CONSIDERING TRANSIENT LOADS IN DRIVETRAIN DESIGN

In wind turbine drivetrain design, considering harsh dynamic loads is critically important to ensure the future reliability of the machine and avoid costly failures.

By Dr. John Coultate

Dr. John Coultate is the Consultancy and R&D Dept. Leader for Romax Technology Ltd., UK. For more information on Romax Technology, Ltd., visit www.romaxtech.com or e-mail Dr. Ashley Crowther, VP Engineering, US Technical Center, ashley.crowther@romaxtech.com.

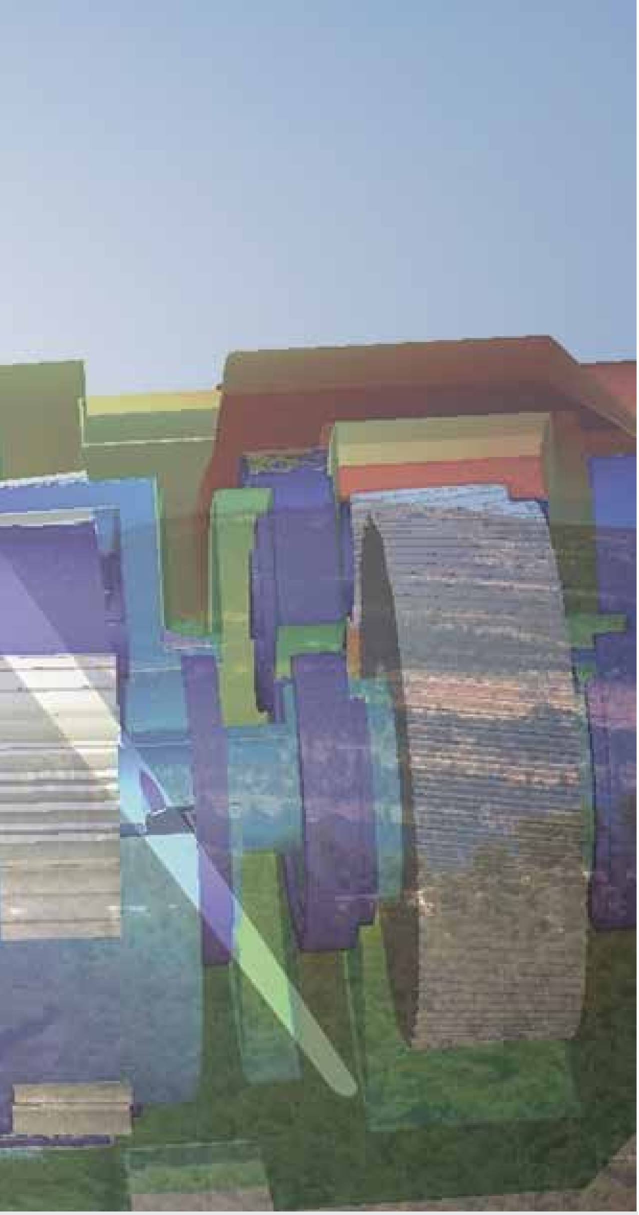
WIND TURBINE DRIVETRAINS MUST SURVIVE harsh, constantly varying loads throughout the lifetime of the turbine. The drivetrain transmits rotor torque to the generator, but in operation it is not just steady-state torque that the drivetrain experiences. In fact, it experiences a whole variety of events with rapidly changing torque and off-axis (non-torsional) loads, any of which can severely damage the machine, potentially leading to failure and very costly repairs.

DRIVETRAIN FAILURES

In order to design a reliable drivetrain, it is crucial to first understand the damaging effect of transient loads such as emergency stops, start-ups, shut-downs, or gusty wind conditions. Figure 1 shows what can happen if this is not done correctly. Potential failure modes such as surface-initiated bearing pitting, gear tooth failures, and fretting fatigue on bearing rings can all occur if transient loads are not accurately considered at the design stage. In more severe cases, the gearbox housing or mounts can fail, potentially leading to catastrophic failure of the whole turbine.

DESIGNING A RELIABLE DRIVETRAIN

For wind turbine or drivetrain design, input loads are typically calculated using multi-body-dynamics



simulation incorporating aeroelastic models and a representation of the turbine controller. These loads simulation software tools are available from commercial and research organizations for the turbine-level load calculation.

Designing a new drivetrain poses a chicken-or-egg conundrum — how can rotor loads be calculated without first having a concept for the turbine and drivetrain? And, conversely, how can a turbine concept be defined without first knowing the loads? This is solved by defining loads in logical stages. For example:

Figure 1: Potential failure modes which can occur due to transient loads – (top) surface-initiated bearing pitting, (middle) gear tooth failure and (bottom) fretting fatigue on

- Concept loads — The turbine designer may assume these based on previous experience on turbines of similar type/power rating, or may be scaled up from experience on smaller turbines.

- Preliminary design loads — These loads are calculated based on initial concepts for the drivetrain, rotor, tower, electrical system, controller, etc.

- Detailed design loads — These loads are calculated using finalised concepts for all turbine components and are used for type certification and component certification.

Accurate turbine-level loads aren't the only thing required for reliable drivetrain design. The methods for analyzing and considering these loads are critical. Slowly varying fatigue loads and static extreme loads are analyzed using standard methods (e.g. ISO 6336 for gear rating, ISO 281 for bearing rating, DIN 743 for shaft rating, etc.) in accordance with certification requirements. For these rating methods, it is essential to consider the behavior of the whole drivetrain, not just the gears and bearings in isolation. Previous studies have shown the importance of including structural flexibility and component-level deflections in these calculations [1]. A RomaxWIND simulation model like that shown in Figure 2 allows the whole drivetrain to be analyzed using a single model, incorporating detailed non-linear bearing models, advanced gear contact models, and flexible representations of shafts and housings. These methods have recently been applied successfully in the design and development of Romax's latest 6MW Butterfly drivetrain platform, shown in Figure 3.

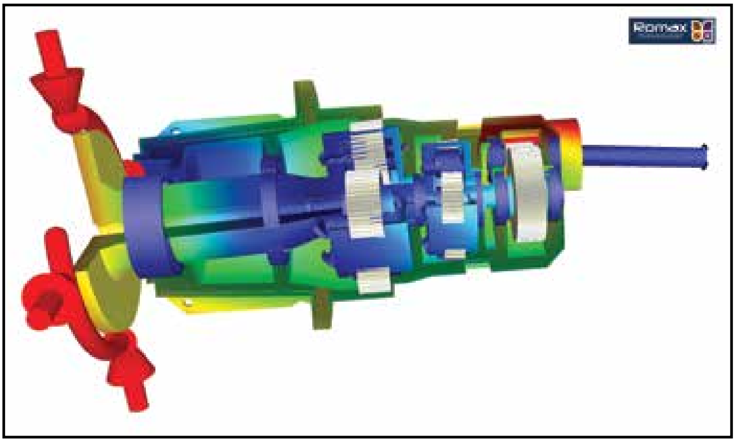


Figure 2: A RomaxWIND drivetrain model used for analysis of fatigue loads and static extreme loads.

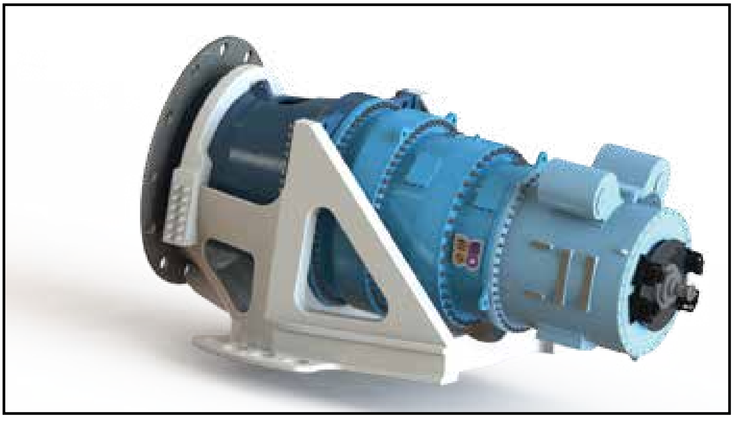


Figure 3: Romax's 6 MW ButterflyTM drivetrain platform design.

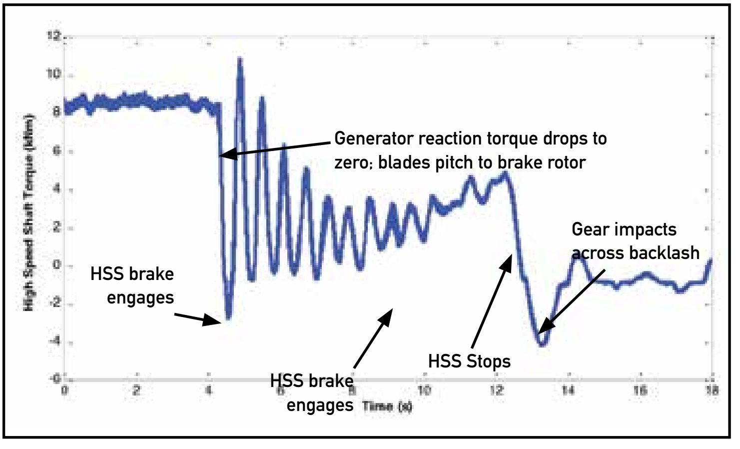


Figure 4: Measured High Speed Shaft (HSS) torque during an emergency stop event on a 2 MW wind turbine.

TRANSIENT EVENTS

Although most wind turbines spend the majority of time running at rated load or at idle, it is widely recognised that damage can occur during short duration transient events such as start ups, shut downs and emergency stops. Figure 4 shows an example of the drivetrain high-speed shaft torque measured during an emergency stop. For events such as this, peak loads can be analysed using industry standard methods for gear and bearing rating but these only capture part of the story. Standard methods consider the effect of a static extreme load but do not consider in detail rapid changes in acceleration or gear impacts that occur during torque reversals. To understand the potentially

Component	Moment of Inertia (kg m²)	Ratio to Main Shaft	Moment of Inertia referred to main shaft (kg m²)	Percentage of total referred inertia (%)
Rotor (blades, hub)	9,258,681.0	1.0	9,258,681.0	87.372
Generator	92.0	107.9	1,071,184.2	10.109
Brake and coupling	14.5	107.9	168,478.6	1.590
Gearbox - Intermediate stage	56.2	29.9	50,347.4	0.475
Gearbox - Stage 2 planet gears	19.1	15.0	21,719.2	0.205
Gearbox - High speed stage	0.8	107.9	9,361.2	0.088
Gearbox - Stage 2 planet carrier	277.1	5.7	9,088.7	0.086
Gearbox - Stage 2 sun gear	4.0	29.9	3,576.9	0.034
Gearbox - Stage 1 planet carrier	1,766.0	1.0	1,766.0	0.017
Gearbox - Stage 1 planet gears	43.6	2.5	1,378.9	0.013
Main shaft	939.1	1.0	939.1	0.009
Gearbox - Stage 1 sun gear	9.5	5.7	310.6	0.003
			TOTAL =	100%

Over 99% of the total drivetrain moment of inertia is from rotor, generator, brake and coupling

Less than 1% of the total drivetrain moment of inertia comes from all other components

Table 1. Data from a 2MW wind turbine drivetrain showing the contribution of each drivetrain component to the total moment of inertia.

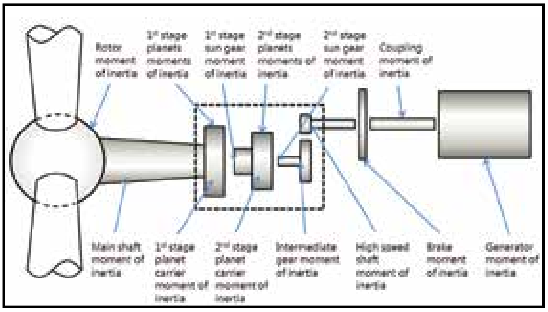


Figure 5: The most significant moments of inertia in a conventional geared drivetrain.

damaging effect of these factors we must use more advanced gear analysis methods.

DETAILED DRIVETRAIN TIME-DOMAIN SIMULATION – WHEN IS IT NOT NEEDED?

The key property to consider in drivetrain time-domain simulation and load calculation is the rotational inertia of each drivetrain component. This is a measure of the component's resistance to change in its state of motion. Components with small moments of inertia can generally be ignored from models used for load calculation but components with large moments of inertia must be considered.

A conventionally geared drivetrain is made up from a number of rotating parts, from the rotor through to the generator, as shown in Figure 5. When drivetrain loads and behavior are calculated during the design process, it is vital that the correct inertias are considered and this is especially important when considering gearbox loads during transient events, such as the emergency stop event shown in Figure 4.

Table 1 shows the contribution of each drivetrain component to the total moment of inertia for a 2MW wind turbine drivetrain. The key conclusion is that over 99% of the total drivetrain moment of inertia is from the rotor, generator, brake, and high-speed shaft coupling, with less than 1% of the total inertia coming from all other components.

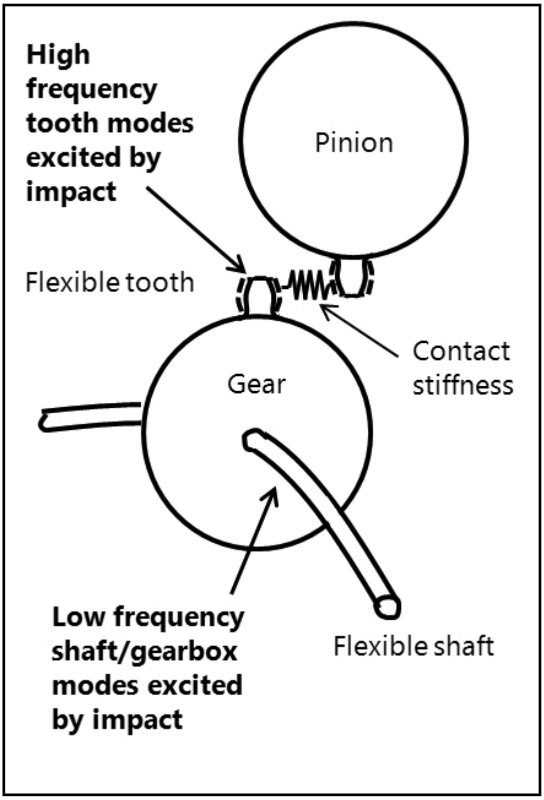


Figure 6: A detailed mathematical model is used to analyze gear stress in the time-domain during a gear impact event.

This means that it is reasonable to ignore the small inertias in the gearbox components (e.g. gears and planet carriers) when calculating turbine-level loads and behavior. In fact, this assumption is commonly made across the industry for turbine load calculation.

It is a common misunderstanding that high fidelity time-domain gearbox models are required for accurate load calculation. This is not true because the small inertias of components inside the gearbox are swamped by the large inertias from the rotor, generator, and high-speed shaft brake and coupling.

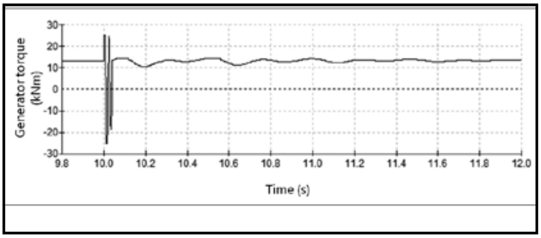


Figure 7: Rapidly changing generator torque during a grid fault event (3-phase short circuit fault) [2].

DETAILED DRIVETRAIN TIME-DOMAIN SIMULATION – WHEN IS IT NEEDED?

Although accurate time-domain gearbox models are not required for turbine-level load calculation, there are special cases where time-domain gearbox models give us vital insight into stresses and failure modes inside the gearbox. An example of one such case is gear impacts that can occur during transient events with rapidly changing loads — such as an emergency stop or a grid fault.

For this type of analysis, the turbine-level loads are used as inputs for a smaller subsystem model – this could be a time-domain model of the gearbox, constructed as shown in Figure 6. This model is then used to analyze instantaneous gear stresses during transient events like the generator grid fault shown in Figure 7.

CONCLUSIONS

A single gearbox failure on a multi-megawatt turbine can cause costs in excess of $500,000. If this is multiplied over several wind farms, the wind turbine OEM's exposure to risk during the warranty period is very high.

In order to reduce the risk of gearbox failures, it is essential that suitable simulation and analysis methods are used to understand drivetrain loads and durability at the design stage. The return on investment is clear. If an OEM can save just one gearbox failure by investing in state-of-the-art drivetrain analysis and simulation tools, then the future benefits are significant.

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