Management Demand: “First-Time-Right”; A new drive-train technology development based on a Virtual Model Approach

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1. SUMMARY

The paper deals with the methodology used in the development and implementation of an innovative electromechanical energy conversion concept, known as DSgen-set®, on a wind turbine (WT).

In order to eliminate the known problem of wind farms being disturbance factors for network quality, an innovative principle is required to avoid the disadvantages of an inverter based system. The newly developed system transforms stochastic wind load acting on the WT into electrical power, over the synchronous generator which is connected directly to the grid. The constant speed of the synchronous generator is controlled via a servo motor.

The main challenge of the development was “first-time-right”. To achieve that goal a virtual model (VM) approach was used, which considers and evaluates all necessary influences on the system. This VM is a complex mechatronic system which consists of the 3 interactively coupled subsystems (mechanical, electrical and controlling).

The developed methodology and the applied tools enable a pre-optimization of the individual sub-systems and the complete DSgen-set® on a virtual test bed before hardware is available. Tests from the DSgen-set® real model (RM) on a test bed were subsequently used for the VM validation. The same approach and method were implemented in further investigations of the complete WT dynamic behavior.

With such an advanced VM which considers all known dynamic influences, a deep understanding and solid basis for further development of mechanical design, electrical engineering and automatic control requirements is supported in an efficient way.

2. INTRODUCTION

Driven by the time-to-market demand when developing a product, it is often not acceptable to perform a trial-and-error methodology and waste many prototypes in order to find a working design. At the moment of commercial launch, the product should appear as if it is field-proven for years and furthermore "teething problems" have been eliminated as much as possible. “First-time-right” is not just the key slogan which management demands, but it is a huge challenge for developers.

Dynamic simulations with modern designing and simulation tools, with increased computer power, make it possible to accept this challenge. The reduction of development costs and consequently material costs, with early identification of mistakes or design weaknesses, makes numerical simulation very attractive in the daily routine of product development. Despite a steady development of design and simulation tools, the integration of the big picture is missing.

Each method and modern tool has its strength, but often a problem can only be approached from one specific side. For example, one system or design which has no problem with solidity and strength can show a trend to oscillate and therefore could be hazardous for the complete construction. Or one could find that the given system does not permit planned controlling at all. In many companies and for different reasons, detailed simulations will be made without the view of the big picture.

Usage of the full coordination of single disciplines in simulations in such a way that the wholeness is bigger than the sum of the individual parts is an asset of SET. The high-quality tools, the experience of the team, the methodology to view the entire system comprehensively and the possibility to validate simulation results in SET's own test bench in order to reintegrate these experiences leads to the profound insight of a mechatronic system.

Integrating all the departments involved makes a sound basis for VM development and making use of all the available tools is a key to the VM approach. And so the key word "first-time-right" could be realized and the challenge completed.

3. DSGEN-SET® SYSTEM: REQUIREMENTS, PRECONDITIONS AND ADVANTAGES

The German Transmission Code 2007 distinguishes between "Type-1" and "Type-2" generating units. Type-1 is a synchronous generator directly connected to the power grid whereas all other generating units are Type-2. [1] Regarding the generating systems used in wind turbines (WT), the widely established systems such as DFIG and PMG-FC, are Type-2 units.

Furthermore, many grid operators consider new wind farms as "disturbance factors" from the perspective of network quality [2]. In order to overcome this problem, an innovative principle, which avoids the disadvantages of an inverter based systems, needs to be applied.

DSGEN-SET® SYSTEM DESIGN

Fig.1 shows the principle of an electro-mechanical system consisting of a differential gear (1 - 3) and a differential drive (4, 5). The WT rotor (11) drives the main gearbox (10) with the given transmission ratio. The differential stage (1 - 3) which represents the core of the entire system [3], is between the main gearbox and the generator (6).

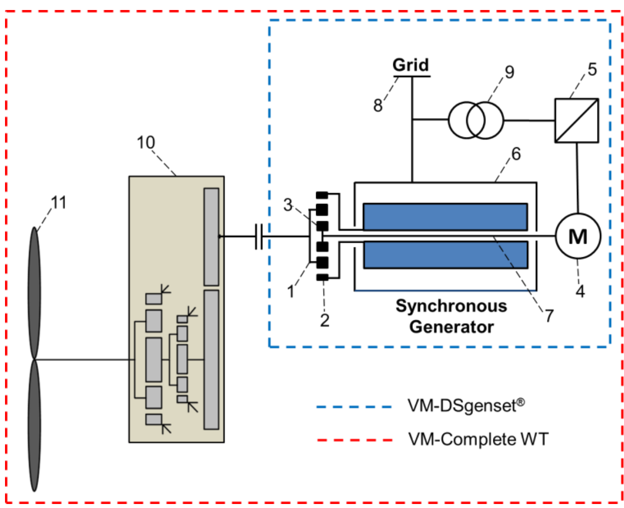

Fig.1: Principal Design of DSgen-set® based on WT and VM

The synchronous generator is connected to the ring gear (2) of the differential gear and driven by it. The pinion (3) on the differential gear (sun gear) is connected to the servo motor (4) by means of a drive-through shaft (7). The differential drive consists of the servo motor (typically a low-voltage three-phase generator) and the frequency converter (5). The frequency converter is connected to the high-voltage grid (8) via the transformer (9). The speed of the differential drive (4, 5) is controlled on one hand to ensure that the variable speed of the WT rotor is converted to constant speed at the generator and on the other to control the torque throughout the entire WT drive train.

The torque at the HSS (high speed shaft) is determined by the available wind and the aerodynamic efficiency of the rotor. The ratio between the torque at the blade rotor-shaft and the differential drive is constant, thus enabling the torque in the drive train to be controlled by the differential drive. The generator speed is constant and given by the grid frequency.

The input power is split into two paths through the differential gear: the servo path and the generator path. Only a fraction of the total power (< 20%) goes through the servo path. The main part of the power flows directly to the generator. A major advantage of the schema shown in Fig. 1 is the simplicity of the differential gear and, as a result, the high efficiency of the differential stage. In addition, the differential gear can also be manufactured as a separate assembly and therefore installed and maintained independently of the main gearbox. (Fig.3)

Fig.3: 2 MW/10 kV WT DSgen-set® prototype on the test bed.

The described system is used as a basis for the VM approach investigations. Generally, the DSgen-set® VM approach could be divided in two parts:

- Detailed VM approach of DSgen-set®. as a basis for the complete system
- Complete WT simulated with VM approach methodology.

The boundaries between those VMs are flexible and could be changed on demand (Fig.1).

4. VIRTUAL MODEL APPROACH

The idea of the VM approach is to get a simulation model as near as possible to real life conditions. With the development of the VM approach, SET strives to comprehend all influences on the electro mechanical differential system as an integral part of the complete WT, even before the real parts are produced. (Fig. 4)

There are obvious obstacles to implement testing on the complete WT in the early development stage. In a step by step method, the first step is the simulation and verification of dynamic behavior of the main subsystems such as DSgen-set®. The available real life conditions need to be verified in order to have confidence in the applied procedures and methods.

4.1 FIRST STEP: BUILDING SUBSYSTEMS

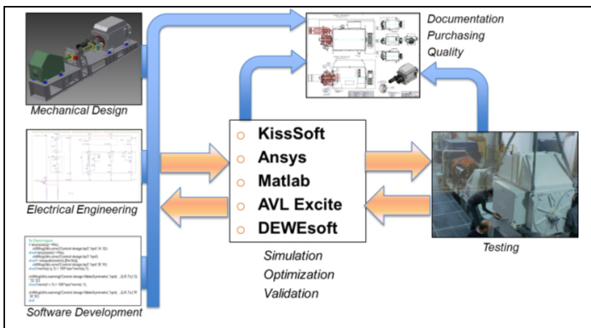

Fig.4: Flow-chart of the VM approach

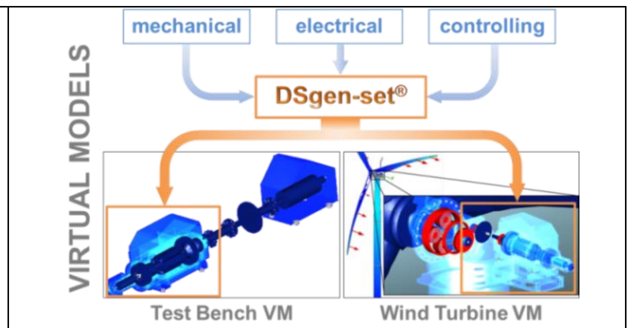

Fig.5: Implementation of DSgen-set® in VM models

In the development of DSgen-set®, considerable efforts were already made in the concept phase. Its design was steadily improved and simultaneously evaluated through VM analysis. From the simulation point of view, the VM consists of a complex mechatronic system with 3 subsystems: Mechanical, Electrical and Controlling. In order to correctly simulate the VM all these subsystems must be modeled accurately (Fig. 5).

A numerical simulation model of the electrical subsystem consists of well-known components like the synchronous generator, the transformer, etc. The specific electrical parameters are taken from the real components of the DSgen-set® which were provided by the components supplier.

The controlling subsystem is part of the solution and indeed a behavioral modeling is good enough. The electrical and the controlling subsystems have a big influence on the complete system, but their influences are simple to predict and to control.

The mechanical part of DSgen-set® is completely new and had to be modeled from scratch. If the mechanical subsystem is not correctly modeled, even if the other 2 subsystems are perfectly modeled, the results of the complete simulation will not be valid.

The complexity of the VM increased steadily during the development process with the acquisition of more detailed input parameters as well as the demands of the controlling system. Those efforts lead to the high fidelity model which is necessary for a comprehensive insight of the system behavior. For a proper dynamic response of the WT drivetrain, the following influences are considered:

- Linear flexibilities of mechanical components
- Nonlinear behavior of drivetrain components (gears, bearings, bushings)
- Electro mechanic behavior of generator
- Electric behavior of the high voltage grid.

The result of this development process is an optimized design of 2MW DSgen-set®, which is then produced as a prototype. To validate the applied VM approach, measurement results of 2MW DSgen-set® were compared with the VM results. A splendid correlation was achieved which increased confidence in the VM method and results.

4.1.1 MECHANICAL SUBSYSTEM

In the VM development of the complete WT the main mechanical components and their dynamic interactions which are considered in this study are:

- DSgen-set® system with synchronous generator (SET own development)
- Blades with main shaft (supplier part)
- Main gearbox (supplier part)
- WT frame and tower (supplier parts)

Flexibility of all included mechanical components with 6 DOF (Degrees Of Freedom) of the drive-train is very important part of study and its verification[1] [4]. Detailed modeling, simulation and verification of the DSgen-set® system with synchronous generator represent the basis for methodology understanding as well as further development of the complete VM. The CAD was the geometrical basis for the development of the DSgen-set®. An in-depth understanding of its dynamic behavior acquired in our own test bench facility is implemented in the VM. (Fig.5)

The main structural properties (mass and stiffness) of those geometrical parts were internally developed (DSgen-set®) or obtained from producers (Main Gearbox, Tower, etc.). Dynamic behavior of the complex mechanical system is simulated using the MBS software AVL EXCITE[2]. Robustness, power and years of experience in developing this software in highly dynamical systems, provide confidence in the simulation results. To consider the linear elastic behavior of bodies, AVL EXCITE Power Unit uses statically and dynamically reduced finite element models (FEM) [5], [6]. The reduction is made in FE software ANSYS[3] using the Craig-Bampton method.

In order to represent the non-linear coupled stiffness behavior of connecting elements (bearings, bushings etc.) in a dynamic system, the non-linear stiffness characteristic for the main degrees of freedom of the bearings are used. The properties of the bearings (radial and axial stiffness) are provided by the bearing manufacturer.

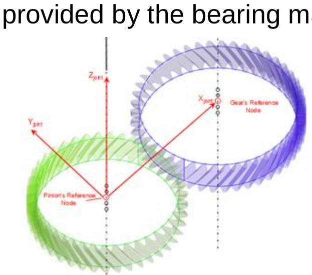

Fig. 6 AVL EXCITE sliced contact gear mesh model

For a detailed representation of the gear mesh nonlinearities, there are two different methods available in AVL EXCITE and both are used in the complete WT model:

1. Engagement line model – gear mesh stiffness curve obtained from standard gear calculation software such as KISSsoft[4].
2. Sliced contact model – nonlinear gear stiffness calculated dynamically based on input data given for respective gear-mesh (Fig.6).

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[1] *The certification requirements of Germanischer Lloyd (GL) do permit usage of rigid parts in some cases too as minimum, but flexibility is to recommend.*
[2] *AVL EXCITE is registered trademarks of company AVL LIST GmbH.*
[3] *ANSYS is registered trademark of the company ANSYS, Inc.*
[4] *KISSsoft is registered trademark of the company KISSsoft AG.*

Both methods consider loss of flank contact and backlash contact which could be used in detailed meshing investigation cases depending of the demand and aim of the investigation [7].

The exact information about the dynamic stiffness characteristics of the blades are scarce and are proprietary of the blade producers. As the focus of these investigations was on the dynamic behavior of the drivetrain, the blade structural nonlinearity is not of major interest, thus an approximate anisotropic FEM model of blades was chosen. This blade model considers several first natural modes while, the stiffness of the blade is approximately specified. The correct mass properties are included in the FEM model.

4.1.2 ELECTRICAL SUBSYSTEM

In parallel to the development of the mechanical parts, SET developed a detailed numerical model for the electrical environment.

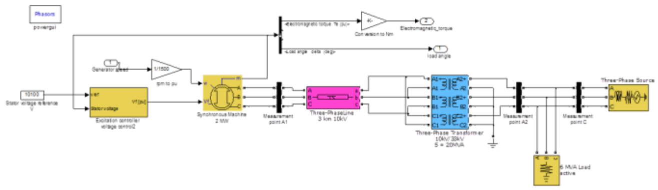

Fig. 7: Electrical subsystem model

With this model it is possible to investigate the electrical behavior of the power grid during short circuits, for instance, and many other electrical relevant load cases.

The SET approach is to use an appropriate simulation environment for the electrical system components, apart from the mechanical environment. The interface between the electrical and the mechanical “world” is the generator.

On one hand, the mechanical components of the generator like shaft, rotor and housing are represented as a multi-body system in AVL EXCITE. On the other hand, the electrical part is a numerical representation of the detailed mathematical model within MATLAB/Simulink[5]. (Fig. 7)

In this way and via a predefined link between both simulation software tools, a co-simulation can be performed by establishing a mechanical-electrical interface to consider the mutual interactions. A description of the electrical system components models can be found in [8].

4.1.3 CONTROLLING SUBSYSTEM

Similar to the electrical system, a controlling system or the controlling algorithms, respectively, are implemented in a MATLAB/Simulink environment for numerical simulation. To make it available for the VM, the co-simulation approach is used. A more detailed description regarding this topic is not necessary to understand the VM approach.

4.2 SECOND STEP: VIRTUAL MODEL OF DSGEN-SET®

The basis for understanding the complete VM is the understanding of one major mechanical component. In this case it is the SET developed DSgen-set® system with synchronous generator.

Demands of VM analysis are:

- Functionality check
- Reliability assessment of each including part
- Certification demands
- Special demands (exceed certification but are of utmost importance for understanding system dynamic behavior).

The investigation procedure to reach these targets is explained below.

[5] *(MATLAB and Simulink are registered trademarks of The MathWorks, Inc.)*

4.2.1 MODAL ANALYSES

The first step in understanding a mechanical system dynamics is modal analysis. It is also required for GL certifications [4]. Obtained natural frequencies are plotted in a 2D Campbell diagram. The extracted information about Strain Energy Density (SED) for each including component could give the first estimation about possible system resonances. By all means, final decision about probability and intensity of those possible resonances is given only with a complete MBS simulation including all nonlinearities, damping appreciations and excitations.

4.2.2 MBS DYNAMICAL ANALYSES

The VM approach would replicate the real system in all operating conditions including testing. The same testing procedure as for the RM will be applied on the VM. In SET VM modeling strategy, the main components of the MBS model with the most influence on the system's dynamic behavior should be represented as flexible bodies. Thus, besides the flexibility of the shafts, clutches, carriers and ring gears, the full flexibility of all gearboxes and housings as carrying structures are necessary. The reason is that in many cases the carrying structures could have a great influence on the resonance building and if kept rigid those influences will be hidden in resonant investigations. The evaluation of results from each MBS dynamic simulations should follow in both frequency and time domain. The challenge experienced in DSgen-set® development was to cover a wide range of excitation frequencies (complete speed range) with a direct connection on the electrical grid. That was the reason for a very detailed investigation of the system vibrations and potential resonances.

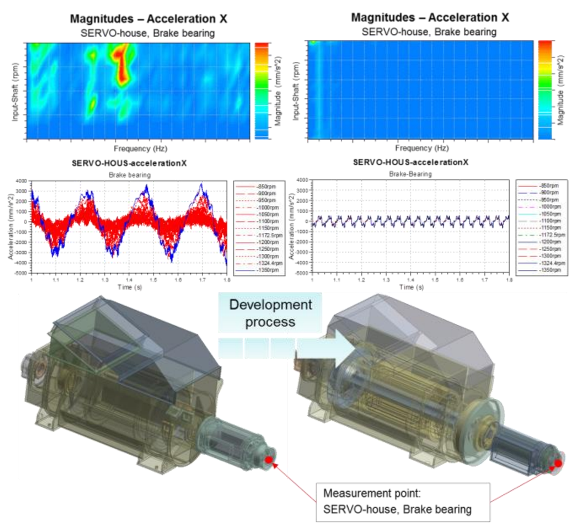

Fig. 8: Elimination of dangerous resonances in VM

The first study was performed using a rigid model of all housings. No dangerous resonances were found. In a further investigation with all flexible models including all housings those first design drafts showed a strong tendency to resonance. These VM results guided further design improvements until all dangerous resonances were removed from the model.

Figure 8 shows frequency domain results (3D Campbell) and time domain of accelerations of one measurement point. The left side shows that the resonance appeared. The right side shows a dynamic picture of the same measurement point after design improvement. This "real life" example showed clearly that flexibility of the carrying structures should be considered in system development.

With the exposure of dangerous resonances before the existence of any physical model in this particular case, the VM approach fulfills its purpose. Furthermore, the same approach was used during the further development of the complete WT.

The very detailed results of displacements, accelerations, and forces/loads of each particular component are extracted in time domain and for all operating speeds. Those results are necessary for further VM integration, which could be done with direct connection i.e. co-simulation with another software (MATLAB/Simulink) or with indirect transfer of results (for example dynamic nodal displacements) to other FE or Fatigue simulation tools.

In order to get the real excitation on the high voltage grid side of the system, the detailed model of the generator and electrical grid are of utmost importance. It should be noted that electro-magnetic torque generated on the electric machines is acting both on the shaft (rotor) as well as on the supporting structure (stator) with the same amplitude but with opposite directions. Those phenomena are well defined in all SET procedures.

There are two possibilities to model electrical components in AVL EXCITE software and those are:

- Existing generator ('Electric Machines' joint)
- Generator modeled in another software (MATLAB/Simulink) with co-simulation

Since SET is developing the complete system including electrical and controlling features with MATLAB/Simulink, the second option appears quite natural.

4.3 THIRD STEP: VALIDATION

Fig. 9: Measurement points for validation tests

The simulation results of detailed flexible model of the complete 2MW DSgen-set® system are validated with RM measured data for all simulated operating conditions.
The main aim of the validation process is to find the most influential and potentially dangerous resonances in the tested RM and compare their positions and intensity level with the VM model.
Figure 9 shows measurement positions at RM that are compared both in time and frequency domain with the same VM measurement points as shown in figure 8.

In the SET testing facility, several validation procedures were performed with very good correlations with AVL EXCITE models (Fig.10). This means that mass distribution, stiffness and damping of the system as well as electrical influences are correctly considered.

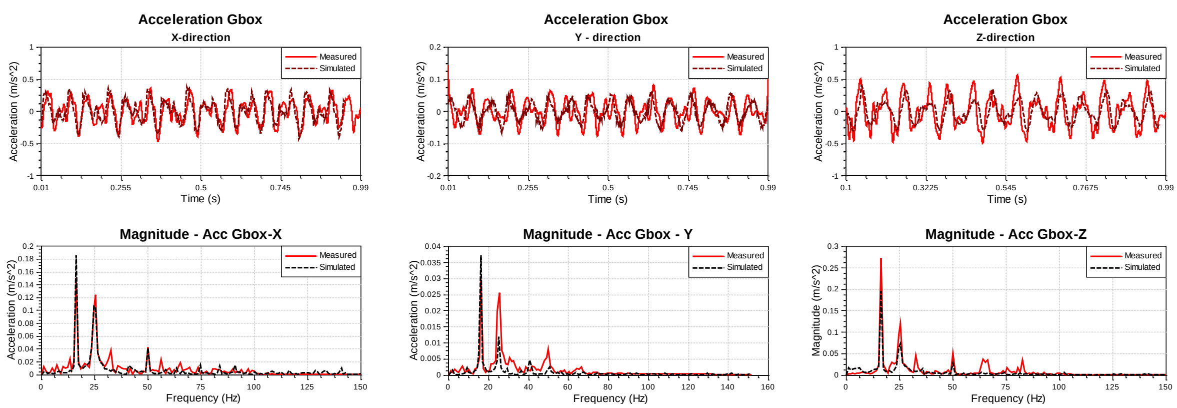

Fig. 10: Comparison of a measurement point in validation tests

4.4 EXTENDED ANALYSES AS SPECIAL DEMANDS OF VM APPROACH

In order to intensify comprehension about dynamic behavior of the developed drivetrain, some additional investigations could be done. VM offers a possibility to investigate a complete system behavior in extreme situations even beyond the point of destruction, which gives a considerable advantage in further detailed development of highly dynamical mechatronic systems.

MICROPITTING PREVENTION: SET METHODIC

Micropitting is a well-known problem which appears on all gear mesh types but big gears are especially sensitive in wind power transmissions.

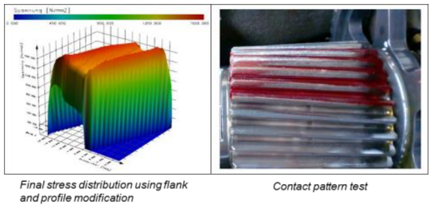

Fig. 11: Micropitting reduction method

The traditional methods to reduce micropitting are to increase oil film thickness, reduce contact surface roughness or optimize the lubricant properties.
Unfortunately, despite steady development of those methods micropitting could not be completely eliminated and very often not even significantly reduced.

Since micropitting is mainly a structural and dynamic phenomenon, SET applied its own developed procedure based on the VM approach to reduce micropitting [7].

It is based on the early recognition of real, dynamical axis misalignments of engaged gear meshes. This new method depends solely on the accuracy of the VM and the accuracy of input data; hence it directly affects the estimation of the micropitting risk. Several validation procedures were performed at SET's testing facility, providing an exact rating regarding axis misalignment and the accuracy of the AVL EXCITE model. (Fig. 11)

PLAIN BEARINGS AS AN ALTERNATIVE: EHD SIMULATION

In a further detailed development of the 2MW DSgen-set®, it was requested to use the radial slider bearings (journal bearings) in SET differential gearboxes.

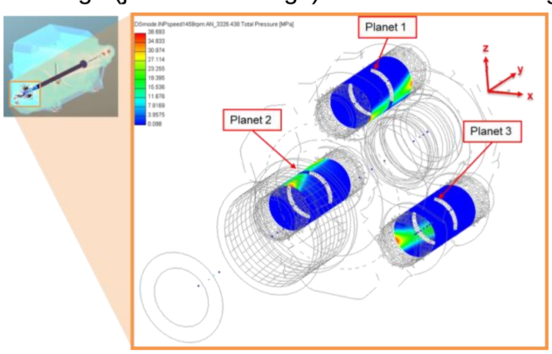

Fig. 12: Plain bearing as an alternative in planetary set

The already prepared VM of the 2MW DSgen-set® with all dynamic loads and boundary conditions was a perfect model for a detailed hydrodynamic investigation of possible and optimized radial slider bearings (Fig. 12). The optimized radial slider bearings solution for this application was materialized using a detailed elasto-hydro-dynamic (EHD) simulation and in cooperation with the bearing producer.

AVL EXCITE offers an integrated EHD solution within MBS simulations and it is the standard engineering package used at SET. [9]

5. COMPLETE WT AS A VIRTUAL MODEL

Finally, the complete WT was prepared as a VM. With the experience and confidence of the methods and procedures used in developing and validating the 2MW DSgen-set® VM and considering the assumptions described in 4.1.1, the same approach was implemented for the complete WT system. The influences of the electromagnetic and controlling sub-systems are applied in the same way for the VM of 2MW DSgen-set® with an extended mechanical model (paragraph 4.1.2 and 4.1.3). In addition to the DSgen-set®, the WT MBS model consists of blades, main-gearbox and support structure (Fig. 5).

For the reasons already explained in paragraph 4.2, all carrying structures used for the complete VM are kept as flexible bodies for standard resonant investigations. Depending on the investigation targets, the components included in the complete VM could be chosen as flexible or rigid. The WT model considers some objective simplifications and restrictions like: blade loads pre-calculated by CFD are acting on blades and not on the tower; the loads are pre-defined and blade deformations are not influencing them; tower ground is rigid etc.

The loads on the investigated drivetrain could be implemented as dynamical torque applied on the main shaft (required by GL certification) or as aerodynamic wind forces applied on the several nodes condensed on each blade (not required for certification).

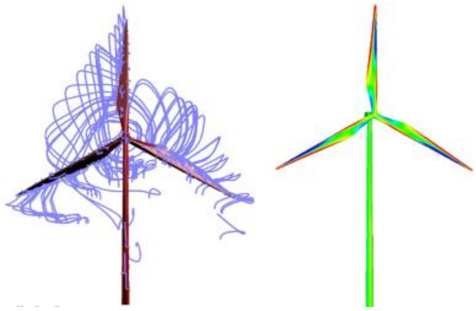

Fig. 13: CFD generated loads on WT blades

Several cases of the aerodynamic wind forces in this particular study are generated by the CFD software AVL FIRE[6]. (Fig.13) These forces can be extracted from any standard wind energy software such as Bladed[7] or Fast/AeroDyn[8] and easily implemented as loads on the VM. Both of those procedures are used in SET depending of the demand of the particular investigation. Investigated forces as well as deformations and resonances are also important information for other companies involved in the implementation of 2MW DSgen-set® on the WT.

It considers, for example. forces and moments generated on the frame mounts, on the gearing meshes or on the connection splines in extreme situations like emergency breaking, Low-Voltage-Ride-Through (LVRT), extreme gusts, etc.

<u>INVESTIGATION OF EXTREME OPERATIVE CONDITIONS</u>

Further analyses of the complete system were conducted to obtain as much necessary information as possible and to gain added value in addition to the "standard" developing steps.

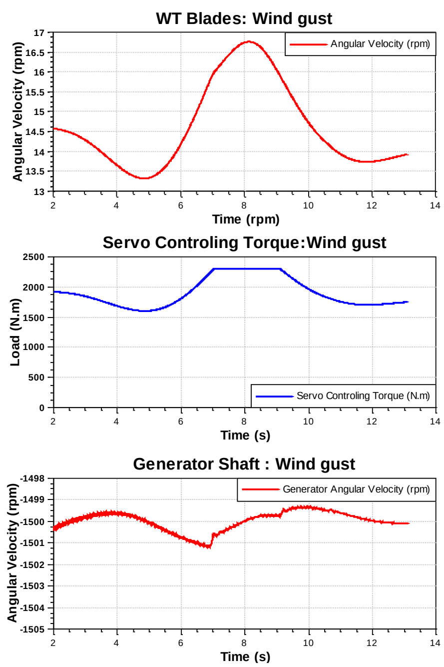

Fig. 14: Extreme wind gust under 12 seconds

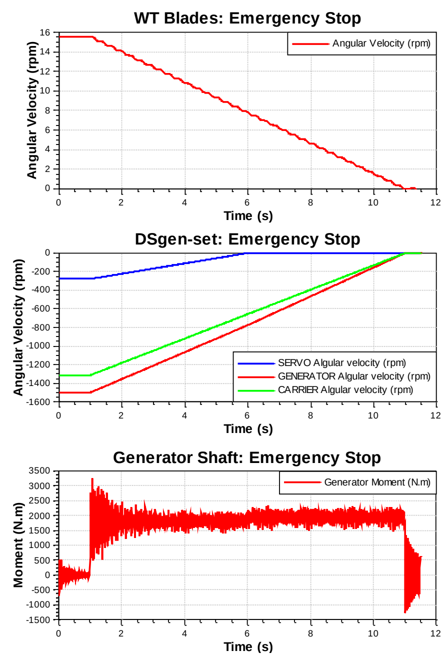

Fig. 15: Emergency stop of complete VM

For example, in the case of **extreme wind gust** a stochastically given input and proved controlling of complete system were used in the investigation. The generator and grid were modeled in MATLAB/ Simulink as well as controlling procedure. The loads were given on the WT hub while the controlled torque on the servo is keeping the production of the electrical power (i.e. generator speed) constant (Fig.14). The reaction forces, displacements, deformations and intensity of possible resonances were studied in detail for all measurement points of interest on the complete VM.

Another extreme situation like **LVRT** and appropriate system reaction with or without emergency breaking is also part of the VM approach investigations. The amplitude of forces on all

[6] AVL FIRE is a registered trademarks of company AVL LIST GmbH
[7] Bladed is a registered trademarks of DNV-GL.
[8] NWTC Computer-Aided Engineering Tools (AeroDyn by David J. Laino, Ph.D.). http://wind.nrel.gov

measurement points of interest such as splines, gears, mounts etc. are obtained and studied in detail (Fig.15). The deformations and displacements as well as the reaction under those extreme conditions were investigated.

The above particular cases included additional investigations which were not presented, like dynamically-controlled drivetrain damping and optimization of the tower and frame using VM approach etc. These will be considered in future SET papers.

6. CONCLUSION

Safety reasons are the main cause for WT certification demand. The certification requires a certain level of simulation to be used in the WT development process and the VM approach fully complies. These requirements are just a small part of the VM approach that offers much more in the WT development process.

The VM approach considers the complete mechatronic system of the WT, including the mechanical, electric and control subsystems. AVL EXCITE offers the possibility to model the complete mechanical subsystem in very fine detail as well as some parts of the electrical and control subsystems. The rest of the electric and control subsystem is modeled in Matlab and linked via co-simulation to AVL EXCITE.

The developed methodology and the applied tools enable a pre-optimization of the individual sub-systems and the complete DSgen-set® on a virtual test bed before any hardware is available. Tests of DSgen-set® on a real test bed are used only for validation of this VM, which fulfills the initial target of "first time right". The model is further extended for other specific analysis targets and for a full wind turbine.

The effective direct integration of a mechanical, electrical and controlling system is a powerful methodology for efficient development of complex mechatronic systems. This approach has proven to be the right choice for the development of SET's DSgen-set®.

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