On Electrodynamic Braking for Small Wind Turbines

November 2012
Latest Revision: April 2013

N. McMahon
Centre for Renewable Energy at Dundalk Institute of Technology

Abstract

Straightforward analysis can show that it is difficult to implement a successful electrodynamic braking system. 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.

1 Introduction

Electrodynamic braking is a method of small wind turbine control that involves short-circuiting the generator stator windings. A short-circuit results in a large back-torque whose magnitude depends on the rate of rotation of the generator 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 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

---

1Contact: niall.mcmahon at dkit.ie/mail.com
observation that the electrical generator has but 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, we can think of these forces acting on a tangent to the radius of the mid-point of the air-gap. A large back-torque acts on the rotor about the axis of rotation.

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.

$$ F_l \propto \Delta F_i \times 2\pi R $$

Where $\Delta F_i$ is the force contribution per unit circumferential length for an element, $R$ is the radial distance out to the air gap and $2\pi R$ is the circumference of the rotor. $F_i$ depends in a simple way on $R$, i.e. $F_i \propto R$.

Remembering that $T = F \times R$, the total associated torque per unit length of generator can be written as, $T_i \propto R^2$. Multiplying $T_i$ by $L$, the length of the generator, gives the total short-circuit torque acting on the rotor, i.e.

$$ T_{total} \propto R^2 L $$

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\(^2\).

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.

The effect on the peak torque of having a relatively large radius for a constant \(L\) explains the attraction of axial flux machines for electrodynamic braking applications: generator geometry matters for electrodynamic braking: axial flux machines have a significant torque advantage.

### 3 Estimating the Electrodynamic Braking Capability of a Small Machine

A 4 m demonstration machine uses an Alxion “STK 300 2M” permanent magnet generator\(^3\). What can we say about this machine? Short-circuit data are available from the permanent generator manufacturer Alxion for its “500 STK 2M”, 150 RPM machine [2]. 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.

Using published data for the 500 STK 2M, and neglecting losses\(^4\), we can write that the torque \(T\) required to maintain an output power \(P\) at a rate of rotation of \(\Omega\) rad s\(^{-1}\), is,

\[
T_{500\text{STK}} = \frac{P_{500\text{STK}}}{\Omega} = \frac{4700}{(150 \times \frac{\pi}{30})} \approx 301 \text{ Nm}
\]

And for the 300 STK 2M,

\(^2\)The same effect could be achieved by maintaining \(L\) constant but increasing \(R\) by a factor of approximately 1.5.

\(^3\)Built by the Centre for Renewable Energy at Dunalk Insitute of Technology as a test platform.

\(^4\)i.e. the efficiency.
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.

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

From the basic analysis already outlined, we can also estimate, using the published measurements, that,

$T_{300\text{STK}} \approx \left( \frac{R_{300\text{STK}}}{R_{500\text{STK}}} \right)^2 \times T_{500\text{STK}} \approx \left( \frac{0.095}{0.175} \right)^2 \times 300 \approx 0.295 \times 300 \approx 88 \text{ Nm}$

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
<table>
<thead>
<tr>
<th>Quantity</th>
<th>300STK2M</th>
<th>500STK2M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-gap, Outside Radius (R) (m)</td>
<td>0.095</td>
<td>0.175</td>
</tr>
<tr>
<td>Rated Speed (RPM)</td>
<td>350</td>
<td>150</td>
</tr>
<tr>
<td>Rated Power (W)</td>
<td>3141</td>
<td>4700</td>
</tr>
<tr>
<td>Rated Input Torque (Nm)</td>
<td>104</td>
<td>376</td>
</tr>
<tr>
<td>Peak Short-Circuit Torque (Nm)</td>
<td>Not published</td>
<td>750</td>
</tr>
<tr>
<td>(Estimate ≈ 270)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>82</td>
<td>80</td>
</tr>
<tr>
<td>Rated Line-to-Line Current (A)</td>
<td>7.3</td>
<td>11.7</td>
</tr>
<tr>
<td>Rated Line-to-Line Voltage (V)</td>
<td>255</td>
<td>237</td>
</tr>
</tbody>
</table>

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

calculated directly from the published data for the 300 STK 2M\textsuperscript{5}. From published data, we can construct an approximate short-circuit torque versus rate of rotation curve for the 500STK2M [2]. The peak short-circuit torque for the 500STK2M is about twice the peak torque at rated power and speed. This is line Gen. 1 in Figure 3. The variation of short-circuit torque with RPM depends on the resistance of the short-circuit [2, 4]. Line Gen. 1 corresponds to a short-circuit at the terminals of the STK5002M machine. If a resistance is added to the circuit, the peak short-circuit torque moves to a higher RPMs, indicated by the broken lines in Figure 3.

Estimating the peak short-circuit torque of the 300STK2M generator using the ratio of radii, we arrive at a peak torque of 221 Nm. Lines Gen. 2(b) to Gen. 2(d) in Figure 3 show indicative short-circuit torque curves for the 300STK2M machine for an increasing short-circuit resistances.

For the wind turbine considered, we can generate a series of rotor torque curves for various wind speeds. These were produced using a blade-element momentum solver, following a version of the algorithm outlined by Hansen [3], after Glauert and Prandtl. 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 obser-

\textsuperscript{5}In fact, using Alxion’s published drawings allows us to use the actual radial distance air gap; this gives a better estimate as the the radial distance to the air gap does not scale linearly with the outer radius of the machine.
vations made at NREL [5]. There is no possibility of stopping the turbine in the region above Line Gen. 2(e). 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 above line Gen. 1. This means possible loss of control in wind speeds as low as 12 m/s. It is interesting to note that a machine parked using electrodynamic braking may remain safe, even in high winds.

4 Energy Dissipation in the Generator

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 as heat. Imagine, in the example above, that we 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 ($T_{sc}$) 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,

$$P_d = \Omega \times T_{sc} = \left(190 \times \frac{\pi}{30}\right) \times 221 \approx 4397 \, \text{W}$$

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

$$E_d \, 0.1s \approx 4397 \, \text{J}$$

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,

$$Q = m \times c \times (t_2 - t_1)$$  \hspace{1cm} (3)

$^6$Although there is not necessarily a correlation.
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 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 [1]. This gives an approximate volume of \( V_{\text{mag}} = \pi \times 0.190 \times 0.005 \times 0.040 = 1.2 \times 10^{-4} \text{ m}^3 \). 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 [1]. 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.

### 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. Caution is advised before implementing electrodynamic braking solutions.

References


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. In the example shown, the overall radius is four times the equivalent radius of the radial flux machine shown in Figure 1.
Figure 3: Torque versus rate of rotation curves for the wind turbine rotor, at various wind speeds, and short-circuit torque curves for two permanent magnet generators of similar construction but different radius. Curves for some possible short-circuit resistances are shown for Generator 2.
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.