. 32, pp. 2369-2385, 2007.

[5] M. A. Khan , " Contributions to Permanent Magnet Wind Generator Design Including the Application of Soft Magnetic Composites," Ph. D. dissertation, Dept. Elec. and Comp. Eng. , Clarkson Univ. ,Potsdam, NY, Nov. 2006.

[6] M. A. Khan, P. Pillay, K. D. Visser, "On Adapting a Small PM Wind Generator for a Multi-Blade, High Solidity Wind Turbine", IEEE Trans. Energy conversion, Vol. 20, No. 3, pp. 685 – 692, Sep. 2005.

[7] Zinger, D. S. , Muljadi, E. 1997. "Annualized wind energy improvement using variable-speed", IEEE Trans Industry Applications, Vol. 33, No. 6, pp. 1444–1447, Nov1997.

***Authors**: M. Abassain and S. Shahghasemi are with Islamic Azad University, Khorasgan Branch, Isfahan, Iran. email: m_a_abbasian@yahoo.com. A. H. Isfahani is with Islamic Azad University, Khomeinishahr Branch, Isfahan, Iran. email: ahassanpour@ieee.org. F. Sheikholeslam is with Isfahani University of Technology, Isfahan, Iran.*