Research Report
2009-06

A Supersynchronous Doubly Fed Induction Generator Option for Wind Turbine Applications

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Abstract - **Doubly fed induction generators are presently used in the large majority of high power wind turbine applications. The present technology specifies that the turbine operate subsynchronously to follow the desired power vs. wind speed profile and to operate only supersynchronously during brief periods where wind gusts exceed the nominal maximum value of thrust. This paper suggests that improved operation is possible if the generator is confined to always operate in the supersynchronous state resulting in improved efficiency, lower cost and greater output power.**

I. INTRODUCTION

Three types of wind power conversion systems have generally been adopted for use worldwide, namely synchronous generators, squirrel cage induction generators and doubly fed induction generators. Modern usage of these machines are implemented as adjustable speed generators (ASGs) which typically employ an ac-to-ac converter to free the machines of constant or limited speed constraints and thus operate more efficiently over a wide range of wind regimes. Of these options the doubly fed induction generator (DFIG) has become, by far the preferred choice by offering important advantages such as;

- Reduced converter cost since only slip power need be handled.
- Reduced cost of the converter harmonic and EMI filters.
- Ability to adjust power factor of the overall generator system and thus contribute to voltage regulation at the point of common coupling.
- Active and reactive power can be controlled independently.

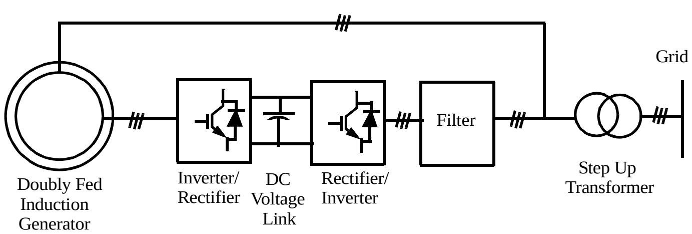

Figure 1 Schematic diagram of the conventional doubly fed induction generator wind power conversion system.

II. THE CONVENTIONAL DFIG ASG

Figure 1 shows a schematic of the DFIG which is in widespread use throughout the world. The converter attached to the rotor consists of a current controlled PWM converter connected to the slip rings of the rotor and a second PWM converter connected the ac grid. The two converters are also connected to a common dc voltage bus supported by a dc link capacitor. Both converters use

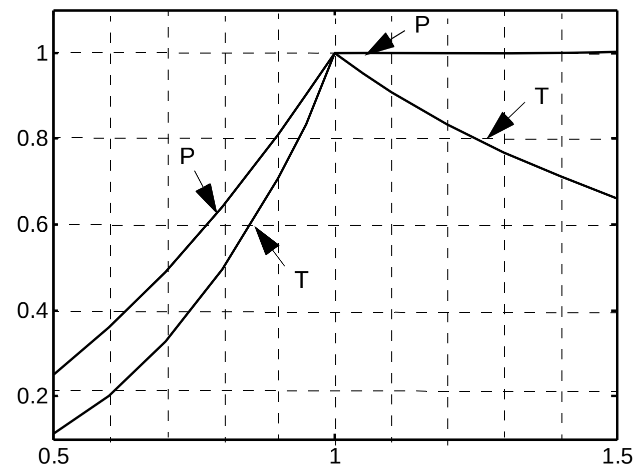

Figure 2 Electrical power output as a function of per unit speed and wind speed.

IGBT/diode or GTO/diode switch pairs so that the converter is capable of operating in all four quadrants of real and reactive power on the utility side of the converter combination.

In an effort to optimize the power throughput from the incoming wind to the electrical power generated, the generator must be controlled to follow the cubic law governing the operation of any fan type prime mover or load. The resulting target for controlling the generator typically becomes that of Figure 2. wherein rated power is reached at one per unit speed corresponding to 50 or 60 Hz operation. Speeds beyond synchronous speed are considered as a brief overload condition which, if persisting for a lengthy period, causes pitch control to dump the blade load. Minimum speed is determined by the availability of the incoming wind at low speed and the economics of operation at this point and typically corresponds to values between 0.5 and 0.75 per unit.

III. STEADY STATE MODEL

Although the standard steady state per-phase equivalent circuit, Figure 3, can be used to determine the performance of a doubly fed induction machine, the formulation of the resulting equations must be modified to suit the fact that the rotor current is the controlled variable rather than the stator current. When doubly fed the per unit power into the rotor circuit comes from two sources

$$P_{r,\,in1} = Re([\,V_2'(I_2')^{\dagger}\,]) \tag{1}$$

and

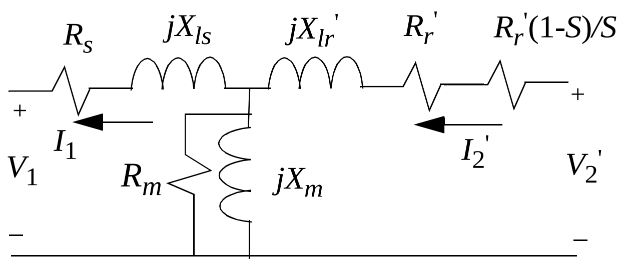

Figure 3 Per phase equivalent circuit of a doubly fed induction generator.

$$P_{r,in2} = T\left(\frac{\omega_r}{\omega_b}\right) = T(1-S) \qquad (2)$$

where (†) denotes the complex conjugate operator and the primed rotor variables are referred to the stator by the turns ratio. Since the machine is a generator, positive T denotes generator operation.

The power lost in the rotor circuit is

$$P_{r,loss} = |I_2'|^2 R_r' \qquad (3)$$

The power out of the circuit is

$$P_{r,out} = Re[\ E(I_2')^{\dagger}\ ] \qquad (4)$$

Conservation of power requires that

$$P_{r,in1} + P_{r,in2} = P_{r,loss} + P_{r,out} \qquad (5)$$

so that

$$Re[\ V_2'(I_2')^{\dagger}\ ] + T(1-S) = Re[\ E(I_2')^{\dagger}\ ] + |I_s|^2 R_r' \qquad (6)$$

or

$$T(1-S) = Re[E(I_2')^{\dagger}\ ] - Re[\ V_2'(I_2')^{\dagger}\ ] + |I_s|^2 R_r' \qquad (7)$$

But

$$\bar{E} = \frac{V_2'}{S} - I_2'\left(\frac{R_r'}{S} + jX_{lr}'\right) \qquad (8)$$

Substituting Eq. (8) into Eq. (7),

$$T(1-S) = Re\left[\left(\frac{1}{S} - 1\right)V_2'(I_2')^{\dagger}\ \right] + |I_2'|^2 R_r'\left(1 - \frac{1}{S}\right) \qquad (9)$$

or

$$T(1-S) = Re\left[\left(\frac{1-S}{S}\right)V_2'(I_2')^{\dagger}\ \right] - |I_2'|^2 R_r'\left(\frac{1-S}{S}\right) \qquad (10)$$

Cancelling out the $1-S$ term

$$T = Re\left[\frac{V_2'}{S}(I_2')^{\dagger}\ \right] - |I_2'|^2 \frac{R_r'}{S} \qquad (11)$$

This resulting equation represents the basic torque equation for a doubly fed induction generator.

Solution of Eq. 11 in terms of the rotor current has been developed by Smith et. al [4]. Expanding Eq. (11),

$$T = \frac{V_{2,re}'}{S} I_{2,re}' + \frac{V_{2,im}'}{S} I_{2,im}' - (I_{2,re}')^2 \frac{R_r'}{S} - (I_{2,im}')^2 \frac{R_r'}{S} \qquad (12)$$

In general, the phase position of the rotor voltage is typically defined as its relative phase position with respect to the stator terminal voltage V_1. Hence, $V_{2,re}'$ and $V_{2,im}'$ can be assumed to be known or specified quantities. Assuming that T and S are also specified, Eq. (12) can be solved for the currents by also assuming that their ratio (power factor) is specified.

An alternative approach to solving Eq. 12 is to assume that the phase position of the rotor current is known rather than the rotor voltage. In this case, assuming the real part of the stator current as reference,

$$I_{2,im}' = 0 \qquad (13)$$

and

$$I_{2,re}' = I_2' \qquad (14)$$

Eq. (12) becomes

$$T = \frac{V_{2,re}'}{S} I_2' - (I_2')^2 \frac{R_r'}{S} \qquad (15)$$

which is simply a quadratic in terms of I_2'. Upon solving Eq. (15)

$$I_2' = \frac{\frac{V_{2,re}'}{S} \pm \sqrt{\left(\frac{V_{2,re}'}{S}\right)^2 - 4\frac{R_r'}{S}T}}{2\frac{R_r'}{S}} \qquad (16)$$

or

$$I_2' = \frac{V_{2,re}'}{2R_r'} \pm \frac{\sqrt{(V_{2,re}')^2 - 4R_r'ST}}{2R_r'} \qquad (17)$$

The voltage $V_{2,re}'$ can also be written as $V_2'\cos\phi_2$ where ϕ_2 represents the phase angle of the rotor terminal voltage V_2' with respect to the rotor input current I_2'. Hence the rotor current I_2' can be determined as a function of slip for any desired torque and specified value of rotor voltage and phase.

Having obtained the rotor current from Eq. (17) it is now possible to obtain the air gap voltage E from Eq. (8). The stator current can then be found from

$$I_1 = I_2' - E\left(\frac{1}{R_m} + \frac{1}{jX_m}\right) \qquad (18)$$

The stator voltage can then be obtained by the stator loop equation

$$V_1 = E - I_1(R_s + jX_{ls}) \qquad (19)$$

In general the voltage obtained will not be identical to the available terminal voltage except for specific combinations of rotor voltage and slip. Hence, an iteration is necessary to converge on the correct values which correspond to the specified stator terminal voltage.

To obtain a suitable answer an search algorithm can be devised as follows: [4]

1) Specify a desired value of torque T and slip S.

2) Loop through Eqs. (17), (8), (18) and (19) for all possible acceptable values of V_2' and $\cos\phi$ and determine the desired V_1.

3) Since the iteration process uses two variables V_2' and $\cos\phi$, a second constraint can be satisfied such as the stator power factor, rotor power factor or efficiency.

4) Select the voltage and phase value satisfying the desired constraints.

5) Modify the target torque and slip and repeat.

IV. Operation Below Synchronous Speed

As shown in Fig. 2, normal operation of the doubly fed generator takes place below synchronous speed. It is important to note that for positive slip S (speeds less than synchronous) the second term of Eq. 11 is *always* negative since $|I_2'|^2$ is always a positive number. Conversely when the slip is negative this term is always positive. Hence, in order to produce a positive (generator) torque below synchronous speed, the first term representing the power input onto the shaft from the external supply must first *cancel* the second term before a positive torque can be achieved below synchronous speed. Above synchronous speed (negative slip) the second term is always positive and both terms contribute to positive generator torque. From Eq. (15) it is evident that in order to simply achieve zero torque it is necessary that the rotor current reach the value

$$I_2' = \frac{V_2'\cos\phi_2}{R_r'} \qquad (20)$$

so that the rotor power loss equal to

$$P_{2,\,loss} = \frac{(V_2')^2(\cos\phi_2)^2}{SR_r} \qquad (21)$$

is wasted as rotor losses before the doubly fed machine can even *begin* to produce generator torque below synchronous speed.

Figure 4 shows a plot of the generator power as a function of speed for increasing values of rotor voltage. The parameters used for this plot and those in succeeding figures are given in Table 1. Note that with zero rotor voltage, the power versus speed curve takes on the usual characteristic. As the rotor voltage increases, the power begins to become positive but substantial voltage is required before the output power is always positive.

Table 1 Doubly Fed Induction Generator Parameters

MW	1.5	$V_{l\text{-}l}$	690 V
f	50 Hz	Poles	2
R_s	0.00706 p.u.	R_r'	0.005 p.u.
X_{ls}	0.171 p.u.	X_{lr}'	0.156 p.u.
X_m	2.9 p.u.	R_m	75 p.u.

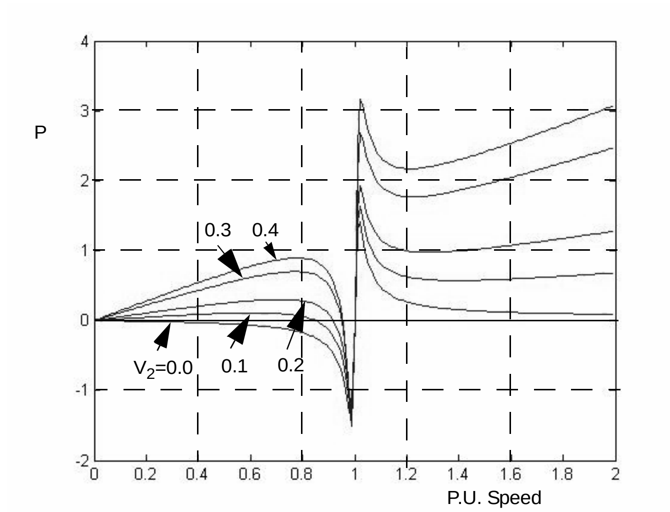

Figure 4 Power produced by the generator for various values of rotor voltage.

Figure 5 shows the rotor power and the stator power assuming that the desired cubic characteristic control law is maintained. This case and in all future calculations, the rotor voltage amplitude and phase have been adjusted so as to create the maximum possible efficiency for each load condition. Note that negative stator power combined with positive rotor power indicates that a portion of the net power is simply circulating around the machine and producing extra losses which, if possible, might be avoided. Over the range of operation the losses varied from 1.4 to 2.5% as the speed changed from 0.5 to 1.0 p.u. As a result the efficiency decreased from 0.975 at rated speed to 0.893 at half speed.

V. Supersynchronous Operation

The problems with circulating power around the machine illustrated by Fig. 5 can clearly be eliminated if operation is confined to speeds above synchronous speed. This can be accomplished by operation as shown in Fig. 6. In this case, because both stator and rotor circuit contribute to torque production, the efficiency now varies from 0.95 to 0.984 and losses from 1.35% to 2.6% as speed

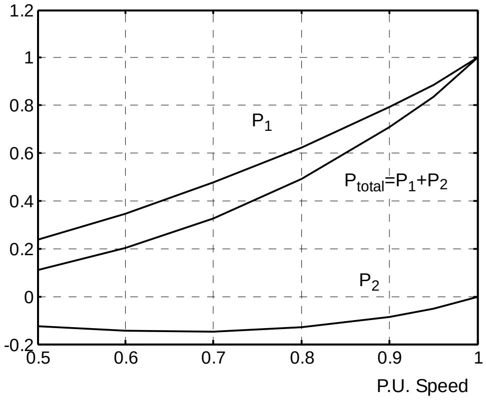

Figure 5 Power produced by the stator and rotor windings and total power for operation below synchronous speed.

changes from 1.0 to 1.5 p.u. The resulting efficiency is clearly a substantial improvement over the conventional case where subsynchronous operation is used. However, since the losses remain much the same it might be questioned how efficiency can be improved. The answer lies in careful examination of Fig. 6 which shows that a 50% increase in power can be produced since the speed has been increased by 50%. Since the rotational speed of the wind turbine blades must remain the same, of course, this result can, of course, only be obtained with a consequent change in the turbine gear ratio.

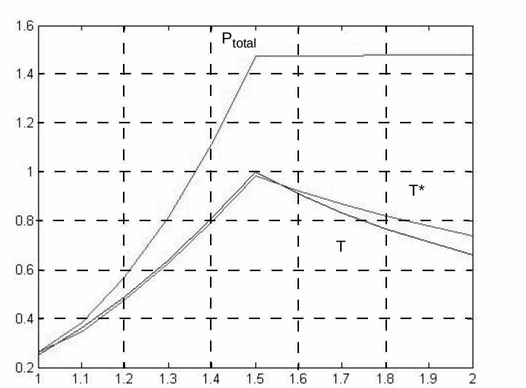

Figure 6 Variation of power and torque with speed assuming that the cubic operating characteristic is shifted to 1.0 to 1.5 p.u. speed.

It can also be noted in Fig. 7 that the rating of the power converter rises above 0.5 p.u. when constant power has to be maintained above the point where rated torque is produced suggesting a large converter rating. This problem can be alleviated if the converter output is simply clamped to 0.5 p.u. by backing off on the torque command as illustrated by Fig. 8. In this case the torque and power begin to decrease with speed beyond the rated torque point. However, since this condition is considered as only an exceptional condition to be weathered only briefly this limitation does not seem to be a major concern.

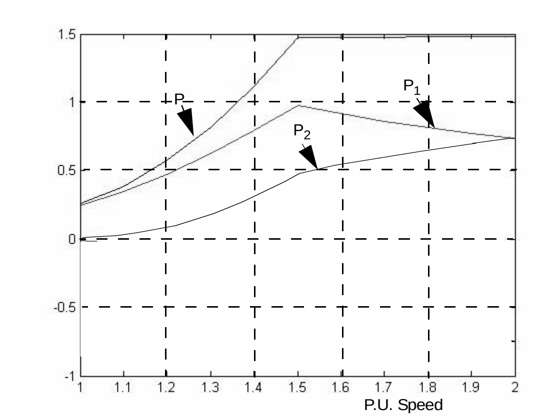

Figure 7 Contributions of stator and rotor power to total power when the power demand curve is shifted to the range 1.0 to 1.5 p.u. speed.

Comparing the power demand from the rotor side power converter of Fig. 5 with that of Fig. 8 (0.15 p.u. vs. 0.5 p.u.) it can be seen that the increase in power comes at the price of a higher converter rating. The increase in power is 0.5 p.u. and the increase in inverter rating is only 0.35 p.u. Also, since the size and weight of a doubly fed induction generator operating only subsynchronously with rating 1.5 p.u. would be roughly 50% larger and heavier, the supersynchronous alternative appears to be an attractive possibility.

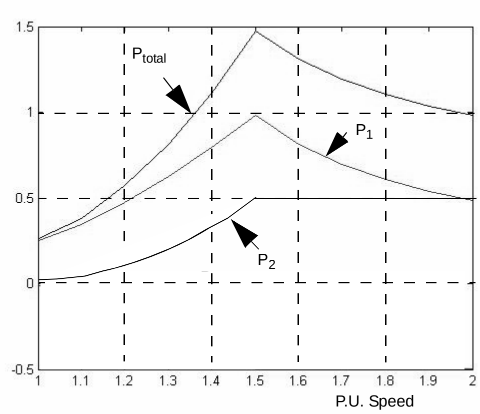

Figure 8 Stator power, rotor power and total power when the rotor power is clamped to 0.5 p.u.

Since the change of operation from 0.5-1.0 p.u. to 1.0-1.5 p.u. has a positive effect on power production, it is interesting to examine whether a further increase in supersynchronous speed would be beneficial. Figure 9 helps one to assess this question. In this case it can be seen that the power output consequently increases to 2.0 p.u. However, the rotor power must rise to 1.0 p.u. to produce 1.0 p.u. torque (and 2.0 p.u. power) at 2.0 p.u. speed. Again cost tradeoff will decide whether such an option will prove useful.

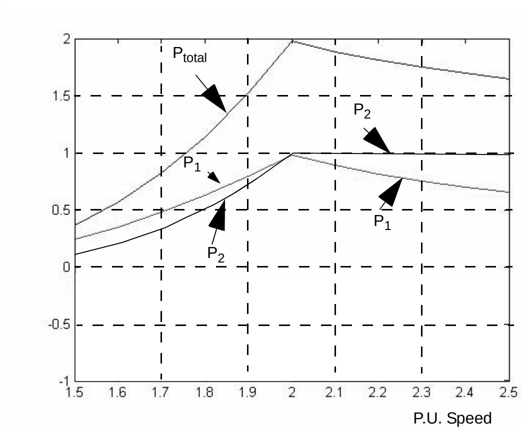

Figure 9 Stator power, rotor power and total power when the rotor power is clamped to 1.0 p.u. and the operating characteristic is moved to 1.5 to 2.0 p.u. speed.

VI. Circuit Implementation

It has been shown that significant improvements in efficiency may be achieved by adopting supersynchronous rather than subsynchronous operation of a wind turbine. An additional 50% power output can be attained by only a 35% increase in converter power. The fact that power flow only from the rotor circuit for both operation on the cubic power characteristic as well as for overspeed conditions allows the power converter to be considerably simplified as well. Figure 10 shows a possible power converter arrangement that requires only diodes for the machine side converter. Control of the converter current is, in this case, achieved by control of the line side converter. Using dioes for one bridge reduces the cost of the converter by nearly 50% compared to the two fully controlled converters of Fig. 1. Hence, the feasibility of restricting operation to supersynchronous speed operation is even more compelling.

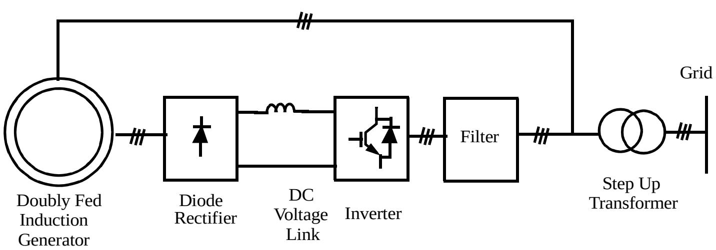

Figure 10 Converter circuit option for supersynchronous operation.

It was mentioned that all of the curves shown in Figs. 5-9 were computed so that all points were achieved at maximum efficiency. Since the diodes of Fig. 10 are uncontrollable it might be questioned whether the operation of the system suffers as the result of using diodes rather than force-commutated switches. In general, diodes operate with a very small delay due to commutation but essentially produce unity power factor operation on the ac side of the bridge. Figure 11 shows the result of re-computing the torque and speed profiles Fig. 6 for unity rotor power factor operation and comparing this result to those obtained for maximum efficiency operation. It is evident that the two modes of operation are nearly the same.

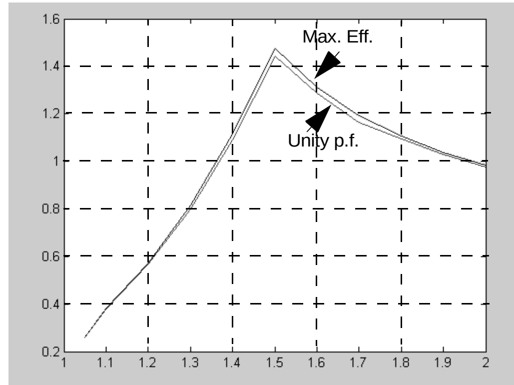

Figure 11 Comparison of optimum efficiency operation with unity rotor side power factor operation.

In general, the use of a current link converter unit has additional benefits. Numerous papers have been written recently on methods to avoid the large overvoltage which appear across the machine side converter as a result of voltage unbalances when a dc voltage bus is used, adding extra complication and cost [5]. With the converter of Fig. 10, these overvoltages simple drop across the link inductor since the diodes are not required to block (and not capable of blocking) these large induced rotor voltages.

VII. Conclusion

This paper has explored the possibility of operating a doubly fed induction wind power generator solely above synchronous speed. It has been shown that operation in this mode results in improved efficiency, a smaller machine and a simple, low cost power converter. This option could prove attractive if the inevitable cost trade-offs suggest that this mode of operation is viable from an overall cost standpoint.

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