Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 3, No. 3, September 2015, pp. 121~128
ISSN: 2089-3272

Economic Selection of Generators for a Wind Farm

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Abstract

The selection suitable generator for wind turbines will be done based on technical criteria and priorities of the project. In this paper, a method for determining the type of wind turbine generator with an example is explained. In the paper, for a 10kW wind turbine, two generators have been proposed. The first case is a squirrel-cage asynchronous generator coupled to the turbine through the gearbox and directly connected to three phase output. Other PM generators that are directly coupled to the turbine and it is connected to the grid using the inverter. The results show that according to wind conditions, a 10kW permanent magnet generator is more advantageous in terms of energy production.

***Keywords**: wind turbine, weibull, turbine generator, permanent magnet*

1. Introduction

Selection of generator type for a wind farm depends on many parameters, such as access to the power grid, power generator, cost limit, turbine type, quality and quantity of wind and priorities such as efficiency, reliability and the maximum energy. Perhaps In most cases, all of the above are effective in choosing a generator. Usually, according to the priorities of each project, some of these factors are more important. For example, in Reference [1], Selection of turbine generator on the basis of economic aspects of generator stability was evaluated and an objective function based on the mean time to first failure and the mean time between two failures. In Reference [2] costs of a wind turbine are provided separately. Price in different parts of the unit (such as blades, gearbox, generator, etc.) based on the function of the diameter of the turbine is calculated. Therefore the cost function was obtained and Due to the energy taken to try to minimize it. In Reference [3] using the Monte Carlo method type of power generator units can be selected. Power Production capacity and production cost factor can be considered as optimization objectives. In Reference [4], using VSC, producing power generators in a wind farm is transferred to the DC bus and then used another converter for the transfer of power to a three-phase AC grid. Turbines always work at a speed that which have the most power to the grid. So it has not a speed governor. This variable speed is not an issue due to using the inverter. In Reference [5] layout optimization of the turbines in a wind farm is done. With the layout and the proper placement of the turbines overall efficiency has increased about 3%. In Reference [6], optimized for PM synchronous generators with direct coupling to obtain the maximum power from the variable wind speed is done. In Reference [7], using the control of the blade pitch it has tried to obtain the maximum energy at low wind speeds. By controlling the pitch at high wind speed output power of the generator is limited to rated value. In Ref. [8], suitable turbine for a rural with 36500kWh annual consumption energy is selected from different turbine manufacturers. The basis of choice of 30kW turbine for the power supply was the maximum efficiency during the year (the highest capacity factor) and climatic conditions of the region. In this paper, a method for selecting the 10kW generator for wind turbine is provided. The basis of selection of obtaining maximum energy from the generator is respect to costs. For this purpose, the objective function is defined based on the cost-benefit consist of the cost of the generator and incurred equipment, the fixed cost of turbines and other equipment, the energy consumption during a year. To calculate the consumption energy, we used the Weibull curve for Sabzevar city. In this project, optimization carried out by two different generators:

1) Asynchronous generator with a direct connection (Direct Online) to the grid and coupled via the gearbox

2) Axial flux PM synchronous generator connected to the grid through an inverter and a direct coupling.

Received April 19, 2015; Revised June 2, 2015; Accepted June 16, 2015

In other words, the first is a fixed speed and the second is a variable speed type. In any case, considering the costs and the produced energy, optimized power generator is calculated and finally, two generators have been compared in terms of cost and benefit.

2. Characteristics of Wind and Turbine

In every region the distribution of wind follows Weibull function that this can be described by Equation (1):

$$h(v) = (\frac{k}{c})(\frac{v}{c})^{k-1}e^{-(\frac{v}{c})^k} \quad (1)$$

h: Weibull distribution function
c : Scale factor (m/s)
k : Shape factor (m/s)
v : Wind speed (m/s)

In this study, we used the standard deviation method to compute Weibull parameters.
To calculate the coefficient of cumulative and frequency distribution of Weibull, first it is necessary to calculate its first parameter that is *k* shape.
Using this method, *k* and *c* are calculated respectively as [9]:

$$k = (\frac{\sigma}{v})^{-1.086} \quad (2)$$

$$c = \frac{v}{\Gamma\left(1+\frac{1}{k}\right)} \quad (3)$$

$$\Gamma(x) = \int_0^{\infty} exp(-u)u^{x-1}dx \quad (4)$$

In order to calculate the mean wind speed, *v*, and standard deviation of wind speed, *σ*, Equation (5), (6) can be used:

$$v = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (5)$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(v_i - v)^2} \quad (6)$$

In terms of Weibull distribution function, *u* and *σ* can be obtained as follows [9]:

$$v = \int_0^{\infty} v f_w(v)dv = c\ \Gamma\left(1+\frac{1}{k}\right) \quad (7)$$

$$\sigma = \sqrt{c^2[\Gamma(1+2/k) - \Gamma(1+1/k)^2]} \quad (8)$$

Figure 1 shows the Sabzevar Weibull diagram based on$c$=7.29m/s and$k$=1.73:

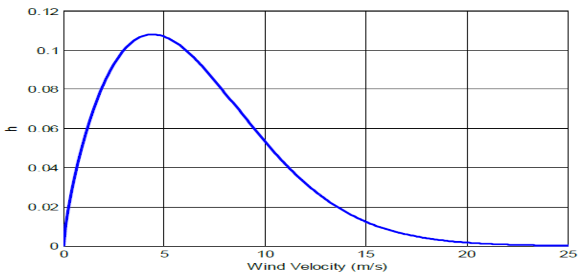

Figure 1. Weibull diagram in Sabzevar region

If we want to calculate the probability that the wind speed is between v_0 and $v_0 + \Delta v$, it is sufficient to take the integral of the function h between these two speeds.

To calculate the wind duration (in hours) between v_0 and $v_0 + \Delta v$ throughout the year, we multiply the probability achieved in a total of 8760 hours of the year:

$$\Delta t = 8760 \times \int_{v_0}^{v_0+\Delta v} h(v)dv \quad (9)$$

Table 1 shows the wind speed data in Sabzevar. Using these data, the parameters *k* and *c* are calculated for the Weibull diagram.

Table 1. The Speed and Wind Power Density in Sabzavar Region

Month	k	c (m/s)	Average power density (W/m^2)	Most probable speed (m/s)
January	1.72	5.77	187.67	3.48
February	1.68	6.44	271.65	3.75
March	1.75	7.22	361.69	4.43
April	1.67	7.42	419.83	4.29
May	1.70	7.66	446.12	4.55
June	1.74	7.66	446.12	4.55
July	1.71	8.20	542.92	4.92
August	1.71	7.82	470.96	4.68
September	1.72	7.90	480.89	4.76
October	1.75	6.99	326.06	4.31
November	1.73	6.07	217.10	3.70
December	1.67	5.68	188.18	3.28
Annual	1.73	7.29	375.15	4.43

The received power of the wind turbine can be calculated from Equation (10):

$$P_{mech} = \frac{1}{2} C_p A \rho v^3 \times 10^{-3} \quad (10)$$

P_{mech}: The received power from wind (kW)
C_p : Turbine performance coefficient
ρ : Bulk density of air (1.1 kg/m3 in 1000m)
A : Area swept by the turbine (m2)

C_p is a quadratic function of ratio of the wind turbine speed in behind of the turbine to front of the turbine and ideally, the maximum value is 0.5. Since the wind speed at the behind of the turbine depends on the geometry of the blades, C_p is expressed based on the ratio of the linear velocity of the tip of the blade to the wind speed or the TSR:

$$TSR = \lambda = \frac{r\omega}{v} \quad (11)$$

r: Radius of the turbine (m)
ω : Angular velocity of the turbine (rad/s)

If the turbine is equipped with a pitch angle control, C_p will be a function of the angle of the blades (β). Turbine studied in this paper is lacking the turbine pitch angle control. Figure 2 shows the variation of C_p in terms of λ:

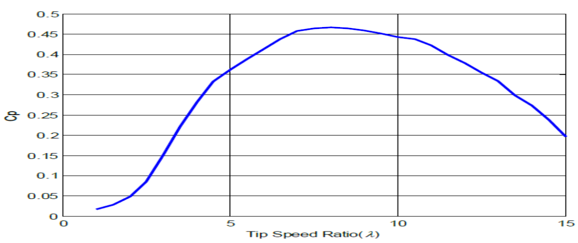

Figure 2. C_p in terms of λ

This diagram is to be drawn by using the design software QBlade for the turbine and its characteristics are as follows:
Diameter turbine=10m
Tower height=11m
$\boldsymbol{v_{cut-in}}$ = 3m/s
$\boldsymbol{v_{cut-out}}$ = 12m/s

3. Energy Calculation

Machine efficiency is usually in nominal operating point. While efficiency is a curve that it is started with zero in non-load and with increasing engine load, increases to a peak (which may be the same as the nominal operating point), and then begins to decline. If we consider a constant value for efficiency from non-load to full load large errors may occur. On the other hand, the machine efficiency diagram is usually not available. For less errors, the machine losses divided into two parts: Constant losses$P_{rot}$and Load dependent losses P_{vLoss}.

The following values show the different parts efficiency in the rated load:

η_{PM} : PM generator efficiency at full load = 0.92
η_{ind} : Asynchronous generator efficiency at full load = 0.81
η_{gb} : Gearbox efficiency at full load = 0.85
η_{inv} : Inverter efficiency at full load = 0.96

For asynchronous generator and gearbox, we will consider 70% of full load losses as constant losses and other losses as load dependent losses. About the PM generator, the mechanical losses are less, we assumed the share of constant losses is 30% and the share of load dependent losses is 70%. In general, if is a share constant loss factor, we have:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out}+P_{loss}} \qquad (11)$$

$$P_{loss} = \frac{1-\eta}{\eta} P_{out} \qquad (12)$$

$$P_{rot} = \alpha\ \frac{1-\eta}{\eta} P_{out} \qquad (13)$$

Machine efficiency without constant losses is as follows:

$$\eta_v = \frac{P_{out}}{P_{out}+(1+\alpha)\frac{1-\eta}{\eta}(P_{out})} = \frac{\eta}{\eta+(1+\alpha)(1-\eta)} \qquad (14)$$

The system can be analysed in three modes:

3.1. The First Case

Turbine is connected directly to a 10kW PM synchronous generator and the output is connected to a 50Hz grid with an inverter. Due to use of the inverter, wind turbine can operate at variable speed. The speed of the turbine can be in the range of 75rpm to 150rpm. From Equation (13) constant losses in this case are as follows:

$$P_{rot(PM1)} = 0.3 \times \frac{1-\eta_{PM}}{\eta_{PM}} \times 10kW = 0.26kW \qquad (15)$$

The efficiency of the generator and the inverter without constant losses can be calculated from Equation (14) as follows:

$$\eta_{v(PM1)} = \frac{\eta_{PM}}{\eta_{PM}+(1-\alpha)(1-\eta_{PM})} \eta_{inv} = 0.905 \qquad (16)$$

3.2. The Second Case

This case is similar with the first case with the exception that the synchronous generator power is 15 kW and it can be changed without any other characteristics changing.

$$\eta_{v(PM1)} = \eta_{v(PM2)} \quad (17)$$

$$P_{rot(PM2)} = 0.3 \times \frac{1-\eta_{PM}}{\eta_{PM}} \times 15kW = 0.39kW \quad (18)$$

3.3. The Third Case

Turbine is coupled to a 10 kW four-pole asynchronous generator through a gearbox with a ratio of 1:20 and three phase generator output is connected directly to the 50Hz grid. The speed of the turbine from non-load to full load varies between 750rpm to 78rpm. Constant losses are calculated as follows:

$$P_{rot(ind)} = 0.7 \times \frac{1-\eta_{ind}\eta_{gb}}{\eta_{ind}\eta_{gb}} \times 10kW = 3.167kW \quad (19)$$

$$n_{v(ind)} = \frac{\eta_{ind}\eta_{gb}}{\eta_{ind}\eta_{gb}+(1-\alpha)(1-\eta_{ind}\eta_{gb})} = 0.88 \quad (20)$$

$n_{v(ind)}$ shows the efficiency of the machine and gearbox without constant losses.

To calculate the annual energy, performance of the wind turbine and generator will be examined separately at low and high wind speeds:

Low wind speed: In this case, the generator works at a lower power than its nominal power and producing power is a function of wind speed andC_p. However, in the case where the PM generator is used, with suitable control of the inverter connected to the generator,$C_p$is a constant value equal to the maximum is 0.466.

For 10kW permanent magnet generator, the annual energy per kWh is calculated from Equation (9) and (10) at speeds between 3m/s and 8m/s as follows:

$$W_{PM1}\Big|_{\frac{3m}{s}}^{\frac{8m}{s}} = \int_{t_1}^{t_1+\Delta t} P_{out}dt = \int_{t_1}^{t_1+\Delta t}(P_{mech} - P_{vLoss} - P_{rot(PM1)}dt = \int_{t_1}^{t_1+\Delta t}(P_{mech} - P_{vLoss})dt - \int_{t_1}^{t_1+\Delta t} P_{rot(PM1)}dt = \eta_{v(PM1)} \int_{t_1}^{t_1+\Delta t} P_{mech}dt - P_{rot(PM1)}\Delta t\Big|_{\frac{3m}{s}}^{\frac{8m}{s}} = \frac{1}{2} \times \frac{8760}{1000} \times \eta_{v(PM1)} C_p A\rho \int_{\frac{3m}{s}}^{\frac{8m}{s}} v^3 h(v)dv \; - \; 0.26 \times 8760 \times 0.4974 = 13888kWh \quad (21)$$

3m/s speed is selected based on (using Equation (10) and Figure 2), that turbine can produce power at least as $P_{rot}$and with increasing wind speed it can be injected power into the grid. In 8m/s speed producing power is equal to the nominal power of the generator and the turbine mechanical power output is equal to the output power with the total system losses.

$\Delta t|_{3m/s}^{8m/s}$ shows the duration of the wind speed between 3m/s to 8m/s and it can be calculated from Equation (9). This value is obtained at 4357 hours.

For 15kW permanent magnet generator, the annual energy per kWh is calculated at speeds between 3m/s and 9.5m/s as follows:

$$W_{PM2}\Big|_{3m/s}^{9.5m/s} = \int_{t_1}^{t_1+\Delta t} P_{out}\, dt = \frac{1}{2} \times \frac{8760}{1000} \times \eta_{v(PM2)} C_p A\rho \int_{\frac{3m}{s}}^{\frac{9.5m}{s}} v^3 h(v)dv - 0.39 \times 8760 \times 0.6 = 23954kWh \quad (22)$$

Because the power of this generator is higher wind speed is considered 9.5m/s. In this speed the mechanical power output of the turbine is equal to the nominal power of the generator and the system losses.

The energy calculation for asynchronous generator is a little different. The turbine speed is constant and with changing in the wind speed, TSR value is changing and according to

Figure 2 causes changing of C_p. Therefore C_p should be considered as a function of wind speed.

In 5.5m/s speed, turbine can produce power at least P_{rot} and gearbox losses and if the wind speed is a bit more to be able to be injected power into the grid. In 11m/s speed, mechanical power output of the turbine is equal to the nominal power of the generator and the total system losses.

If the wind speed is compared with the previous case, we can see in the previous case, the wind turbine has produced 17kW power with 9m/s speed, while in this case producing power is 14.5kW in 11m/s. The reason is that the permanent magnet generator using the inverter, possibility to change of the speed of the generator exists at maximum of C_p.

$$W_{ind}|_{5.5m/s}^{11m/s} = \int_{t_1}^{t_1+\Delta t} P_{out}dt = \eta_{v(ind)} \int_{t_1}^{t_1+\Delta t} P_{mech}dt - \int_{t_1}^{t_1+\Delta t} P_{rot(ind)}dt = \frac{1}{2} \times \frac{8760}{1000} \times \eta_{v(ind)} A\rho \int_{\frac{5.5m}{s}}^{\frac{11m}{s}} C_p(\lambda)v^3 h(v)dv - P_{rot(ind)}\Delta t|_{\frac{5.5m}{s}}^{\frac{11m}{s}} = 12764kWh \quad (23)$$

High wind speed: In this case, with the controlled removal of the wind turbine from the wind direction (Furling), power from the wind is reduced and the output power of the generator is not exceeded from nominal value. In this case, the output power of the generator is equal to the nominal power. For 10kW permanent magnet generator we have:

$$W_{PM1}|_{8m/s}^{12m/s} = P_{out}\Delta t|_{\frac{8m}{s}}^{\frac{12m}{s}} = \eta_{inv} \times 10kW \times 8760 \times \int_{8m/s}^{12m/s} h(v)dv = 18112kWh \quad (24)$$

Δt shows the duration of the wind speed for the mentioned speeds during the year.

For 15kW permanent magnet generator we have:

$$W_{PM2}|_{\frac{9.5m}{s}}^{\frac{12m}{s}} = P_{out}\Delta t|_{\frac{9.5m}{s}}^{\frac{12m}{s}} = \eta_{inv} \times 15kW \times 8760 \times \int_{\frac{9.5m}{s}}^{\frac{12m}{s}} h(v)dv = 14145kWh \quad (25)$$

For asynchronous generator we have:

$$W_{ind}|_{11m/s}^{12m/s} = P_{out}\Delta t|_{11m/s}^{12m/s} = 10kW \times 8760 \times \int_{11m/s}^{12m/s} h(v)dv = 3218kWh \quad (26)$$

All of the above integrals are numerically calculated using MATLAB software.

The total annual energy delivered to the grid is as follows:

10kW PM generator:

$$W_{PM1} = W_{PM1}|_{3m/s}^{8m/s} + W_{PM1}|_{8m/s}^{12m/s} = 13888 + 18112 = 32000kWh \quad (27)$$

15kW PM generator:

$$W_{PM2} = W_{PM2}|_{3m/s}^{9.5m/s} + W_{PM2}|_{9.5m/s}^{12m/s} = 23954 + 14145 = 38099kWh \quad (28)$$

10kW asynchronous generator:

$$W_{PM1} = W_{ind}|_{5.5m/s}^{11m/s} + W_{ind}|_{11m/s}^{12m/s} = 12764 + 3218 = 15982kWh \quad (29)$$

4. Compare the Cost and Value of Produced Energy Generators

Table 2 shows the costs and Table 3 shows the value of the energy produced in one year. Any one of the generators are not effective. The energy production of this type is economically for more than 45 penny per kilowatt-hour. In any case, in this paper, the advantages of each generator studied in comparison with other types.

Table 2. Approximate cost in various parts of the wind turbine

Estimated Costs		
Asynchronous ($)	Permanent Magnet ($)	
4800	4800	Blades
760	5200	10kW Generator
	8000	15kW Generator
1480	1480	Tower
600	600	Panel
--	4400	10kW Inverter
	6800	15kW Inverter
400	400	Measurement and control equipments
60	60	Cable
--	1000	Charging Control
520		Gearbox
800	800	Foundation
800	800	Installation costs
10220	19540	Total Cost 10kW
	24754	Total Cost 15kW

Table 3. Energy production cost in a year (13.34 p/kWh [10])

Type of generator	Energy production in a year (kWh)	Energy value in a year (penny)
PM 10kW	32000	426880
PM 15kW	38099	508241
Asynchronous	15982	213200

The cost of building of asynchronous is about 52% the cost of building of permanent magnet (10 kW). While the energy produced is about 50% of the permanent magnet. Although the difference is not too much.

From the continuity of energy production, asynchronous generator is started producing power from the 5.5m/s speed. In the case, permanent magnet generator can be produced power for 3m/s speed. This means that the asynchronous generator is stopped in most situations. Due to the asynchronous generator is operating at constant speed, all the changes of wind power appear as a tension in the blades and the structure that cause reduce the life of the structure the turbine. Therefore, in this respect, 10kW permanent magnet generator is a better choice.

About 15kW permanent magnet wind turbine, cost of building of this type is about 27% more than 10kW type. While produced energy is only 19% higher, which indicates the advantage of 10kW type.

However, it is important to note that these results are true only with a given Weibull curve in Figure 1. If the turbine installed in a region with the higher average wind speed, asynchronous generator would be more advantageous than 10kW permanent magnet type. However, in this case of 15kW can also be a suitable option.

5. Conclusion

Selecting the type of wind turbine should be done in each region. The results show that according to wind conditions, a 10kW permanent magnet generator is more advantageous in terms of energy production. Also this type of generator has the inherent advantages such as less tension in turbine and structures, greater coherence in injection power into the grid. It should be considered the energy advantage is not perennial and in a region with higher average wind speed, asynchronous generator is more advantageous due to lower initial cost.

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