Referred Generator Inertia:
a new and decisive advantage for the Torque Limiting Gearbox (TLG) system

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Abstract

The TLG system is a patented mechanical/hydraulic method of achieving variable speed (VS) operation. Because the gearbox provides VS, a constant speed generator can be used, in fact a synchronous generator with consequent cost and electrical advantages. Use of a wind-powered synchronous generator directly on line is a unique feature of the TLG system.

Since 1990, the author had been promoting the TLG system on the basis that it is an effective and cost-effective means of achieving VS operation. He promoted VS operation in general as being necessary to provide torque limitation on a wind turbine, and the TLG system in particular as being cost-effective because it provides narrow-band VS and because it does not attempt to recover energy from the VS system.

As other electrical VS systems have been developed over this period, the author continued to promote the TLG system on this basis - that it is more cost-effective than the competing VS systems. Technically however, the author had assumed that electrical VS systems deliver similar torque-smoothing, and that therefore, apart from some secondary technical advantages, the primary advantage of the TLG system is its cost-effectiveness.

Recently it has been drawn to the author's attention by a leading gear design expert that:

- wind turbine gearboxes are suffering premature failures, even in electrical VS windmills
- referred generator inertia (RGI) is a probable cause of this problem.

This led to one of those "light bulb" moments. **Electrical VS systems do not actually provide torque limiting to anywhere near the same degree as the TLG system.** In the previous 12 years a simple and fundamental advantage of the TLG system had been overlooked. Whether or not RGI proves to be the cause of the current gearbox problems, Newton's Second Law means that it is definitely a source of significant torque fluctuations on the gearboxes of electrical VS windmills. And the TLG system does not suffer from such torque fluctuations for the simple reason that the generator speed does not vary.

This paper explains what RGI is, and why it leads to significant torque fluctuations in electrical VS windmills. The magnitude of these fluctuations is estimated to require an additional 20-30% gearbox application factor. The equivalent inertial torque fluctuations in the TLG system would be about 0.03% by comparison. As a result a gearbox for an electrical VS windmill should (all else being equal) be 20-30% heavier and more expensive than a TLG. Or, if windmill designers have overlooked this effect and tried to take too large an advantage from the partial torque-limiting provided by electrical VS systems, it would result in gearboxes of comparable weight but prone to premature failure.

In either case it points to a decisive advantage for the TLG system, especially in Australia and New Zealand where market conditions require developments on high wind speed sites giving higher running hours above rated and more frequent high power gusts.

Introduction

It is now 12 years since the prototype TLG system was installed in a 200 kW 3-bladed windmill in Devon, England. Immediate results showed remarkable torque smoothing and power control. The prototype ran for several years and, remarkably for that windmill, it was not reinstated to its original fixed-speed, induction generator configuration. Instead the TLG system remained in service until that windmill was decommissioned. During that period the windmill rating was increased to 230 kW, the cut-out wind speed was increased to more than 29 m/s, and the "ramp-down" to 150 kW in high winds was eliminated (an effective uprating of 53%[1]). All these increases in output were a direct result of the torque smoothing provided by the TLG system.

Back in New Zealand since 1990, the author had been promoting the TLG system on the basis that it is an effective and cost-effective means of achieving VS operation. He promoted VS operation in general as necessary to provide torque limitation, and the TLG system in particular as cost-effective because it provides narrow-band VS and because it does not attempt to recover energy from the VS system. (It does not make sense to attempt energy recovery from a system which is not active below rated, because the energy handled in its active, above-rated mode would ordinarily be dumped in those winds anyway).

As other electrical VS systems have been developed over this period, the author continued to promote the TLG system on this basis - that it is more cost-effective than the competing VS systems. Technically however, the author had assumed that electrical VS systems deliver similar torque-smoothing, and that therefore, apart from some secondary technical advantages, the primary advantage of the TLG system is its cost-effectiveness.

But during the last 12 years a simple and fundamental advantage of the TLG system has been overlooked. The author's explanations of the TLG system had used mechanical engineering equations like:

$$P = T.\omega \text{ (Power = torque times angular velocity)} \qquad \text{- Eq. 1}$$

and the differential form of that equation:

$$\Delta P = T\Delta\omega + \omega\Delta T \qquad \text{- Eq. 2}$$

$$= T\Delta\omega \text{ (for constant torque)} \qquad \text{- Eq. 2a}$$

$$= \omega\Delta T \text{ (for constant speed)} \qquad \text{- Eq. 2b}$$

The author's explanations had simplified the situation by assuming that either Eq. 2a or 2b applied, i.e. the system could be treated as either constant torque (which is essentially valid for the TLG system) or constant speed (which was essentially valid for most windmills in the 1980's).

However a much simpler piece of high school physics had been neglected, Newton's Second Law of Motion, which most people recognise as:

$$F = m.a \text{ (Force = mass times acceleration)} \qquad \text{- Eq. 3}$$

and which is used in rotating systems as:

$$T = I.\alpha = Id\omega/dt \text{ (Torque = rotational inertia times angular acceleration).} \qquad \text{- Eq. 4}$$

With the focus in these explanations being on the torque rating of the gearbox, to neglect inertial effects was (and is) valid for the TLG system, because the inertia "downstream" of the gearbox is negligible. However for electrical VS systems, this is not the case. This means that, in the transient situations which are of interest in wind turbine design, Eq. 4 needs to be considered. The inertia of different parts of the drive-train need to considered individually and it can not be assumed that constant torque on one part of the drive-train will ensure that torque is constant throughout the drive-train.

[1] Throughout this paper, where percentages are used (for wind speed, power or torque), it means a percentage variation relative to a mean or rated value. For example in this instance, 53% of 150 kW is 80 kW (the magnitude of the transient when 150 kW increases to 230 kW).

This paper will consider the implications of Eq. 4 but firstly review the first term in Eq. 2, ΔP, the variation in the input aerodynamic power.

The Problem of Windmill Power Control

The subject importance of this paper could be questionable if it were not for the magnitude of the power transients that wind turbine rotors produce during wind gusts. This "new advantage" of the TLG system over electrical VS systems would be quite academic if these transients were only of the order of 10% of rated power. If this were the case, there would be little point in worrying about RGI, though by the same token there would be little justification for VS operation!

The magnitude of these aerodynamic power transients is much higher, typically 25% but not uncommonly 75-100% or more. It is this fact which led gearbox designers of fixed-speed windmills in the 1980's to insist on an overall safety factor of at least 2, meaning that **a 250 kW windmill had to have a 500 kW gearbox to accommodate these 100% overloads.** And it became common to derate fixed-speed windmills in winds above 15 m/s ("ramping" down the demand power) by about 40%, eg to 150 kW, so as to protect the gearbox from the even higher excursions experienced in those wind speeds. Having to run a 500 kW gearbox at a mean of 150 kW implies 350 kW (233%!) power excursions!

Those who have not worked closely with wind turbine design and monitoring might find this surprising. Indeed it is fairly astounding to those who <u>have</u> worked closely with windmills! It seems unusual for three reasons:

- the power in the wind tends to be underestimated because of our familiarity with air as fairly light and insubstantial stuff (you can't even see it!)
- wind turbines are unique in the power sector because they are the only turbines where the "working fluid" can not be controlled before it reaches the turbine itself (think of steam, gas and hydro turbines by contrast)
- the aerodynamics of lifting aerofoils are not intuitively obvious. The lifting aerofoils used on modern wind turbines are very responsive to changes in wind speed, but while this can be analysed, few people would claim to "have a feel" for it. Glider pilots perhaps would come closest, as they bring their wonderfully light, efficient wings down through the turbulent boundary layer for landing.

Because of these three factors it is worth analysing the roots of the windmill power control problem, which has tended to be underestimated by designers in the last twenty years.

In analytical terms the first factor above is expressed as the cubic relationship between power and wind speed: $P \propto V^3$. The second factor is expressed as turbulence intensity or gust factor. A typical value for gust factor is 1.5, meaning that within a ten minute period the highest 3-second gust is 50% higher than the 10-minute mean. If these two factors are put together it implies that a 50% gust can cause a 238% power transient (because $1.5^3 = 3.38$).

But the third factor, combined with the nature of windmill power curves and control systems, means that it is not as simple as this. For pitch-regulated windmills, particularly high power transients are possible in high winds because the aerofoils are feathered (reducing the angle of attack) which keeps them in the very responsive part of the lift curve. In addition the flat mean power curve above rated means that the rotor as a whole is working below its maximum efficiency. In a gust the efficiency can increase, and a relatively larger proportion of the enormous power in the wind at such speeds is converted to mechanical power in the rotor.

The following table illustrates this point. If the Windflow 500 were running at the mean wind speeds indicated in the first row, it would generate about 545 kW of mechanical power in the rotor to generate 500 kW electrical from the alternator. If a 50% wind gust occurs and the blade pitch stays constant, the power transient increases in absolute (extra kW) terms, and relative (% increase) terms, as the wind speed increases, to be even higher than the theoretical value of 238% in 24 m/s winds.

Mean Wind Speed (m/s)	13.7	15	20	24	30*
Aerodynamic power transient:-kW	480	692	1,155	1,537	2265
(50% gust with constant blade pitch) -%	88%	127%	212%	282%	415%

*Note: most wind turbines shut down at 25 m/s – the Windflow 500 will continue operating to 30 m/s.

Table 1: Increase in power transient with wind speed in above rated winds.

These figures are for comparative purposes only because the pitch does not in fact stay constant. The above table neglects the effect of the pitch-control system, which always attempts to spill the gust power as soon as it detects it. In fact the discussion so far has neglected gust rates and the detailed dynamics of the problem. Suffice to note that wind power ramp rates in excess of 200% per second are common, and seriously challenging for anyone who thinks that active control systems can simply be designed faster. For a start there are limits on the rate at which blades can be pitched without overloading the pitch mechanism.

In any event Table 1 makes a valid point that, for pitch-regulated[2] windmills, the problem for the control system becomes larger in higher winds. It also highlights the fact that electrical VS windmills which are experiencing gearbox problems will tend to do so sooner in high wind sites (eg Tararua Wind Farm).

To sum up this section, no matter how fast the control system, it will have to deal with aerodynamic power transients of this general magnitude, even if (in the case of VS systems) it prevents the transient from getting through the generator as an electrical power transient. This is an important point to bear in mind – **the wind turbine rotor of a pitch-regulated windmill will generate large aerodynamic power transients and the smooth electrical power output from VS systems should not disguise this fact.**

The rest of this paper will discuss how different pitch-regulated systems deal with these transients. For simplicity, "ΔP" will be assumed to be 100%, i.e. a transient doubling of aerodynamic power, in winds below 15 m/s, and 200% in winds above 15 m/s.

Fixed-speed Windmills

In the case of fixed-speed windmills, Eq. 2b applies and the aerodynamic power transients go through the gearbox as torque transients, and come out of the generator as electrical power transients. This then provides an error signal for the pitch control system to try to do something about it, but of course it is too late to provide good control. The gearbox torque and electrical power are thus subject to transients similar to those in Table 1. As a result it becomes necessary to ramp down the mean power in high winds, as mentioned above.

For fixed-speed windmills, the typical value for ΔTg (gearbox torque transient) is inherently the same as ΔP. This is evidenced by the need with these designs for:

- a gearbox safety factor of 2 to cover operation between rated wind speed and 15 m/s, and
- ramping the demand power down in winds above 15 m/s typically by more than 33% (which corresponds to a gearbox safety factor of 3, because 2.0/0.67 = 3).

In fact the above is a very simplified explanation. They are not truly fixed-speed windmills. This would require the use of a synchronous generator. While this would be desirable on cost grounds (synchronous generators are mass-produced for the diesel-genset market), it is impossible because of this same power control problem. Torsional drive-train oscillations (which we have not discussed as they can otherwise be omitted from this paper) are set up by the effect of an "irresistible force" (a wind gust) hitting an

[2] For stall-regulated windmills the reverse happens. Significant power transients occur around rated, but their relative magnitude falls as wind speed increases, because the blades become deeply stalled. This was a significant advantage for stall-regulated designs over their fixed-speed pitch-regulated competitors in the1980's. Put another way, it became an argument for VS systems in the 1990's because without them, pitch-regulated windmills simply weren't doing the job – they were not regulating the electrical power output adequately.

"immovable object" (a synchronous generator on line with the national grid). This would cause wild swings in power and the rapid destruction of the windmill.

Therefore "fixed-speed" windmills all use induction generators which do not run at fixed-speed, but accelerate (typically 2%) as the torque applied increases to rated. This provides some torsional "give" in the system to keep the torque and power fluctuations within reasonable limits. But even so, ΔTg is typically 100% in winds below 15 m/s and 200% above. The only difference between stall-regulated and pitch-regulated windmills in this respect is that the former do not need to (not that they could anyway) ramp down the mean power in high winds. Otherwise they both need gearbox safety factors of 2.

VS Systems

For the purposes of this paper VS systems can be divided into two categories:

- the TLG system and
- electrical VS systems.

The key difference between these systems is that:

- in the TLG system, the generator speed is fixed[3] while the windmill rotor speed varies due to a differential stage in the gearbox. Torque is regulated by a hydrostatic torque reaction circuit, with the two main components being a radial piston pump (which reacts one of the members of the differential stage) and a relief valve, whereas
- in electrical VS systems the generator speed varies, with speed and torque being regulated by a variety of methods. Very close torque control can be achieved **at the electrical interface between the generator rotor and stator.** Normally electrical VS systems use a gearbox with a fixed ratio between the turbine and generator.

Referred Generator Inertia in Electrical VS Systems

In order to analyze this key difference (fixed- versus variable-speed generator), we need to separate the electrical VS drive-train into:

- the turbine rotor (subscript "a" for aerodynamic)
- the gearbox (subscript "g" referring to its input (low speed) side)
- the generator rotor (subscript "r")
- the generator stator (subscript "s").

Consider the electrical VS system in equilibrium initially (neither accelerating nor decelerating) at rated power, P_{rated}, rated speed, ω and rated torque $T_{rated} = P_{rated}/\omega$. (In these conditions VS systems provide narrow-band speed control so changes in ω can be neglected in converting power to torque). In a transient situation, if torque is controlled at one point in the drive-train, all the transient power ΔP_a will be used for inertial acceleration of the components up to that point and an inertial torque term, ΔT_a, should be introduced to determine the upstream torque values as follows:

$$P_a = P_{rated} + \Delta P_a = (T_{rated} + \Delta T_a)\omega \qquad \text{- Eq. 5}$$

where:

$$\Delta T_a = (I_a + RGI).d\omega/dt \qquad \text{- Eq. 6}$$

where:

I_a = the turbine rotor inertia

RGI = referred generator rotor inertia = $G^2 I_r$

(G = the gearbox ratio, I_r = the generator rotor inertia)

Note that:

[3] In fact the TLG system enables the use of a synchronous generator directly on line, which is unique in the wind turbine industry.

1. the generator inertia must be referred to the input side of the gearbox for this equation and that this involves multiplying I_r by G^2.
2. It is assumed there are only two significant inertias in the system, the turbine rotor and the RGI. The validity of this assumption will be checked later.

Using free-body analysis, the ΔT_g term (gearbox input torque transient) is ΔT_a less the inertial torque absorbed in the turbine rotor, i.e:

$$\Delta T_g = \Delta T_a - I_a .d\omega/dt = RGI.d\omega/dt = \Delta T_a.RGI/(I_a + RGI) \qquad \text{- Eq. 7}$$

Similarly if we wished to check the other ΔT terms in the drive-train we would find that:

$\Delta T_r = \Delta T_g /G = G.I_r.d\omega/dt$ (neglecting the inertia of the gearbox internals, brake disc and HSS),

and since the generator rotor acceleration is $G.d\omega/dt$,

$\Delta T_s = \Delta T_r - I_r .G.d\omega/dt = 0$

So the electrical VS system can be keeping the torque at the rotor/stator interface perfectly smooth but the drive-train upstream is experiencing inertial torque transients.

And it is the torque transient on the gearbox which is of most concern since that causes mechanical stresses on the gear teeth and bearings.

As indicated in the discussion of the root problem of windmill power control, ΔP_a can typically be 100%, 200% or up to 415% of P_{rated} (and see box at right for an explanation of how VS operation can increase this value!). Assuming 100%:

$$\Delta T_a = T_{rated} \qquad \text{- Eq. 8}$$

Therefore:

$$\Delta T_g = T_{rated}.RGI/(I_a + RGI) \qquad \text{-Eq. 9}$$

In other words (for ΔP_a of 100%) the gearbox will experience torque transients in the same proportion to the rated torque as the RGI is to the total system inertia.

So what is this proportion? For a 52 m, 850 kW 3-bladed electrical VS windmill, we estimate the following figures:

- $I_a = 850{,}000$ kg.m^2 (estimated)
- $I_r = 28$ to 45 kg.m^2 (depending on type of generator)
- G = 57.69 (1500 rpm generator : 26 rpm turbine)
- RGI $= G^2 I_r = 93{,}195$ to $149{,}778$ kg.m^2

Therefore $RGI/(I_a + RGI) = 10\text{-}15\%$. This is the proportion of the ΔT_a term that the gearbox must transmit to accelerate the generator as its speed varies. From Eq. 9 (which assumes ΔP_a is 100% and thus $\Delta T_a = T_{rated}$):

$\Delta T_g =$ 10-15% of T_{rated} (for ΔP_a = 100%, ie winds below 15 m/s)

= 20-30% of T_{rated} (for ΔP_a = 200%, ie winds above 15 m/s).

Is ΔP_a different for VS Windmills?

The question can be raised "ΔP_a of 100% might be typical of fixed-speed windmills, but might it not be lower for VS windmills?"

In fact aerodynamic power transients would be expected to be higher for VS windmills. Why? Because pitch responsiveness will tend to be slower in a VS windmill than a fixed-speed windmill. This is normally thought of as an advantage of VS windmills, brought about by the time delay required to accelerate the turbine rotor (and any other inertias!) in a gust.

The speed has to exceed a certain set point before the blades feather and this provides better capture of the gust energy – a "flywheel" effect. The longer the blades stay at fine pitch, the more energy is captured, but also the higher the instantaneous power generated by the rotor, especially as the power tends to increase as the rotor speed increases.

This would be an unfettered advantage if drive-train inertias other than the turbine rotor were negligible. This is the case for the TLG system and results in the gust power being almost completely absorbed in turbine rotor acceleration.

But if the RGI is not negligible, this delayed pitch response will compound the gearbox torque transients beyond the 30% level estimated in this paper.

Note that this assumes the electrical VS system provides perfect torque control at the rotor/stator interface (i.e. $\Delta T_s = 0$). So the electrical power output will be quite smooth (apart from any ripple due to the varying speed). But instead of providing smooth torque throughout the drive-train, the fact of having the generator rotor accelerated by substantial wind gusts, combined with the G^2 factor, means that in high winds **torque overloads of the order of 30% are imposed on the gearbox.**

Inertia in the TLG System

Many parts of the TLG drive-train operate with VS so the question must be asked – "does the TLG system not also suffer from a similar effect as RGI?" The answer is yes, but the magnitude is negligible. The equivalent component which must be accelerated in a gust is the radial piston torque limiting pump ("TL pump"), which is geared to the turbine with a higher ratio than that for the generator (about 54:1 in the Windflow 500). However the TL pump has an inertia of only 0.025 $kg.m^2$, about 0.1% that of a generator rotor. So even allowing for the increased gear ratio, the inertial torque ripple on the main gearbox will be 2 or 3 orders of magnitude less than that of an electrical VS system. Therefore it would take a gust transient power of about 400% for the TL pump to impose a 0.5% inertial torque transient on the gearbox.

In other words the TL pump inertia is negligible.

There are no other accelerated inertias in the TLG system which are not also present in electrical VS systems (basically the gearbox internals, brake disc and the high speed shaft). Consideration of the basic geometry of these components indicates that their rotational inertia is quite negligible. Thus simplifying the electrical VS system to two inertias (turbine and generator) is not too much of a simplification.

Summary and Conclusion

Recently it has been drawn to the author's attention by a leading gear design expert that:

- wind turbine gearboxes are suffering premature failures, even in electrical VS windmills
- RGI is a probable cause of this problem.

This led to one of those "light bulb" moments. **Electrical VS systems do not actually provide torque limiting to anywhere near the same degree as the TLG system.** In the previous 12 years a simple and fundamental advantage of the TLG system had been overlooked. Whether or not RGI proves to be the cause of the current gearbox problems, Newton's Second Law means that it is definitely a source of significant torque fluctuations on the gearboxes of electrical VS windmills. And the TLG system does not suffer from such torque fluctuations for the simple reason that the generator speed does not vary.

The magnitude of these RGI fluctuations is estimated to require an additional 30% gearbox application factor. This assumes that aerodynamic power transients of 200% typically occur in winds above 15 m/s. This is readily defensible once the magnitude of the windmill power control problem is appreciated because:

- it corresponds to the effective safety factor of three for the gearbox provided by the power ramp-down of fixed-speed windmill designs
- it neglects the increase in transient power due to slower pitch responsiveness in VS windmills
- it is well under the 238% transients which follow from the cubic law applied to a 50% gust or the 282% transients possible (based on rotor aerodynamics) in a 50% gust on top of a 24 m/s wind.

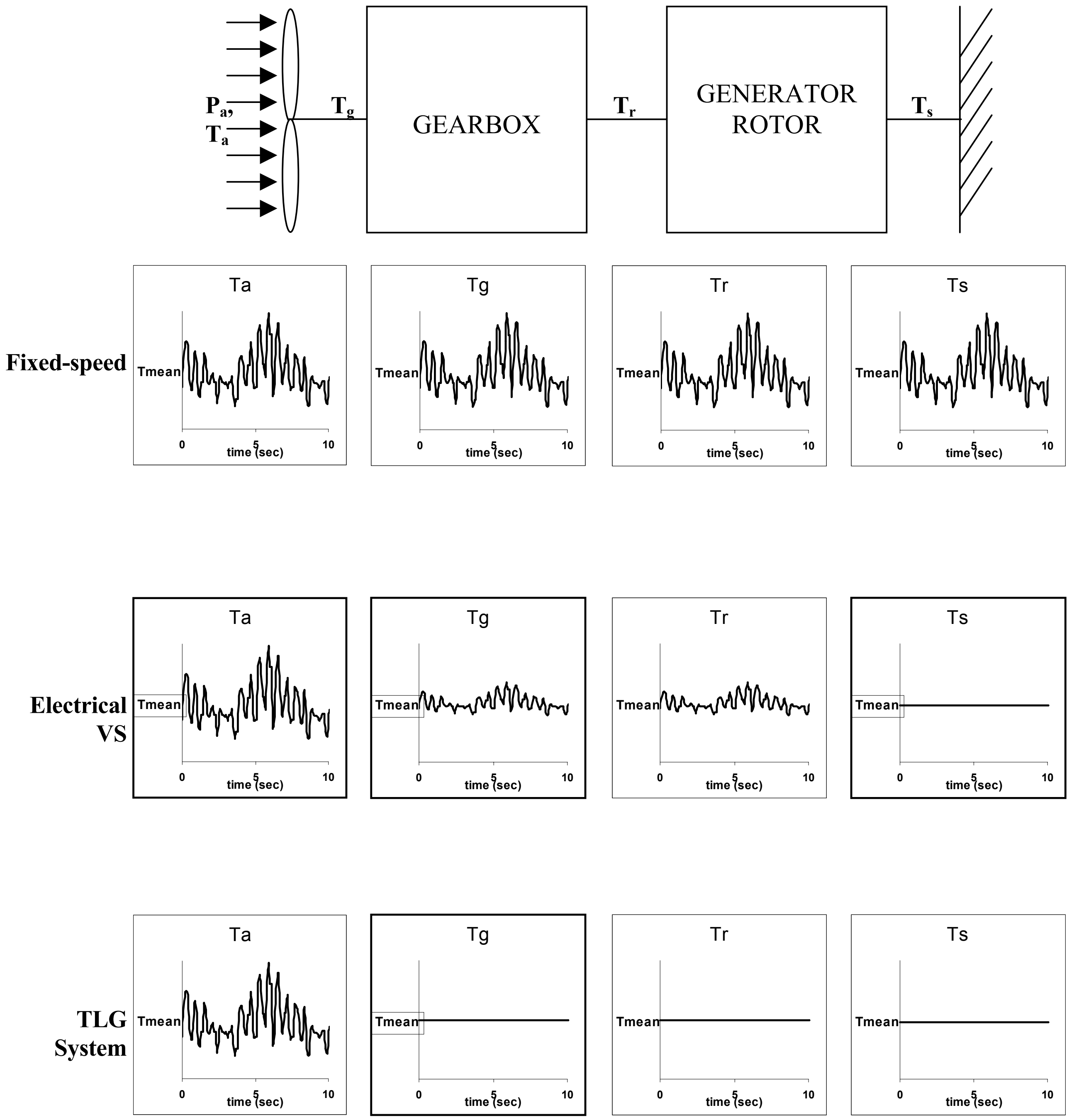

Figure 1 – Comparison of torque fluctuations through the drive-train

The equivalent inertial torque fluctuations in the TLG system would be at most 0.5% by comparison. Figure 1 illustrates this graphically.

As a result a gearbox for an electrical VS windmill should (all else being equal) be 30% heavier and more expensive than a TLG. Or, if windmill designers have overlooked this effect and tried to take too large an advantage from the partial torque-limiting provided by electrical VS systems, it would result in gearboxes of comparable weight but prone to premature failure.

Alternatively electrical VS windmill gearboxes could be designed “only” 15% heavier if the traditional power ramp-down in winds above 15 m/s is adopted (with consequent loss of revenue). This might be the economic option at the relatively low wind sites of northern Europe and most parts of the world.

In any event case it points to a decisive advantage for the TLG system, especially in Australia and New Zealand where market conditions require developments on high wind speed sites giving higher running hours above rated and more frequent high power gusts.

Acknowledgement

The author would like to acknowledge the insight of gear design expert, Ray Hicks, MBE, who drew the problem of RGI to the author’s attention. He further estimates that the relative effect on gearbox torque transients will tend to increase as turbine size increases (largely due to the higher gearbox ratios), with the $1/6^{th}$ power of rotor diameter. But that could be the subject of another paper!

References

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