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Dual-Speed Wind Turbine Generation

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Abstract

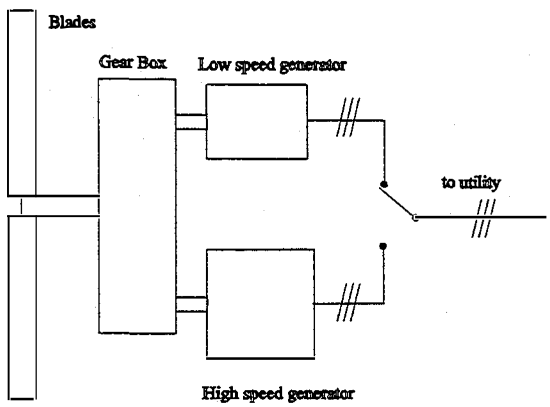
Induction generator has been used since the early development of utility-scale wind turbine generation. An induction generator is the generator of choice because of its ruggedness and low cost. With an induction generator, the operating speed of the wind turbine is limited to a narrow range (almost constant speed). Dual-speed operation can be accomplished by using an induction generator with two different sets of winding configurations or by using a dual output drive train to drive two induction generators with two different rated speeds.

With single-speed operation, the wind turbine operates at different power coefficients (Cp) as the wind speed varies. Operation at maximum Cp can occur only at a single wind speed. However, if the wind speed varies across a wider range, the operating Cp will vary significantly. Dual-speed operation has the advantage of enabling the wind turbine to operate at near maximum Cp over a wider range of wind speeds. Thus, annual energy production can be increased. The dual-speed mode may generate less energy than a variable-speed mode; nevertheless, it offers an alternative which captures more energy than single-speed operation.

In this paper, dual-speed operation of a wind turbine is investigated. Annual energy production is compared between single-speed and dual-speed operation. One type of control algorithm for dual-speed operation is proposed. Some results from a dynamic simulation will be presented to show how the control algorithm works as the wind turbine is exposed to varying wind speeds.

I. Introduction

Utility-size wind turbines have been developed for many years [1]. The reliability of wind turbine generators has improved dramatically. More attention is directed to improve energy capture, load alleviation, and other characteristics that will bring down the cost of energy. Many avenues have been explored and considered such as the development of variable-speed wind turbines [2-5] and some variable-speed systems use direct drives to eliminate the operation and maintenance and the losses of the gearbox even in small scale applications [6-8].



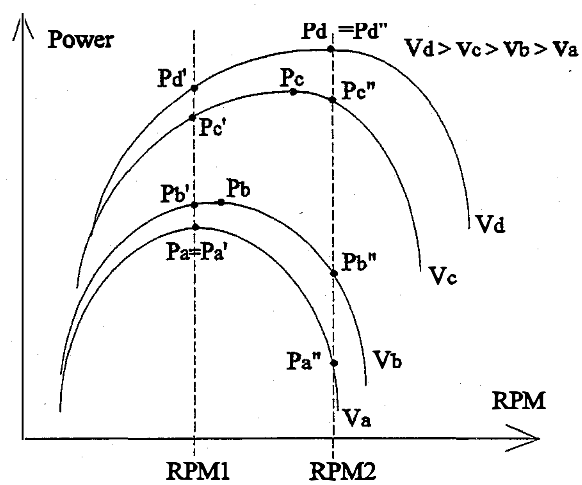


Figure 1. The physical diagram of a dual-speed wind turbine generation

Figure 2. Power versus RPM for dual-speed operation

The system under consideration is shown in Figure 1. The wind turbine is connected to two induction generators via a gearbox. The smaller generator (generator 1) has a slower synchronous speed and the larger generator (generator 2) has a higher synchronous speed. Dual-speed operation can also be implemented by using an induction generator with two sets of windings; each winding has a different number of poles [9]. Using two speed systems instead of single-speed generation has several advantages. In the starting mode, for direct on-line start, the smaller induction motor (higher leakage inductances and resistances) is used to start the wind turbine, thus the inrush current will be lower. The efficiency of an induction generator is normally designed to have an optimum efficiency near its rated power. Thus in the lower power region (lower rpm), the wind turbine can be operated with a smaller generator and it is operated until it reaches its rated power. At low power output, the efficiency can be improved by using the smaller generator.

This paper is divided into 5 sections. In section II, the background of dual-speed operation will be discussed. In section III, the control algorithm will be presented and in section IV the energy calculation will be explored (detailed information regarding energy calculation can be found in reference [10]). Finally, the conclusion will be discussed in section V.

II. Dual-Speed Operation

In a fixed-frequency operation, a wind turbine starts generating power when the rpm reaches a certain rotor speed. An induction generator starts to generate power when the rpm is higher than synchronous speed. The synchronous speed can be computed as:

$$\text{Synchronous rpm} = 120 * \text{frequency} / \text{poles}. \quad (1)$$

Thus for a constant frequency operation, the more poles the generator has, the lower the synchronous rpm. It can be expected that the higher the synchronous rpm, the higher the wind speed will be before the generator starts generating. Figure 3 shows the power generated by the wind turbine for different rotor speeds (high-speed shaft rpm). For an induction generator, the rotor rpm varies with the slip. The slip is normally very small (<5%). Thus practically, the rotor speed in this paper is considered to be constant.

In Figure 2, the output power of a wind turbine for different wind speeds are shown as a function of rpm. The peak power operating points for different wind speeds are given as Pa, Pb, Pc, and Pd. Suppose that the wind turbine is operated only at RPM2, in the higher wind speed region (Vc and Vd), the wind turbine may operate close to its peak Cp (Pc" and Pd"); thus the difference from maximum power generated is small. However, in the lower wind speed region (Va and Vb), operation at RPM2 of the wind turbine will generate a much lower power than maximum power at maximum Cp. Similarly, if the wind turbine is operated only at RPM1, it will be optimized for lower wind speed regions and the operation in the higher wind speed region will be inefficient.

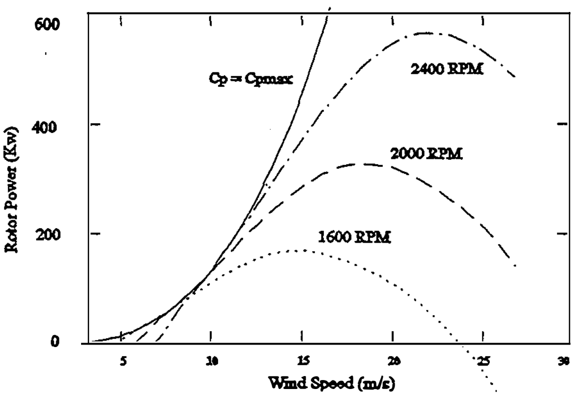


Figure 3. Fixed speed and max Cp operation of a wind turbine

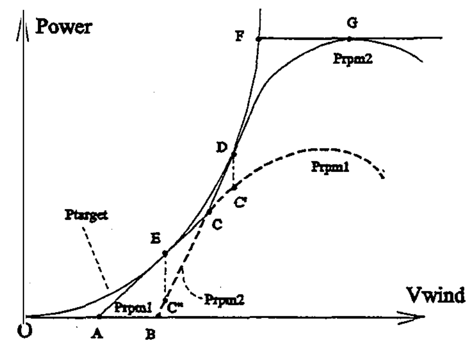


Figure 4. Power versus wind speed for dual-speed operation

From the Cp characteristic, the power versus wind speed can be drawn for different rpm. It can be expected that at higher rpm settings, peak power will occur at a higher wind speed. The maximum power that can be generated by the wind turbine operating at fixed speed does not correspond to the Cpmax. At the rotor speed settings, the system starts generating at higher wind speed (i.e., at 1600 rpm, the system starts generating below 5 m/sec while at 2400 rpm it starts generating at about 7 m/sec). A fixed speed turbine operates at maximum Cp only at one particular wind speed. Operation at other wind speeds is not at maximum Cp.

Dual-speed generation can be accomplished by using a single generator with a two winding arrangement (generator with dual pole configuration 4/6 or 6/8 poles). It can also be implemented by using two different generators (i.e., one generator has four poles and the other one has six poles). The dual-speed operation of a wind turbine generator has the advantage of capturing more energy compared to single-speed operation.

III. Control Algorithm of the System

The operation of a wind turbine at two different speeds is described by Figure 4. The system can be started by operating the induction machine at lower rpm to start the wind turbine. As the rotor speed reaches the (lower) synchronous speed, the wind turbine starts generating and continues to generate until another set point is reached. For example, we may specify a preset power (Pchosen) as the set point. Once the Pchosen is reached, and the wind continues to increase for ΔT seconds, the wind turbine should be transferred to the higher rpm mode, rpm2. During the transition, the rotor is accelerated by the wind. In the acceleration mode (from rpm1 to rpm2), there is no electrical connection to the utility, thus the energy from the wind is converted entirely to kinetic energy to increase the rotor speed.

At low wind speeds, the generator is started by motoring the lower speed motor. Unless any kind of soft start is in place, the start-up is a direct on-line start which will draw current from the utility. Fortunately, with a smaller induction motor to start, the current drawn from the utility will not be as large as the larger induction motor. When the rotor speed reaches the rpm1, the wind turbine starts generating at rotor speed rpm1 (with a variation of a few percent of slip). The generated power increases until it reaches a chosen power (Pchosen) setting. The operation can be determined from the following simple logic:

```
if (power < Pchosen) then
  use rpm1
else if (power > Pchosen) then
  use rpm2
end if
```

where

power	=	measured power	
rpm1	=	lower rotor speed (smaller generator)	(along A E C ....)
rpm2	=	higher rotor speed (larger generator)	(along C D G ....)
ptarget1	=	$0.5\ \rho\ C_{ptarget}$ Area $(\text{Radius/TSRtarget})^3\ \omega_{m1}^3$	(point E)
ptarget2	=	$0.5\ \rho\ C_{ptarget}$ Area $(\text{Radius/TSRtarget})^3\ \omega_{m2}^3$	(point D)

ptarget1 $<$ pchosen $<$ ptarget2

The Pchosen is the set point at which the transfer from rpm1 to rpm2 should be initiated. This power should be chosen between point C' to C" as shown in Figure 4. As shown in Figure 4, the best possible power choice would be point C. At this point the power that can be generated has the maximum gain with respect to power generated by single-speed operation. The difference in power generation between variable-speed (VS) and single-speed rpm2 is area OBDFG. The difference in power generation between dual-speed (DS) generation and single-speed-rpm2 is area ABC and will be called ΔP.

With this option, the generator must be wound to operate at two different speed settings (for example, the generator might be wound to operate at switchable poles such as six and eight). Another option is to operate the wind turbine with two generators of different pole number, such that the lower-speed generator is sized to Pchosen, and the higher-speed generator is sized to take the whole power. For a four pole and a six pole generator, the size of the smaller generator (six poles) can be estimated with a cube relationship, about 8/27 (about 30%) of the size of the larger generator.

The transfer can also be implemented by sensing the rotor slip. When the generated power reaches Pchosen and the wind speed keeps increasing after some ΔT, the wind turbine operation must be transferred to another setting, i.e., operation in high speed rpm (rpm2). Unlike variable-speed operation, the dual-speed operation will have a transient operation during the transition from rpm1 to rpm2. During the transfer of operation of the wind turbine from rpm1 to rpm2, the low-speed generation must be deactivated, and thus the generated power will go to zero. As the wind speed increases, the energy from the wind accelerates the rotor speed and the energy from the wind is fully converted into kinetic energy and stored in the inertia of the rotor. When the rotor speed reaches rpm2, the generator is reconnected again with new synchronous speed at rpm2. Thus the transfer at point C is not instantaneous. We could expect that there are transient phenomena in the wind turbine during this transition.

To illustrate the implementation of dual-speed wind turbine generation, Figure 5 and Figure 6 are given to represent a simulation of the system. In Figure 5, the wind speed input is shown. The wind speed used is ten-minute data that has an average of 6 m/s with a rough wind condition. In Figure 6, the rotor speed is shown to follow the wind speed variation, in the low wind speed region the system operates with rpm1 and in the higher

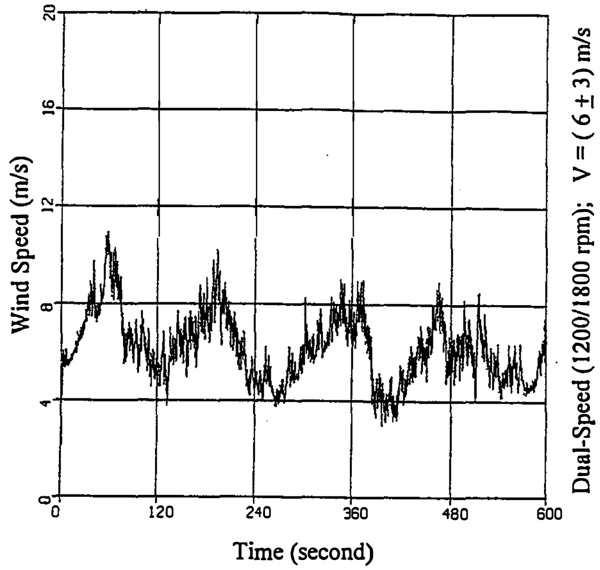


Figure 5. Typical wind speed for rough condition 6 m/s average

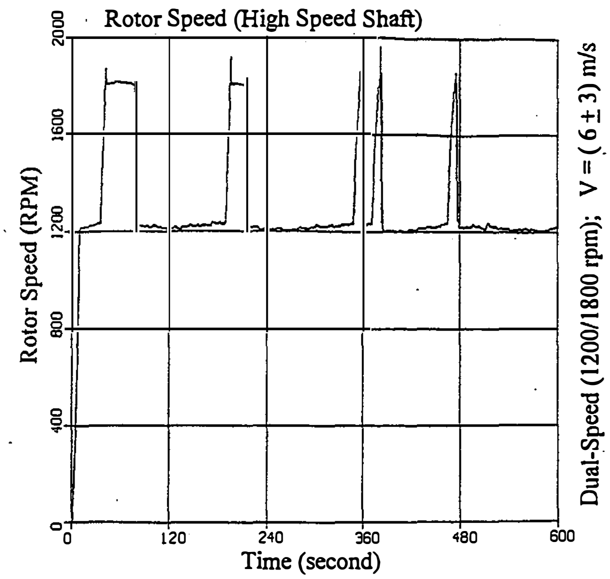


Figure 6. Rotor speed variation as the wind speed changes

wind speed region the system operates with rpm2. When the wind speed increases, the power generated increases until it reaches the power limit which can be detected by power sensor or slip sensor. The transfer from generator 1 to generator 2 can happen if there is enough wind to accelerate the wind turbine from rpm1 to rpm2. During the transfer, both generators are off-line. The system is in an idle condition for a preset idle-time. If during that time the wind speed decreases, the rotor speed will not increase to rpm2, the system will reconnect the wind turbine to generator 1. On the other hand, if there is enough energy in the wind to bring the rotor speed to rpm2 within the preset idle-time, the system will be connected to generator 2.

When generator 2 is operated, and the wind speed decreases, the system will be transferred back to generator 1. The transfer from generator 2 to generator 1 happens by switching from generator 2 to generator 1, thus there

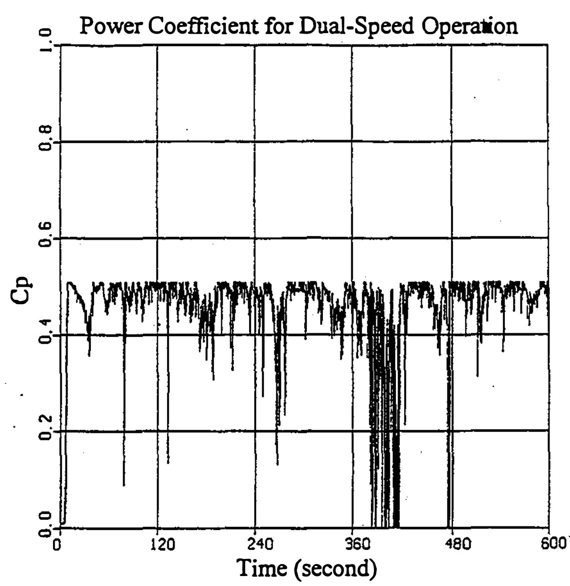


Figure 7. Power coefficient, Cp, for dual-speed operation.

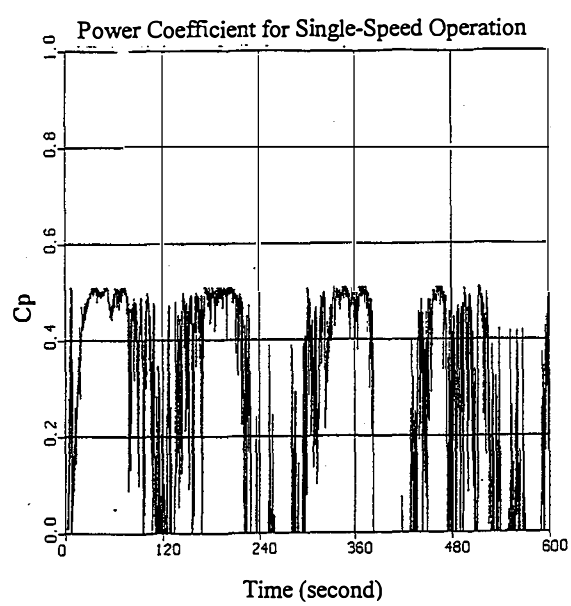
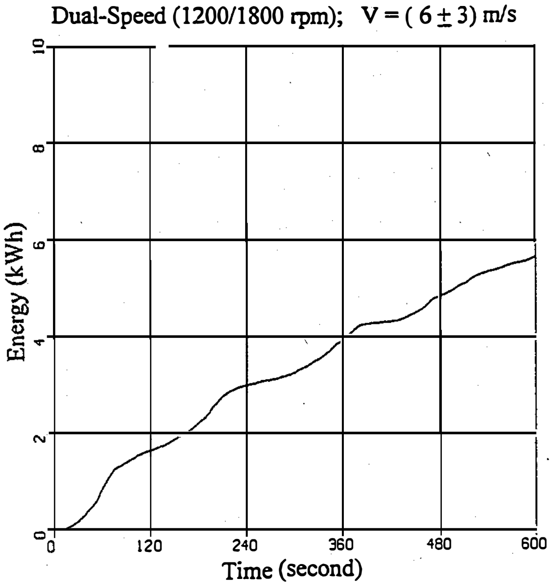


Figure 8. Power coefficient for single-speed operation.



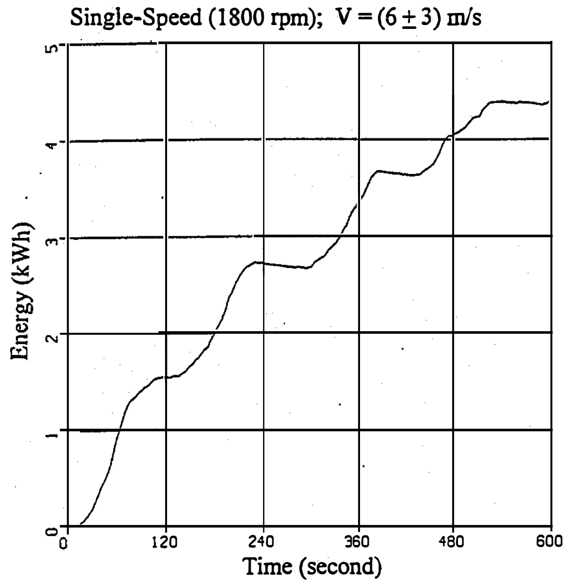


Figure 9. Energy generated for dual-speed operation Figure 10. Energy generated for single-speed operation

is no idle time during the transfer from generator 2 to generator 1. Thus generator 1 is operated in the braking mode to change the rotor speed from rpm2 to rpm1. To limit the number of speed transitions, a more sophisticated algorithm must be used. The algorithm must be designed to maximize energy while minimizing the number of times the wind turbine changes its speed.

IV. Energy Production

The energy production can be illustrated by showing the characteristics of the wind turbine in dual-speed mode using the wind speed input presented in Figure 5. In Figure 7, the power coefficient Cp of dual-speed operation is shown. The power coefficient varies as the wind speed varies and the rotor rpm follows the trends of the wind speed in two discrete values. As a comparison, a wind turbine with generator 2 only is shown in Figure 8 to illustrate single-speed (rpm2) wind turbine operation. As can be expected, the operating Cp for a single-speed system in general is lower than the Cp for a dual-speed system.

The energy collected by the two different systems is shown in Figure 9 and Figure 10. In Figure 9, the dual-speed energy captured during the 10-minute simulation is shown. Note that this is the total energy generated by both generators. The energy generated by a single-speed wind turbine system (generator 2) is shown in Figure 10. It can be seen that there is a significant difference between dual-speed operation and single-speed operation.

The annual energy production (AEP) can be computed by employing a Rayleigh Distribution at a specific site, for example at a 5.8 m/s site. The AEP is computed for different wind turbine systems. In Figure 11 and Figure 12, annual energy is computed from steady-state analysis. Energy can be computed by multiplying the power generated at each wind speed by the density function at a particular wind site and then integrating the result and multiplying by the number of hours per year to get annual energy.

The annual energy distribution generated for different wind speeds is given in Figure 11. From Figure 11, it can easily be seen that dual-speed operation has a significant gain in the lower wind speed region for the site of 5.8 m/sec annual wind speed average. Annual energy generated for different wind speed averages can be illustrated in Figure 12. It can be seen that the AEP for dual-speed operation is higher than the AEP of a single-

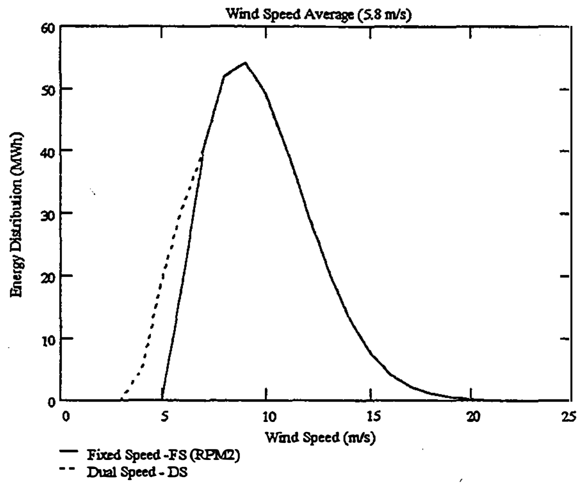


Figure 11. Annual energy distribution at different wind speeds for annual wind speed average of 5.8 m/sec

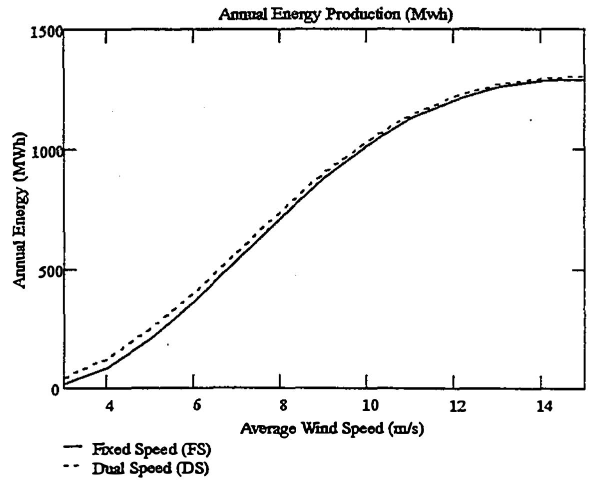


Figure 12. Annual energy production for different annual wind speed averages

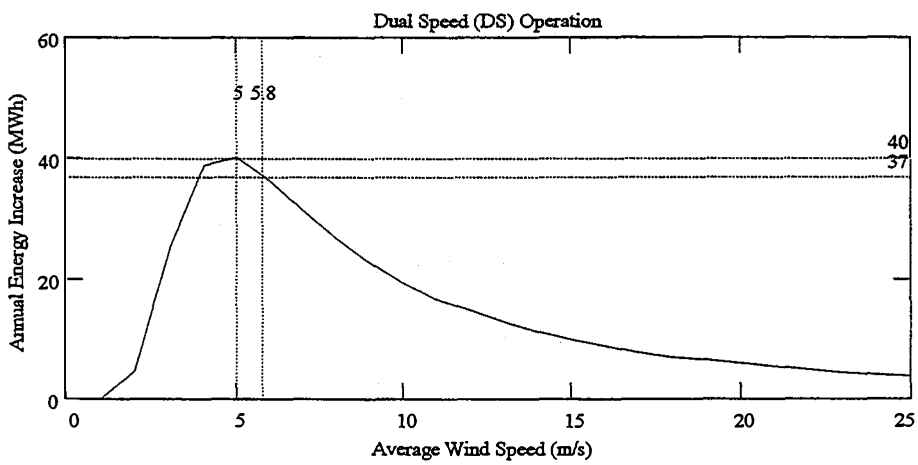


Figure 13. Annual energy increase for dual-speed system

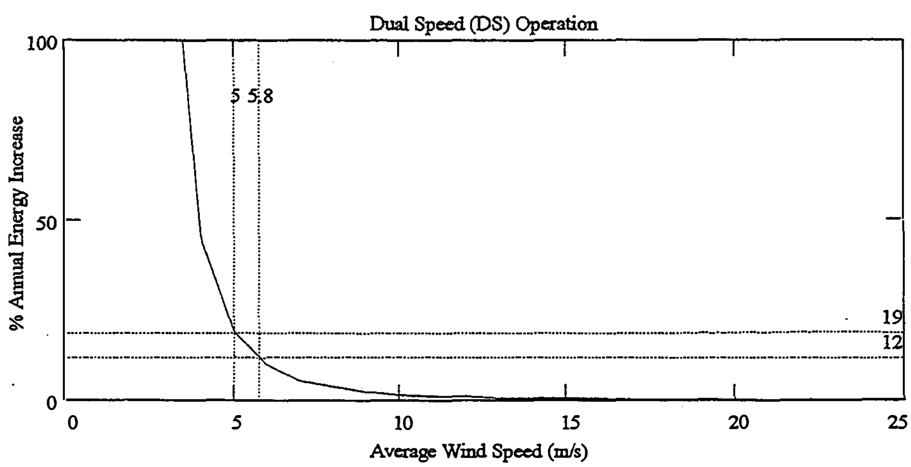


Figure 14. Percent annual energy increase for dual-speed system

speed/fixed-speed system especially in the lower annual-wind-speed average, the contribution of generator 1 (lower rpm) is very significant. The annual energy increase can be computed and the percent change can be plotted. In Figure 13 and Figure 14, the annual energy increases (actual and percentage) are shown. The baseline for annual energy is single-speed operation at rpm2. The annual energy increase is computed as shown in Equation 2 and Equation 3:

$$\text{AEI} = (\text{Annual Energy New System} - \text{Annual Energy RPM2}) \quad (2)$$

$$\%\text{AEI} = (\text{AEI} / \text{Annual Energy RPM2}) \times 100\% \quad (3)$$

Two points are marked on each curve; one corresponds to 5.8 m/s sites and the other corresponds to maximum points.

V. Conclusion

Dual-speed operation has advantages over single-speed operation in terms of the energy capture, higher efficiency in the low power output, and lower starting transients. The initial investment is slightly higher than for single-speed operation; however, it is lower than for variable-speed operation. Induction generation is a mature technology and is very rugged. Thus operation and maintenance is easier and cheaper. The control strategy used in this simulation can be improved and modified for different wind sites.

Acknowledgements

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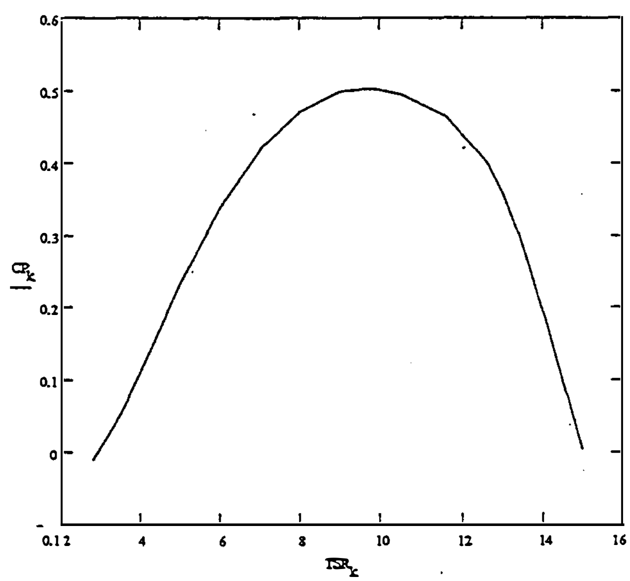
Appendix: General data of the wind turbine generation systems.

The wind turbine parameter:

Blade diameter = 26 m
Rated power = 285 kW
Highest rpm = 57 rpm (low speed shaft)



Cp_TSR of the wind turbine