On Electrodynamic Braking for Small Wind Turbines

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Abstract

Straightforward analysis can show that it is difficult to implement a successful electrodynamic braking system for a small wind turbine system, i.e. of swept area less than 200 m^2 and power rating of 50 kW. Two principal difficulties are: (i) the peak short-circuit torque of the electrical generator can be far too low to overcome the torques associated with the wind turbine rotor, even at wind speeds close to rated; (ii) the energy dumped into the generator during braking is significant and can cause swift heating to high temperatures. Transient electrical effects can also lead to electrical and electronic component failures. Documented failures in machines of up to 10 kW indicate that it is the case that electrodynamic braking is not well understood throughout the industry. Additionally, the academic literature on the topic is sparse. In this paper, we show how very straightforward analysis can shed light on the edge cases for electrodynamic brake systems and help to avoid expensive errors.

1 Introduction

Electrodynamic braking is a method of small wind turbine control[1] that involves short-circuiting the generator stator windings. A short-circuit results in a large *back-torque* of a magnitude that depends on how fast the generator turns and the dimensions and configuration of the generator; two principal configurations are *radial* or *axial* flux designs. In general, turbine manufacturers that use electrodynamic braking expect that the magnitude of this back-torque, a negative quantity by convention, will be larger than

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[1] The current consensus is that a *small wind turbine* is a machine with a swept area of up to 200 m^2, or a diameter of almost 16 m, equating to a power output of about 50 kW. See IEC 61400-2.

the magnitude of the wind turbine rotor torque, positive by convention. The acceleration of the wind turbine rotor depends on the net torque: a net positive torque will cause the rotor to accelerate; a net negative torque will result in deceleration.

The trouble is that in high wind speeds, the magnitude of the rotor torque will often exceed that of the back-torque *at normal rates of rotation*, i.e. in some instances it will be impossible for electrodynamic braking to bring the turbine to a stop or even to slow it down. This results directly from the observation that the electrical generator has only one peak short-circuit torque while the rotor has a different peak torque for *every possible wind speed*: for a fixed rate of rotation, the rotor torque increases with the wind speed; this in not always understood, as repeated failures show. Some straightforward mathematical models can help to avoid this very expensive error.

2 Generator Geometry and Its Effect on Short-Circuit Torque

In a typical modern small wind turbine permanent magnet generator, the magnets are attached to the surface of a cylindrical rotor. Between the magnet layer and the stator windings is a small air gap. As shown in Figure 1, the windings are assumed to form a layer attached to the surface of the stator, immediately adjacent to the air gap, opposite the magnets.

If the generator windings are short-circuited as the generator rotor is driven, opposing forces are generated in the magnets and the windings. Taking an axial section through the generator, it is reasonable to assume that these forces act on a tangent to the radius of the mid-point of the air-gap.

The tangential force acting on the rotor, per unit length of generator, F_l, can be calculated by summing the force contributions from infinitesimal circumferential elements, i.e.

$$F_l \propto \Delta F_l \times 2\pi R \tag{1}$$

Where ΔF_l is the force contribution per unit circumferential length, per unit length of generator, for an element, R is the radial distance out to the air gap and $2\pi R$ is the circumference of the rotor. F_l depends in a simple way on R, i.e. $F_l \propto R$. Remembering that $\tau = F \times R$, the total associated torque per unit length of generator can be written as, $\tau_l \propto R^2$. Multiplying τ_l by L, the length of the generator, gives the total short-circuit torque acting on the rotor. It follows that,

$$\tau_{total} \propto R^2 L \tag{2}$$

If we assume that the *magnetic loading* and *electric loading* are both held constant, i.e. that ΔF_l remains constant, this identity will remain true as R varies [1, 2]. In reality, this assumption may not be quite valid[2]. For a regular radial flux machine, R and L are well defined; L is the length of the magnet layer. This is often close to the total length of the generator.

It is evident that doubling the generator radius will quadruple the peak torque. Doubling the length of a radial generator will double the peak torque. The same effect could be achieved by maintaining L constant but increasing R by a factor of approximately 1.5.

Axial flux generators are a little more complicated. From Fig. 2, we can see that L can be roughly approximated as twice the length of the magnets, measured radially, and R can be taken as the distance from the centre of rotation to the middle of the magnets. This layout results in a larger radius of action for a given power output. The effect on the peak torque of this increased radius of action explains the attraction of axial flux machines for electrodynamic braking applications: generator geometry matters for electrodynamic braking: axial flux machines, in general, enjoy a significant torque advantage.

3 Estimating the Electrodynamic Braking Capability of a Small Machine

A 4 m demonstration machine, built by the Centre for Renewable Energy at DkIT as a test platform, uses an *Alxion* STK 300 2M permanent magnet radial-flux generator. What can we say about the electrodynamic braking potential of this machine? Short-circuit data are available from *Alxion* for its 500 STK 2M, 150 RPM machine but not for the STK 300 2M [3]. *Alxion's* generators are modular. Differentiating parameters include the radius at which the electromagnetic force acts, represented by the outside diameter of the air-gap (R), the generator length (L), and the length of the windings. Alxion's specifications for the STK 300 2M and the STK 500 2M are tabulated in Table 1.

Using the nominal rated power of the 500 STK 2M published by *Alxion*, and neglecting losses, i.e. the generator efficiency, we can write that the torque τ required to maintain an output power P at a rate of rotation of Ω rad s^{-1}, is,

[2] As a note, there are a number of simplifications implied here. There is an assumption that the number of poles remains constant with increasing radius. Additionally, higher winding voltages associated with higher velocities and higher winding resistances/inductances - there are more wires - both mean reduced short-circuit currents. The result can be a deviation, in reality, from the estimates presented here.

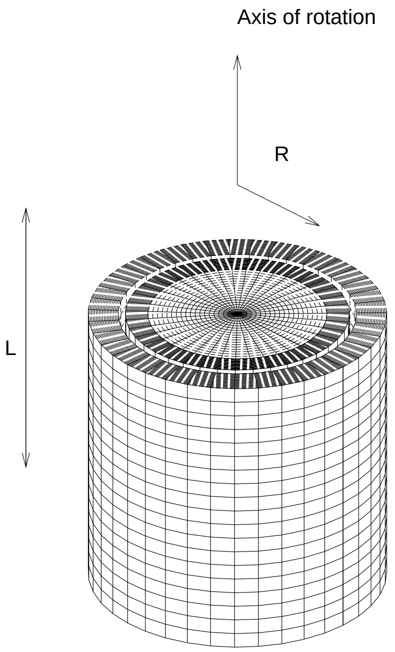

Figure 1: An idealised radial flux permanent magnet generator. Starting at the centre, the layers are, in order: (i) rotor hub; (ii) magnet layer; (iii) air gap; (iv) stator windings. The overall radius can be denoted R. The radius of action of the resultant short-circuit force is from the centre of rotation to half-way across the air-gap.

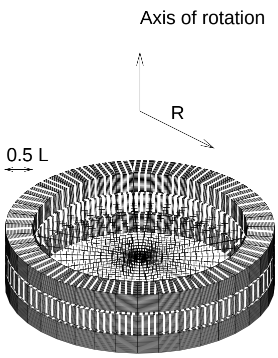

Figure 2: An idealised axial flux permanent magnet generator. A rotating ring of magnets is sandwiched between two stationary rings of windings. The flux length, L, in this case can be taken as twice the radial length of the magnet ring. In the case of a single layer of windings, L is simply equal to the radial length of the magnet ring. The radius of action of the resultant short-circuit force is from the centre of rotation to half-way across the magnet ring.

$$\tau_{500\textsc{stk}} = \frac{P_{500\textsc{stk}}}{\Omega} = \frac{4700}{(150 \times \frac{\pi}{30})} \approx 301 \text{ Nm}$$

In the same way, for the 300 STK 2M,

$$\tau_{300\text{STK}} = \frac{P_{300\text{STK}}}{\Omega} = \frac{3141}{(350 \times \frac{\pi}{30})} \approx 86 \text{ Nm}$$

We can also estimate $\tau_{300\text{STK}}$ using the analysis already outlined, i.e.

$$\tau_{300\text{STK}} \approx \left(\frac{R_{300\text{STK}}}{R_{500\text{STK}}}\right)^2 \times \tau_{500\text{STK}} \approx \left(\frac{0.095}{0.175}\right)^2 \times 301 \approx 88 \text{ Nm}$$

Here, we assume that the *overall* radius of the generator scales with the radial distance to the air gap. This estimate is about 2% higher than the 86 Nm calculated directly from the published data for the 300 STK 2M[3]. From published data, we can construct an approximate short-circuit torque versus rate of rotation curve for the 500 STK 2M [3]. The peak short-circuit torque for the 500 STK 2M is about twice the torque at rated power and speed. This is shown in Figure 3.

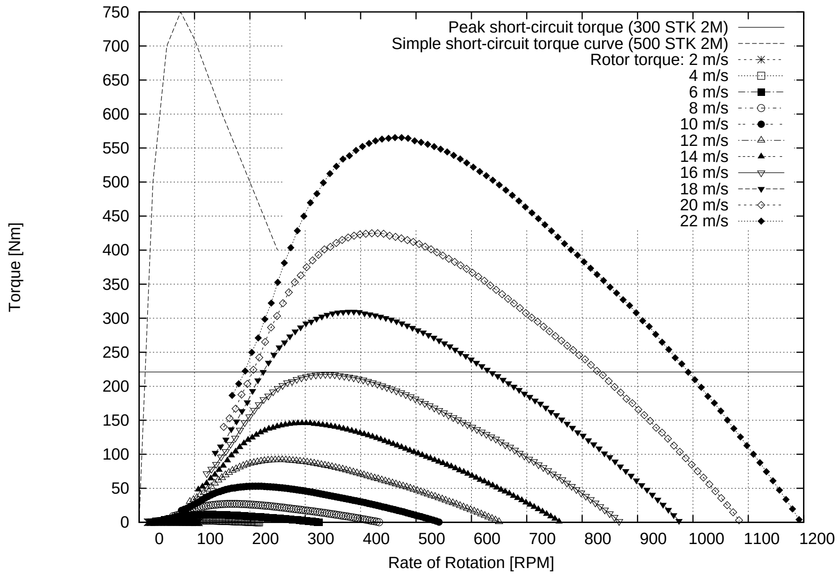

Figure 3: Torque versus rate of rotation curves for the wind turbine rotor, at various wind speeds, the simple short-circuit torque curves for 500 STK 2M permanent magnet generator, using data from *Alxion*, and the peak short-circuit torque for all short-circuit resistances for the 300 STK 2M.

Estimating the peak short-circuit torque of the 300 STK 2M generator using the ratio of radii as outlined, we arrive at a peak torque of 221 Nm. The variation of short-circuit torque with RPM depends on the resistance

[3]*Alxion's* published drawings allows us to use the actual radial distance to the air gap.

of the short-circuit [3, 4]. If a resistance is added to the circuit, the peak short-circuit torque moves to a higher RPM. The solid horizontal line in Figure 3 shows the approximate peak short-circuit torque for the 300 STK 2M machine for all short-circuit resistances. Adding resistance to the short-circuit is equivalent to connecting in a load, i.e. resistance dissipates power as heat.

For the 4 m rotor diameter wind turbine considered, we can generate a series of rotor torque curves for various wind speeds. These were produced using a standard blade-element momentum solver. The algorithm is not outlined here but clear exposition and a version of the algorithm are provided by Hansen [5]. From Fig. 3, it can be seen that the generator will have limited ability to slow or stop a machine using its short-circuit torque in wind speeds of about 18 m/s and higher. This coincides with observations made at NREL [6][4]. There is no possibility of stopping the turbine in the region above the solid line. Below this line, the electrodynamic braking system must be able to vary the short-circuit resistance. Otherwise the braking control will be even more limited at high rates of rotation, i.e. for a simple short-circuit across the terminals, there will be no control anywhere outside of the simple short-circuit line for the 300 STK 2M. This means possible loss of control in wind speeds as low as 12 m/s.

Varying the short-circuit resistance is most easily done by connecting a load to the circuit. At one extreme, an ideal short-circuit, all the energy captured by the wind turbine rotor during the braking period is dissipated in the generator, shifting the peak generator torque to a low rate of revolution; at the other extreme, the connected load dissipates all the energy, shifting the peak torque to a higher rate of revolution. It is worth noting that an ideal simple short-circuit is difficult to achieve. All components, including wiring, have some resistance.

It is interesting to note from the torque graph that a machine *parked* using electrodynamic braking may remain safe, even in high winds[5]; for this to be true, the rotor torque must be lower than the simple short-circuit torque. If the wind speed is high enough or if the winding resistance increases - due to heating from a previous braking attempt, for example - then the machine may start up from a parked state.

4 Additional Technical Challenges

Aside from *control authority*, the major problem facing the electrodynamic braking system designer is that the energy *has to go somewhere*. All the energy captured by the rotor during the braking period is dumped into the generator and ends up as heat. Imagine, in the example above, that we

[4]Although there is not necessarily a correlation.

[5]As per IEC 61400-2, parked machines may turn slowly.

attempt to brake from 190 RPM in a wind speed of 22 ms^{-1}, a strong gale. The machine is unloaded and the electrodynamic brake is the only means of control. At 190 RPM in a wind speed of 22 ms^{-1}, the rotor produces a positive torque of a little over 221 Nm. The electrodynamic brake has no ability to stop the machine in this situation: its maximum braking, i.e. short-circuit, torque (τ_{sc}) is 221 Nm. The net torque is a little above zero: the turbine will continue to accelerate, but slowly at first. If we assume, in this case, that the brake is activated for 10 s and that the rotor's speed remains constant at around 190 RPM, then the power dissipated will be,

$$P_{\text{d}} = \Omega \times \tau_{\text{sc}} = \left(190 \times \frac{\pi}{30}\right) \times 221 \approx 4397 \text{ W}$$

The energy dissipated in the generator in 1 s will be:

$$E_{\text{d 01s}} \approx 4397 \text{ J}$$

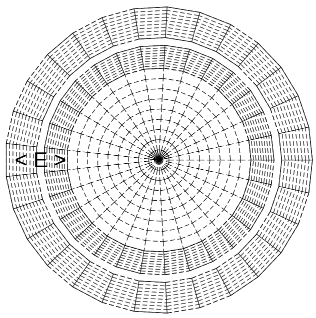

Figure 4: During a short-circuit that lasts a time t and that produces a torque exactly equal in magnitude but opposite in direction to the wind turbine rotor torque, we write that the energy dissipated in the generator is E joules. It is assumed that half this energy is dissipated in the rotor and half in the windings.

Assuming that the rotor hub and the air gap act as perfect insulators, we can write that the heat, Q, dissipated in the magnets is,

$$Q = m \times c \times (T_2 - T_1) \tag{3}$$

Where m is the mass of the band of magnets, c is its specific heat capacity and T_1 and T_2 are the start and end temperatures respectively. Rearranging, we can write that the temperature of the magnet band, T_2, after addition of an energy Q is:

$$T_2 = \frac{Q + mcT_1}{mc} = \frac{Q}{mc} + T_1 \tag{4}$$

If we assume that exactly half of the rotor kinetic energy E is dissipated in the magnet material and half in the stator windings, $Q = E/2$ and we can write,

$$T_2 = \frac{E}{2mc} + T_1 \tag{5}$$

In this case, from experience and from *Alxion* drawings, the magnets can be idealised as a band of iron with an average diameter of 0.190 m, a thickness of 0.005 m and a width of 0.040 m [7]. This gives an approximate volume of $V_{\text{mag}} = \pi \times 0.190 \times 0.005 \times 0.040 = 1.2 \times 10^{-4}$ m^3. We use a typical iron density of 7870 kg m^{-3} and a typical specific heat capacity, c, of 450 J kg^{-1} K^{-1}. The mass turns out to be 0.940 kg. Using these quantities in equation just derived,

$$T_2 = \frac{4397}{2 \times 0.9395 \times 450} + T_1 \tag{6}$$

$$T_2 \approx 5.2 + T_1 \tag{7}$$

A braking attempt in the situation just described could result in a temperature increase of 5.2 °C *per second*. Brake activation for 10 s will lead to a temperature increase of 52 °C. This is not unreasonable. A temperature jump of this magnitude is more than enough to cause damage to a generator. A normal operating temperature is 80 °C [7]. Raising the internal temperature to 132 °C frequently may cause permanent damage to the magnets. Other components may fail in such temperatures. In the worst case, components inside the generator may fail catastrophically. It is possible to imagine technical solutions to this problem. For example, The temperature increase may be acceptable if the turbine is brought under control quickly. In this situation, a cooling system could limit the peak temperature to within the generator's operating limits by dissipating energy from the generator at the same rate that the wind turbine collects it from the wind.

In addition to the problems of control authority and heat, the transient electrical effects associated with short-circuits can have dramatic consequences for the electrical and electronic components involved. These transients can lead to component failure. All components involved in the short-circuit system must be rated appropriately. Electromagnetic compatibility effects associated with transients can conceivably cause interference in nearby components and equipment.

5 Conclusion

Two important considerations for electrodynamic braking are: (i) the peak short-circuit torque of the electrical generator can be far too low to overcome the torques associated with the wind turbine rotor. Or, conversely, wind turbine rotor torques can quickly exceed generator short-circuit torques, even at wind speeds close to rated; (ii) the energy dumped into the generator during braking is significant and can cause rapid heating to high temperatures. Transient electrical effects can also lead to electrical and electronic component failures. Caution is advised before implementing electrodynamic braking solutions.

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Quantity	300 STK 2M	500 STK 2M
Air-gap, Outside Radius (R) (m)	0.095	0.175
Rated Speed (RPM)	350	150
Rated Power (W)	3141	4700
Rated Electrical Torque (Nm)	86	301
Peak Short-Circuit Torque (Nm)	Not published	750
Efficiency (%)	82	80
Rated Line-to-Line Current (A)	7.3	11.7
Rated Line-to-Line Voltage (V)	255	237

Table 1: Published quantities associated with *Alxion's* 300 STK 2M and 500 STK 2M generators.