GRID CONNECTED WIND TURBINES - SRI LANKAN EXPERIENCE

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ABSTRACT

All over the world wind energy sources are becoming widely used as environmentally friendly, small scale energy sources. In Sri Lanka, first grid connected wind farm is now installed in Hanbantota as a pilot project.

In this paper a simple model, which can be used to represent a grid-connected induction generator especially as a fixed speed and a variable speed wind turbine, is presented. Modifications that are required in the model for the analysis of variable speed wind turbine are performed. The characteristics of the fixed speed and the variable speed operation of the induction generator are obtained using the mathematical model developed.

The wind statistics obtained from a site 2 km away from the pilot wind farm in Sri Lanka is analyzed. The output yield so far from this pilot wind farm is compared with the expected output. Advantages of variable speed wind turbines over fixed speed wind turbines for the site studied is also discussed. Finally, problems associated with grid connection of fixed speed and variable speed wind turbines are highlighted.

INTRODUCTION

Windmills have been in existence for many years, mainly for grinding grain or pumping water. The use of windmills to generate electricity is a twentieth-century development, initially at low power levels such as battery charging. The first oil-price shock in 1970s and increasing concern for environment stimulated interest in alternative energy sources, and R&D into modern wind turbine technology received a substantial boost in several countries.

The first grid connected wind farm was installed in Sri Lanka in 1999 in Mirijjawilla, which has an installed capacity of 3 MW. As the interest towards wind generation is now increasing in the country, time has come to look back and learn from the first pilot wind power plant.

In order to select a suitable location for a wind farm, it is very important to do a detail wind statistic study. One of the commonly collected statistical data is the annual wind speed. Annual wind speed of a site varies from year to year due to climatic variations. Therefore, the usual way that the energy potential of a site is determined is by correlating the data of a local anemometer with those of the nearest meteorological station(s), which will have records going back to 10-20 years. Using the annual wind speed statistics, probability of occurring a specific wind speed over a year can be determined. Once the wind statistics are available, a suitable wind turbine can be selected to harness the maximum possible energy from the wind at that site.

Three-phase induction generators are commonly used to generate power from wind. An induction generator operates at a speed that is effectively constant, fixed by the frequency of the utility system, therefore wind turbine rotor must also operate at a fixed speed as the gearbox has a constant ratio. This means the wind turbine cannot be operated at maximum efficiency over a wide range of wind speeds. Some early designs attempted to overcome this limitation by using two generators with different operating speeds, both driven from the high speed shaft of the gearbox. The smaller, slow speed generator was used at low wind speeds. As the wind speed increased, the slow speed generator was disconnected and the larger, high speed generator brought into service. In some modern large wind turbines, this two-speed concept has been developed by placing two different speed windings inside the same generator. Two-speed operation can significantly increases the number of hours a turbine is generating but may have only a modest effect on annual energy yield.

Recent developments in power electronics have made continuously variable-speed drives a practical possibility and this concept can be cost-effective under some circumstances.

A suitable location for a good wind farm is also governed by non-technical aspects. It should be remote from habitation to limit the impact of turbine noise and intrusion. Further, in order to minimize wind turbulence, obstructions to wind flow should be minimum. Therefore, a good site for a wind farm is normally in the areas of low population density, where electrical infrastructure is very week. Weak distribution networks impose various restrictions on connecting wind farms to them, such as poor voltage regulation, poor quality of power, and stability problems. In order to overcome these problems, the capacity of the wind farm, which is connecting to the weak network, should be less than one fifteenth of the network fault level.

In literature, a simple mathematical model to represent induction generators under stand-alone mode of operation is presented (Murthy, Malik and Tandon, 1982, Doxey, 1963]. Further, generalized theory based complicated model for an induction generator to study grid connection and stand-alone applications is presented in (Pena, 1995). However, a simple model, which can be used to represent a grid-connected induction generator especially as a fixed speed or a variable speed wind turbine, is not presented anywhere. In this paper, characteristics of fixed speed and variable speed operation of induction generator using a simple mathematical model are presented. Modifications that are required in this model to analyze the variable speed wind turbine are developed. Using the 3 MW grid connected wind farm in Mirijjawila, selection criteria for a suitable turbine and problems associated with grid connection are highlighted.

CHARACTERISTIC OF THE INDUCTION GENERATOR

Approximate equivalent circuit to represent the induction generator under different operating conditions is shown in Fig.1 (Murthy et. al. 1982).

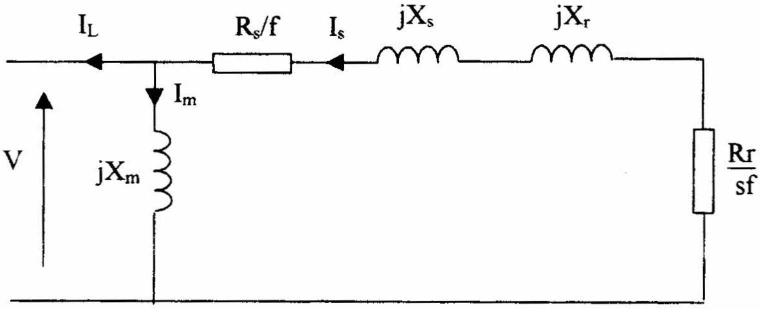

Fig. 1. Approximate equivalent circuit of the generator

Where, R_s and X_s are the stator resistance and stator reactance respectively
R_r and X_r are the rotor resistance and rotor reactance respectively
X_m is the magnetizing reactance
s is the slip
f is the p.u frequency with respect to the mains frequency

If $X_l = X_s + X_r$, then stator current is given by the following equation.

$$|I_s| = \frac{V}{\sqrt{\left(\frac{R_r}{f} + \frac{R_s}{sf}\right)^2 + X_l^2}} \tag{1}$$

If angle between the voltage phasor $\underline{V}$ and the current phasor $\underline{I_s}$ is ϕ, then

$$\sin\phi = \frac{X_l}{\sqrt{\left(\frac{R_r}{f} + \frac{R_s}{sf}\right)^2 + X_l^2}} \tag{2}$$

$$\therefore |I_s| = \frac{V\sin\phi}{X_l}$$

Active power output of the generator

$$\begin{aligned} P &= VI_s\cos\phi \\ &= \frac{V^2}{2X_l}\sin 2\phi \end{aligned} \tag{3}$$

Reactive power output of the generator

$$\begin{aligned} Q &= VI_s\sin\phi + VI_m \\ &= \frac{V^2}{X_l}\sin^2\phi + VI_m \end{aligned} \tag{4}$$

Substituting from equations (1) and (2) to equations (3) and (4), variation of the active power and reactive power with slip can be obtained.

$$P = \frac{V^2\left(\frac{R_r}{f} + \frac{R_s}{sf}\right)}{\left(\frac{R_r}{f} + \frac{R_s}{sf}\right)^2 + X_l^2} \tag{5}$$

$$Q = \frac{V^2 X_l}{\left(\frac{R_r}{f} + \frac{R_s}{sf}\right)^2 + X_l^2} \tag{6}$$

FIXED SPEED AND VARIABLE SPEED OPERATION OF WIND TURBINES

Fixed speed operation

For a wind turbine power extracted by the rotor is equal to the multiplication of the power available in wind upstream relative to the rotor disc area and a constant called coefficient of performance, C_p. On other wards, C_p is defined as the fraction of energy extracted by the wind turbine of the total energy that would have flowed through the area swept by the rotor if the turbine had not been there.

The tip speed ratio of the rotor is defined as,

$$X = \frac{V_{tip}}{V_{wind}} = \frac{\omega R}{V_0} \tag{7}$$

where, R - radius of the rotor in m
ω - rotational speed of the rotor in rad/s
V_o - undistributed wind speed in m/s

Typical curve showing the variation of the coefficient of the performance with the tip speed ratio is given approximately by Fig.2 (Walker, Jenkins, 1997). Note that this curve may vary from turbine to turbine.

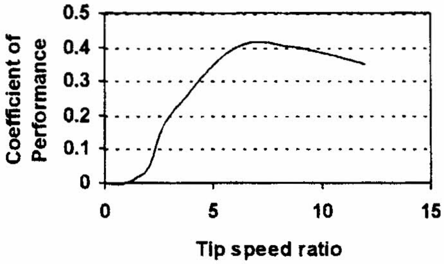

Fig 2. Coefficient of Performance A.D. Vs. Tip-speed ratio for a typical wind turbine

Under fixed speed operation, the speed of operation of the induction generator is fixed by the mains system. At the rated wind speed, tip speed ratio is normally selected to obtain the maximum possible coefficient of performance, thus machine produce the maximum power. As wind speed comes down from its rated value, rotational speed of the machine decreases and operating slip is also decreasing. This in turn decreases the power output of the machine. For a normal wind generator, variation in the slip is in the range of 0 - 5 %. In this operating region, according to equation (5) , $P \approx V^2 s / R_s$ and active power output is directly proportional to the slip.

At a lower speed called cut-in wind speed, enough energy can not be extracted from wind to overcome the mechanical losses within the turbine. Therefore, wind turbine is normally switched off for speeds below cut-in wind speed.

At speeds above the rated wind speed, the power output of the wind turbine can increase beyond the rated power output of the induction generator. Therefore, in order to maintain the power output at its rated value, power of the wind turbine should be limited or regulated. There are two main regulation techniques namely pitch regulation and stall regulation. In pitch regulation, the turbine blades are rotated mechanically, where as in stall regulation the blades are allowed to go into aerodynamic stall.

Variable speed operation

There are many strategies that can be used under variable speed operation. One commonly used technique is to maintain C_P at its maximum value. This can be achieved by maintaining tip speed ratio at a constant corresponding to the maximum C_P. According to equation (7), as ω is in the same order as the synchronous speed ω_s, if ω_s can be varied proportional to the wind speed, V_o, then tip speed ratio can be maintained at the required constant value.

For the variable speed operation of the induction generator, if the operating frequency is f_o and mains frequency is f_s, then slip (s) is given by the following equation.

$$s = \frac{120 f_o / p - \omega_r}{120 f_o / p} = \frac{f_o / f_s - \omega_r / \omega_s}{f_o / f_s} = 1 - \frac{v}{f} \qquad (8)$$

where, p is the number of poles in the machine,
ω_r is the rotational speed of the rotor,
ω_s is the synchronous speed at the mains frequency, and
v is the p.u speed of the rotor.

In this operating mode, the generator is decoupled from the network thus, allowing rotor to rotate freely at a speed corresponds to the wind speed. Under this condition, as wind speed is varying v is changing and if f can be varied proportionally to maintain slip at the rated slip, then power output of the generator can be maintained at its maximum for any wind speed.

Fig. 3 shows one approach to variable speed operation but, as this technology is still evolving, there are several alternative architectures. In the arrangement of Fig. 3 the rotor and gear box are coupled to the generator. A rectifier unit converts the three phase ac into dc and rectified dc is converted back to 50 Hz ac by an inverter. The fundamental principle of operation is that, because all the power is rectified to dc and then inverted to ac, the generator is now decoupled from the network and can operate over wide range of speeds.

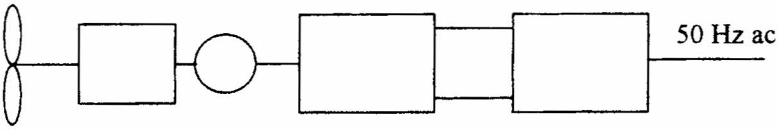

Fig. 3. One Variable speed wind generation technique

CASE STUDY: MIRIJJAWILA PILOT WIND FARM

Wind statistic for the site

The site studied is 2 km away from the pilot wind farm, i.e. Mirijjawila. Hourly wind data from the Mirijjawila site, obtained at two heights, 20 m and 34 m for the year 1998, is used for this study. Using the logarithmic function of the vertical wind speed variation (Walker, Jenkins, 1997), the hourly wind speed at the hub height of the wind farm was obtained. Data at the hub height was used to obtain the probability density function of the site. Probability density function times the number of hours per year vs. wind speed is shown in Fig. 4. In order to select a suitable wind turbine for a site, an approximate probability density function with wind speed at the hub height of the wind farm is sufficient. Therefore, the wind distribution in Fig. 4 is used for further studies.

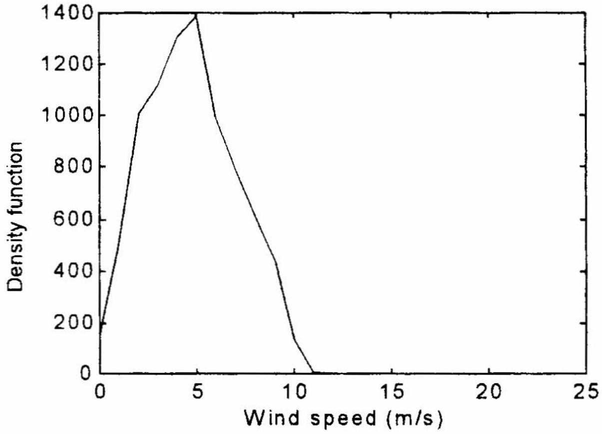

Fig. 4. Probability density function for the Mirijjawila site for the year of 1998

Fixed speed operation of the wind farm

This wind farm has total installed capacity of 3 MW consisting of five wind turbines of 600 kW each. The turbine used is commercially available, MICON, three blade, fixed speed, wind turbine (CEB, 1999).

Fig. 5 shows the variation of wind turbine active power output and reactive power requirement with the rotational speed of the rotor under fixed speed operation, calculated using equations (5) and (6). Relevant data for the induction generator is given in Appendix A.

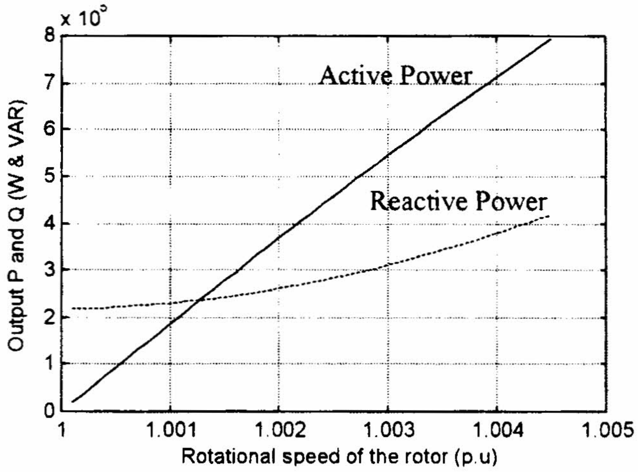

Fig. 5. Operating characteristic for the fixed speed operation

According to Fig. 5, the active-power vs. slip characteristic of the wind turbine is a straight line from zero to rated slip. Since the cut-in wind speed of the turbine is 3.5 m/s and the rated wind speed is 12 m/s, the power curve for the fixed speed wind turbine can be derived as shown in Fig. 6.

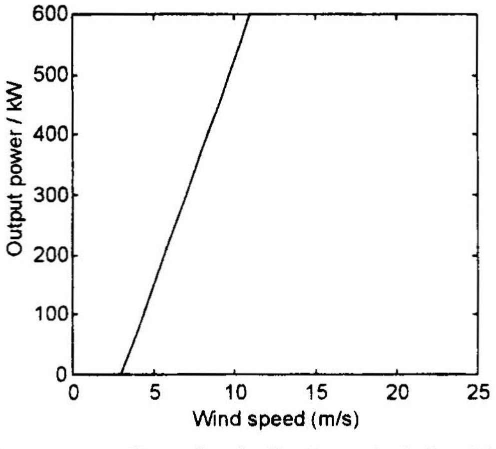

Fig. 6. Power Curve for the fixed speed wind turbine

Variable speed operation of the wind farm

If a variable speed wind turbine, which is operating at a constant *v*/*f* ratio corresponds to the rated slip, was used instead of a fixed speed wind turbine, then the variation of wind turbine active power output and the reactive power requirement with the rotational speed of the rotor is shown in Fig. 7. However, in practical applications, how far *v*/*f* ratio can be maintained at a constant is depending upon the control strategies used for the inverter and the converter.

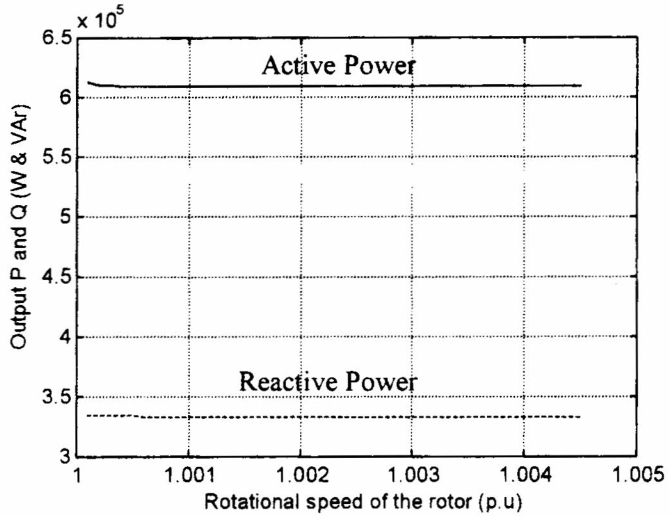

Fig. 7. Operating characteristic for the variable speed operation

Energy Production

Using the probability density function shown in Fig. 4 and power curve of the generator shown in Fig. 6, the annual energy production of the wind farm under fixed speed operation was calculated. In order to calculate the energy output, the following equation was used.

$$Energy = \sum_{u=0}^{\infty} P(u) \bullet h(u) \tag{8}$$

where, P(u) - power o/p of the wind turbine at the speed u.
h(u) - probability density function * 8760

It was found that under fixed speed operation of the wind farm, it could produce 11,071,764 kWh of energy per year.

Estimations using probability density function shown in Fig. 4 and power curve of the generator shown in Fig. 7, show that maximum energy obtained using a variable speed wind turbine is approximately four times the fixed speed energy output.

DISCUSSION

From the study it was found that the probability of wind speed which is occurring maximum number of times is 5 m/s. Probability of occurring any speed above 12 m/s is zero. Therefore, it is very clear that critical wind speeds at which the fixed speed wind turbine reaches its maximum output (from 12 m/s to 25 m/s), do not contribute to the power output.

When comparing the estimated energy output for year 1998 and actual energy output (CEB, 1999) of the wind farm in 1999, it was found that actual energy output of the wind farm is approximately 45% of the estimated value. This is mainly because of two reasons. Firstly, when computing the estimated wind speed, hourly average wind speed is used. Secondly, the wind distribution, used for estimating the annual energy output, is at 2 km away from the actual wind farm site and therefore, an approximate figure.

From the foregoing discussion it is clear that for a site like Mirijjawilla a standard fixed speed wind turbines are not suitable. Other option is to use a variable speed wind farm. If variable speed wind turbines, which can absorb maximum energy at any speed, are used then theoretical energy yield is 4 times of the fixed speed energy output.

From Figs. 5 and 7, it is clear that the reactive power requirement of the wind turbine is varying with wind speed in the case of the fixed speed operation, whereas it is constant under variable speed operation. Under fixed speed operation, shunt capacitors equal to the no load reactive power requirement of the wind turbine is connected at the induction generator. As wind speed is increasing, the wind generator absorbs its additional reactive power requirement from the grid. If the grid is weak, then this may create stability problems, thus decreasing the total capacity of the wind farm, which could be connected to that network. However, in the case of the variable speed operation, as the reactive power requirement of the wind turbine is constant, shunt capacitors of that value can be connected at the generator end. Then reactive power drawn by the system becomes zero, thus improving the system stability.

CONCLUSIONS

A simple model, which can be used to represent a grid-connected induction generator especially as a fixed speed and a variable speed wind turbine, was developed. The model was modified to analyze the variable speed operation of the wind turbine. The characteristics of the fixed speed and the variable speed operation of induction generator were obtained using the simple mathematical model.

Pilot wind farm of an installed capacity 3 MW in Sri Lanka was used as a case study to discuss the advantages and disadvantages of the fixed speed and variable speed operation of induction generators.

Wind data at the hub height of the wind farm was calculated using the measured wind data at 20 m and 34.2 m. Using the estimated wind data, approximate probability distribution of the wind was obtained, and it was found that wind is concentrated around 0 - 12 m/s having the peak around 5 m/s.

By considering the wind distribution and the power curve of the turbine, it was shown that the fixed speed wind turbine selected is not suitable for this site. It was shown that a variable speed wind turbine could yield four times higher energy than that of a fixed speed wind turbine for the site considered. However, before confirmation of this figure further studies are required to be carried out, using computer simulation of the real system with detail representation of the power system, power electronics, machines and control system.

It was also shown that, variable speed wind turbines with larger capacity could be connected to a weak system without loosing the system stability. As most of the feasible wind sites are located in far away places from the main grid this is an added advantage.

ACKNOWLEDGEMENT

Author would like to thank Mr. Kariyawasam, CE, Small Power Projects, CEB for providing wind data for the site for the year 1998.

APPENDIX A

Gear ratio of the wind turbine = 55.806
Maximum value of C_p = 0.42
Tip speed ratio at maximum C_p = 5.07
Cut-in wind speed = 3.5 m/s
Rated wind speed = 12 m/s
Stator resistance = 0.0057217 Ω
Rotor resistance = 0.002569 Ω
Stator reactance = 0.0687 Ω
Rotor reactance = 0.0751 Ω
Rated slip = 0.356 %

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