Reliable Validation and Commissioning of Hybrid Power Plants

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ABSTRACT

Traditionally, wind farms consist of several Wind Turbine Generators (WTGs) carefully selected and sited to secure maximum annual energy production and minimize the turbine load for the specific site and necessary reactive power compensation to ensure grid code compliance. The correct grid integration and selection of compensation equipment is handled by performing site-specific Electrical Pre-Design (EPD) studies. Utilizing detailed simulation models of the selected WTGs, a Power Plant Controller (PPC) and the selected combination of Original Equipment Manufacturer (OEM) compensation equipment such as Mechanical Switched Units (MSU), being either capacitors or reactors, and STATCOM is key to ensure grid code compliance. In extreme weak grid areas, the EPD studies might also require a Synchronous Condenser (SynCon) to be installed.

This paper will detail our ongoing efforts to secure reliable commissioning of hybrid Power Plants.

Hybrid Power Plant, Power Plant Controller, Dynamic Plant Components, Modeling, Qualification, Integration, Validation, Commissioning.

I. INTRODUCTION

In recent years the rapid maturing of the Photo-Voltaic (PV) industry has enabled the construction of 100+ MW utility scale solar farms. Equally rapidly we have seen the maturing of large MW-size Battery Energy Storage Systems (BESS). Presently we are seeing the emergence of industry scale P2X pilot projects all aiming to utilize renewable energy for either hydrogen or ammonia production.

Based on the observed technological development all renewable energy production technologies and BESS' are now being combined into renewable power plants. Thus, in terms of size, a renewable power plant can be anything from one WTG and a PPC up to very large hybrid power plants including wind, solar, battery, MSU, STATCOM, SynCon, P2X etc. all controlled by a dedicated hybrid plant PPC.

In order for Vestas to consistently ensure grid code compliance for any combination of renewable power plants, we are driving four initiatives all aiming at reducing the risks associated with commissioning renewable power plants such as incompatible component models, incompatible -signals, -communication protocols and -control strategies, control at commissioning of a site and cyber security.

The initiatives are 1) Maintenance of high-quality of Vestas WTG- and PPC-models for dynamic and transient studies for grid code compliance, 2) Development of Vestas hybrid PPC features and best practice commissioning guidelines, 3) Qualification of third-party OEM dynamic components i.e. the main electrical plant components that has their own control systems such as STATCOM, PV-inverter, SynCon etc. and 4) Performance of dedicated grid integration studies to ensure optimal balance of plant design and grid code compliance, and conduct commissioning studies to ensure smooth commissioning test.

II. RISKS ASSOCIATED WITH COMMISSIONING HYBRID POWER PLANTS

Considering a hybrid power plant model as a puzzle as depicted in Figure 1. with different OEMs supplying pieces for that puzzle, there is a significant risk that some of those pieces will not fit together creating an incompatibility that will impact the interconnection process, either delaying the grid code assessment or leading to inaccurate results. To overcome this, Vestas developed a detailed requirement specification to integrate 3rd party OEM models into Vestas model environment.

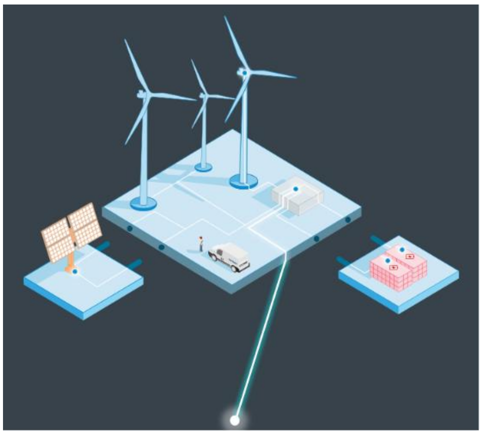

Figure 1. Hybrid power plant as a puzzle

In addition to the wind turbines, Vestas PPC also has the capability of controlling and operating up to 4 external components controlling the injection of active power, named as Producers. Examples of Producers include non-Vestas WTG's and PV controllers. Vestas Power Plant Controller can also control and operate up to 4 external components of each type, controlling the injection of reactive power, named as Providers. Example of Providers include non-Vestas WTGs, PV-modules, STATCOMs and SynCons. Additionally, Vestas PPC can control and operate 4 Energy Storage Systems (ESS) controlling the injection of active power. Example of these ESS include Battery ESS. Finally, Vestas PPC can also control and operate up to 4 MSUs that offer the possibility of offsetting the reactive power injected at the Point of Common Coupling (PCC), therefore granting a wider static Q range.

Vestas PPC interface guarantees the correct communication between the PPC model itself and other external models and entities. For the configuration of Vestas PPC interface, the PPC control zone must already be defined: number of WTG groups and types, PV plant controller, BESS plant controller, PCC (monitored bus and branch), STATCOM / Synchronous Condenser controller and MSU controller.

A. *Incompatible component models*

To perform a wind power plant simulation, models for all different components in the plant are required in the same power system simulation tool. Vestas develops electrical simulation models for all their different variants of WTGs and PPC. The rest of the electrical Balance of Plant (eBoP) components, considered as passive elements, are generally developed by the simulation tool developer, and utilized as standard library models (transformers, cables, sources, etc.).

When developing a hybrid power plant, several different companies will supply their active/reactive power plant generation units and will develop their own simulation models. These models are used by the windfarm developer/owner to assess grid code compliance of a given hybrid power plant. To complete the assessment, it is necessary to combine all models developed by different OEM's to ensure they are compatible when using them in the same simulation environment. Assuming Vestas as developer of the power plant controller for a given hybrid power plant, it is necessary that models supplied by 3rd party companies are compatible with Vestas model environment and capable to communicate with Vestas PPC.

Vestas PPC interface is divided in four submodules: (I) Communication from WTG, PV and/or BESS to PPC; (II) Communication from PPC to WTG, PV and/or BESS; (III) Interface with modelled network delay; (IV) Communication of references to PPC. The signals exchanged between PPC and external models/entities, and processed by these submodules, are represented in Figure 2. , as well as the user defined delays and conversion factors that are applied to each one of them.

B. *Control communication and cyber security risks*

Various risks are associated with performing commissioning of hybrid power plants. Early involvement and engagement in the phases prior to the actual commissioning is vital to secure the required transfer of information.

1) *Information transfer*

Standard signal exchange definitions do not exist across hybrid assets, meaning that OEM specific details such as protocol, signal addresses/names, units (e.g. W, kW or MW) etc. has to be configured in accordance with the individual component implementation. This leads to risk of communication problems and misinterpretations. It also complicates control as some signals required for controlling assets properly may not be available.

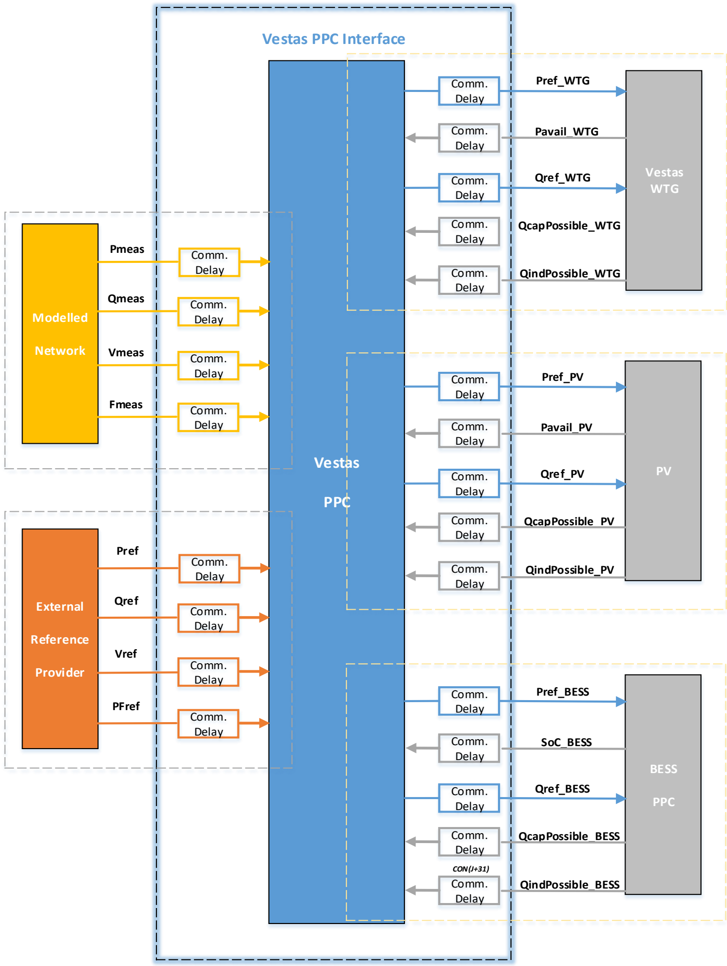

Figure 2. Exchange signals between PPC and external models, conversion factors and delays – signals from WTG, PV and/or BESS to PPC in grey; signals from PPC to WTG, PV and/or BESS in blue; signals from modelled grid in yellow; reference signals to PPC in orange.

The signals are used for different purposes and this must be considered when designing the communication setup. For control signals, a fast transfer rate (10-100 Hz) and a low latency is required. For signals related to supervision of the assets slower transfer rates is acceptable (<=1Hz).

a) *Control signals:*

- Reference signals
- Capability signals
- Feedback signals
- Operational signals (mode, heartbeat etc.)

b) *Supervision signals:*

- Status signals
- Alarm/warning/event signals

A key aspect to consider is sign convention and e.g. whether storage assets is adhering to Generator or Load convention.

2) *Protocol standards*

Different protocol standards can be considered taking into consideration requirements for communication speed, cyber security etc., while keeping availability across the different hybrid asset OEMs in mind:

- OEM specific protocols e.g. Vestas AP and Road Runner Protocols
- Simple standard protocols e.g. ModBus TCP/Serial
- Protocols with built in Cyber Security features (e.g. encryption) such as IEC61850

3) Cyber Security

Cyber security aspects have gotten increasing focus as more and more components in the plant network are interconnected by ethernet based communication networks making it vulnerable to attacks. In order to mitigate the risks related to the hostile disturbance of the operation of the hybrid power plant, several precautions can be taken. Among these are device hardening and network decomposition into domains where the communication between these can be controlled by packet inspection and routing mechanisms. This prohibits devices in the hybrid power plant network to communicate unless it is explicitly allowed for by the network rules embedded in the routers and switches making up the network topology. The device hardening together with user authentication for device access must prohibit unauthorized access to the various ethernet based devices and prevent that the operation of these are disturbed.

A cornerstone in the security is the network security. For that purpose, VLAN segmentation or firewall-based isolation is essential. This basically means that the network switches, firewall and routers can control which device can communicate with which device and on which port. A challenge in this aspect is to allow 3rd party OEMs to access a device in the park while the same device is an integrated part of the plant control network. This is relevant for example for STATCOMs where a 3rd party OEM is responsible for the maintenance, but still the electrical capabilities of the STATCOM is controlled by Vestas PPC. This is solved by adding port specific rules on the network equipment.

III. The Vestas PPC and hybrid features

A plant control will need to have a hierarchical architecture that all the controllers in the plant must follow. The Vestas PPC use the Cascaded Control concept for controlling individual assets of a hybrid power plant. It is a very flexible concept which supports a large variety of plant topologies taking into consideration the different assets characteristics (renewable generation, storage etc.) and dispatch power references accordingly to secure optimal use of available resources.

A. Control architecture

The control architecture can be configured in accordance with the required grouping of assets:

- Combined control of assets as one plant (cascaded control with one combined plant reference).
- Separate control of assets (individual references to each asset).
- Combination where e.g. PV and WTGs are controlled combined while BESS is controlled separately.

For combined control of assets, the dispatch logic will stop discharging storage assets such as batteries before curtailing renewable assets below their available power.

B. Hardware-in-the-loop test of the PPC

To verify the control functionalities offered by the PPC, a sequence of test steps is used. The first step is to perform a simulation of the plant control by a laptop simulation of the control code.

Once that has successfully been done, the next step is to deploy the control software to PPC hardware that is interconnected to either a) a WTG hardware controller setup representing one turbine or b) a server setup where a large number of turbines are simulated in software and a simplified model of the local grid is simulated. In the latter server setup rms values for voltage and current in the Point of Connection (PoC) are used as input to an amplifier that are generating current and voltage output. The amplifier output, which is representing scaled values of the active and reactive power produced in a real plant by means of scaled voltage and current, are detected by a hardware power meter. Subsequently, these measurements are fed back into the PPC closing the control loop. In this way, the control and communication performance can be tested in a setup with the real PPC hardware, the real power meter demonstrating the scalability and flexibility in terms of control type as well as number of control loops and WTGs.

C. Control and control hierarchy commissioning

Pre-requisites for the functional commissioning process:

- The first step is to do the commissioning of each unit based on the specific OEM commissioning guidelines.
- The second step is to use the PPC unit to communicate to each unit and test that it can communicate with all the units and each unit respond to a demand as it should.
- The last step is to configure the PPC according to the defined control architecture in accordance with point A.

1) Grid stability/safety control

The first step is grid stability/safety control functions. In reference to the needed control architecture selected in section A, we can now commission the needed functions related to grid code compliance functions like Voltage Control, Frequency Control etc.

The commissioning of grid code related functions is done according to IEC 61400-21.

The aim of grid stability/safety control functions is to ensure that the electrical grid integrity is maintained in order to reduce the risk of protection relays are tripping in the grid resulting in grid outage. The individual unit safety like “over current” protection or “structural overload” protection must be handled within each unit and tested individually as certification utilities require.

The safety of the grid has higher priority compared to ancillary services like Frequency Response.

2) Ancillary services and environmental functions

The second step in functional commissioning is the list of functions that are not related to grid safety but might still be related to long term grid stability or environmental safety.

Hybrid plant specific functions like power balancing.

Environmental related functions will also need to be tested in this step. These are functions like shadow/flicker avoidance, noise reduction, bat protection etc.

3) Task priority management

When conflicts arise between different tasks it will be handled in respect to priority of the simultaneously occurring events, where safety/grid stability events have highest priority. As an example, if an under frequency event occur, when the plant need to support the grid by increasing power production, simultaneously with a noise reduction event requesting to pause generation of power production, the plant control will disregard the pause signal for the noise reduction in order to support the grid frequency and help stabilize the grid.

When talking about hybrid plants it is important that the commissioning test are designed to cover all the scenarios of combined control and not only the individual control of each asset.

IV. Securing third-party OEM interface

In a hybrid power plant, dynamic main electrical components such as WTGs, STATCOMs, SynCons, PV-Plant inverters and BES-System inverters influence the grid code compliance of the whole plant. To ensure stable and compliant operation, the following conditions must be fulfilled for the dynamic components:

- The component control system interface to the PPC must work as specified by Vestas
- The component including its control system must have the correct performance and functionalities as specified in the specific component Technical Purchase Specification (TPS) both in normal and in any contingency operation
- The component inclusive its control system must have the correct autonomous dynamic behavior as specified in the TPS during grid faults
- Validated models of the component inclusive its control system for the relevant simulation environments must be available.

If the contracts towards customers and equipment OEMs are signed before the above is ensured, Vestas takes a large risk of delaying the projects which can lead to liquidated damages for Vestas and losses for the customers.

In the sales projects, there is usually not enough time to perform a component assessment before signing the contracts. Therefore, it is necessary to have qualified dynamic plant components before signing agreements.

A. *Qualification of 3rd party OEM components to mitigate risks*

1) Introduction

Centered around the 3rd initiative of this paper i.e. dealing with qualification of 3rd party OEM dynamic components, are the definition of specifications for main dynamic electrical plant components and the evaluation of selected 3rd party OEM components towards becoming a Vestas qualified dynamic component OEM.

By this initiative we uphold the intent of Vestas Material Risk Policy and General Requirements to Customer Commitments - Grid Compliance Regulations for purchasing of 3rd party electrical plant components.

Generally, by following the resulting set of component specific TPS for each dynamic component and above mentioned Grid Compliance Regulations, Vestas upholds our quality requirements on delivered component models, component control systems interface to our PPC- and SCADA-systems and on Cyber Security of 3rd party dynamic plant components. By this we secure a considerable reduction of plant risk and lowering cost of poor quality for each new hybrid power plant project.

To reach these objectives, Vestas Power System Integration department is in the process of developing a complete set of standardized TPS' for all main dynamic electrical plant components in a hybrid power plant:

- STATCOM Module
- Synchronous Condenser Module
- PV-Plant Module
- BES-System Module
- Yaw Power Back-Up (Diesel-Genset)
- MV/HV Transformer OLTC
- MSU-C with step control
- MSU-R with OLTC
- Active Harmonic Filter

Besides the actual dynamic component, each of these modules include step-up transformer, switch gear etc. to enable connection to the plant substation MV busbar(s).

2) Applied Process

To perform a full OEM/component qualification is an elaborate and time-consuming process. Therefore, it was decided to concentrate on component model and component control system interface and performance qualification as a first step towards providing fully qualified dynamic component OEMs to Vestas Procurement and Technical Sales organizations. Hence, for each new selected dynamic plant component and OEM, the below process for component qualification is applied:

- D-FMEA created or updated
- Requirements created or updated
- Limited TPS created or updated
- OEM Self-Evaluation conducted for new OEMs only
- A dedicated design and verification plan (DVPL) created or updated
- Perform internal Vestas Model test and validation (see below)
- Perform external PPC Interface & Performance test and validation at OEM factory test facilities.

Generally, Design - Failure Mode and Effects Analysis (D-FMEA) is the method widely used by the industry to identify and mitigate the risks during the design stage of a product. In our case we focus on identifying the potential failure modes of the dynamic plant component (system of interest) caused by design deficiencies.

3) Development of component specific TPS

Based on the D-FMEA a limited TPS package is developed for each new dynamic plant component that besides the specific component module TPS also includes fully generic documents containing the Vestas requirements on Cyber Security and Ecological Design.

Each component specific limited TPS is concentrated on elaborate sections on Vestas requirements for dynamic performance, specific control system interface requirements to secure a seamless interface to the Vestas PPC on site, component mathematical models intended for strengthening our ability to build valid hybrid power plant models for dynamic and transient grid code compliance studies. Further it includes our SCADA and Cyber Security requirements as depicted in Figure 3.

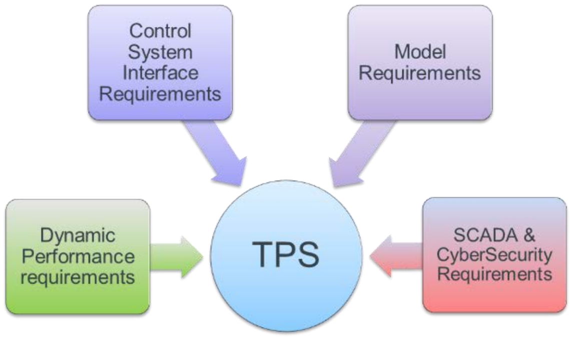

Figure 3. Main parts of limited TPS for dynamic plant components

4) Conduct of OEM Self Evaluation

The OEM Self Evaluation Process (SEP) is a screening process that has been developed for use as the first of three steps for a Vestas preferred OEM to become a qualified OEM of the selected main dynamic plant components.

Figure 4. below depicts the SEP as consisting of three legs that must be completed by the OEM within the process:

1. Commercial parameters – request for information (RFI)
2. OEM quality system – OEM assessment
3. Technical and product capability assessment based on Vestas component specific TPS compliance.

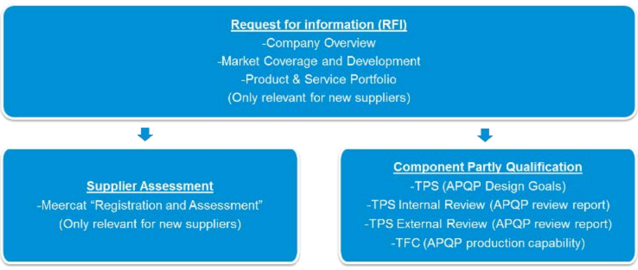

Figure 4. OEM Self-Evaluation Process

As shown in Figure 4. the commercial evaluation of the product group is based on a RFI questionnaire that collects details from the OEM in order to understand their commercial strategy and market approach towards Vestas and their fitness to the Vestas Global Evaluation Program.

The OEM Assessment is based on Vestas' OEM registration system and quality assessment questionnaire. These are part of Vestas OEM onboarding process where the OEM must pass an OEM quality system assessment covering the OEM's maturity level relating to: Management & Leadership, Production & Operations, Engineering & Technology, Supply Chain and Safety & Sustainability.

The Advanced Product Quality Planning (APQP) – part approval process is a well-known concept within the automotive industry and has been the backbone for maturing quality performance at OEMs for decades. The concept of APQP is adapted to the business boundaries and special conditions differentiating Wind from Automotive using APQP4Wind which is a common quality assurance methodology for the global wind industry.

TFC = Team Feasibility Commitment.

Finally, in the Component Qualification the OEMs are asked to self-evaluate and -document how well they comply to the requirements to be found in the component specific TPS.

Following a completed OEM SEP, the OEM will be subjected to an internal Vestas evaluation and ranking process the purpose of which is to decide if the OEM can be accepted to proceed to the following qualification steps aiming at test and validation of the selected OEM component it selves.

5) Component model test and validation

As an integral part of the component qualification process we put high emphasis in obtaining high-quality mathematical models of the selected dynamic plant component for the main commercially available software packages. These different software packages must cope for static, dynamic RMS-type and transient EMT-type analysis of both component, hybrid power plant and power system.

As part of the component qualification process and in agreement with the selected OEMs, which are covered by a mutual Non-Disclosure Agreement, Vestas ask the OEMs to hand out their component models for selected software packages. Then these component models are being tested and validated internally by Vestas following below dedicated process:

- OEM meeting - first model assessment
- Mapping of performance legitimacy
- Mapping of validation legitimacy
- Model interface
- Model documentation availability
- Model usability
- Model availability
- Model hand out (RMS +EMT)

- Internal integration of OEM partly RMS and partly EMT models in purposely developed Vestas modelling environments
    - Model consistency
    - Model robustness
    - Model compatibility
- Vestas internal model test and validation process
- OEM meeting - final model assessment
- Q/A session with the findings in above points.

At this point we can judge if the component models for the selected software packages can be qualified or not.

6) Component control system test and validation

Finally, the component control system is being tested and validated through below OEM qualification sequence. The same sequence will be followed for each new component / OEM:

- Design Verification Plan and Reports (DVPR) are developed as test preparation
- Interface test (at OEM factory/Lab)
- Performance test (at OEM factory/Lab)

For the interface- and performance test a full Vestas PPC-rack is shipped to the agreed OEM factory / laboratory facility. At this facility it will be connected to the component control HW/SW system. The component control system will then be connected to the selected component hardware that must be grid connected to enable the conduct of closed-loop performance test.

As an example, the principles of the interface- and performance tests are depicted in Figure 5. and Figure 6. for a STATCOM located in a hybrid power plant. In this plant the STATCOM is operated in subsidiary-mode to the Vestas PPC, but it controls the plant mechanical switched compensation units (MSU).

7) Component Interface testing

An interface test is conducted between PPC and the component control system without any main components connected (see green circle in Figure 5.). The purpose is to test communication between the two controllers.

The Interface test will focus on verifying the communication interface and the signal list. This include testing:

- Protocol specific configuration (Baud-rate, Endian etc.)
- Signals (Set points, capability feedback etc.)
- Scaling - relative (per unit) or absolute (e.g. kW)
- Detection of loss of communication and resulting behavior.

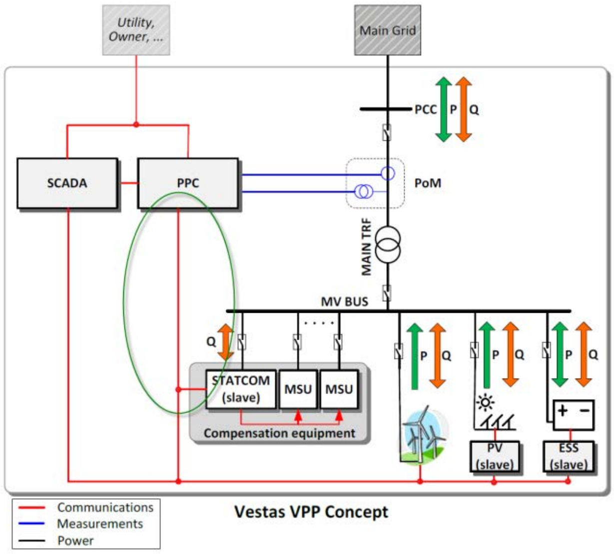

Figure 5. Component control system interface test (green circle - open loop).

8) Component Performance testing

The performance test will be conducted at the OEM test lab/site where a full closed loop test setup with a grid connected component system are established. are set up. This is illustrated by the green circles in Figure 6.

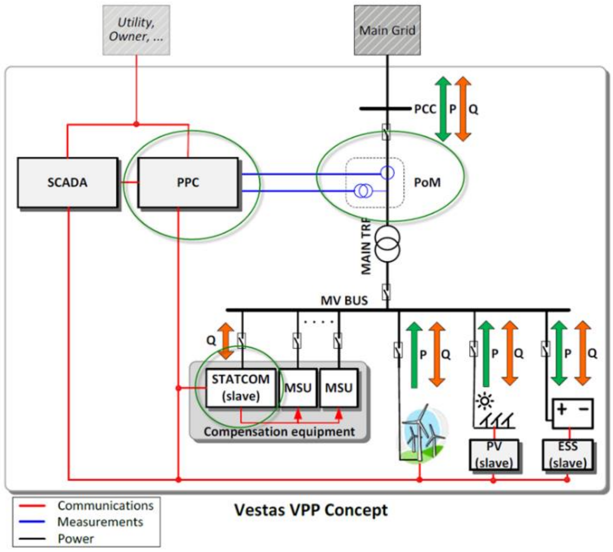

Figure 6. Component and control system performance test (green circles - closed loop).

Using this OEM lab setup, the electrical performance values of the component, such as initial delay, risetime etc. are verified. The performance test includes:

- Active Power control
- Reactive Power control
- Fault Ride Through

If the interface- and performance test of the selected component and its control system are passed, then that specific dynamic component from the selected OEM is deemed accepted to become a Vestas qualified third-party OEM main power plant component. As such it will be added to an internal catalogue of qualified dynamic power plant components used by our global procurement and technical sales organizations worldwide.

B. *Model integration tests*

As mentioned in the risk section (II.A), there is a risk of incompatible models from different OEMs when integration is carried out in a single modelling environment. To mitigate this risk, a series of model integration test have been defined by Vestas to ensure a smooth operation across different electrical simulation models from different OEM's.

Model integration test are not defined to assess the compatibility, consistency, and robustness of the hybrid power plant model. The purpose of the abovementioned type of test is to ensure models developed by different companies that join forces in a hybrid power plant project, are compatible and can be used in a single modelling environment.

1) *Compatibility test*

This type of test aims to ensure all the required signals by Vestas power plant controller are available from different active and reactive power generators models. First step in model integration test is to import 3rd party models into Vestas model environment to ensure models are compatible.

After initial compatibility has been verified by ensuring compilers and versioning have been confirmed, the next step is to verify the signal availability. It is fundamental for the PPC to receive the required signals to properly control the different active and reactive power sources. Once available signals are included in the model, it is possible to dispatch correctly all setpoint to all components in the hybrid plant and achieve the desired control strategy.

2) *Consistency test*

Transmission System Operators (TSO) for several markets demands from OEMs and project developers to perform grid interconnection assessment simulations in multiple simulation tools of different nature (RMS and EMT). In conjunction with this requirement, models must show similar performance response under equivalent operation conditions.

The response from models must be within predefined tolerances of grid code requirements. Therefore, a series of test are carried out for the following conditions to compare the responses between EMT and RMS models. Evaluating the responses is within a predefined tolerance:

- Fault disturbance tests with:
    - Three-phase-to-ground fault scenarios [all models].
    - Single-phase-to-ground fault scenarios [when tools support unbalance faults].
    - Two phase-to-ground fault scenarios [when tools support unbalance faults].
- Non-fault disturbance tests [all models]:
    - Step response test on active power set-point.
    - Step response test on reactive power set-point and/or power factor.
    - Step response test on voltage set-point.
    - Step response test on grid voltage magnitude.
    - Ramp response test on grid voltage magnitude change.
    - Step response test on frequency.

Considering various factors such as:

- Grid Short Circuit Ratio (SCR).
- Grid X/R ratio.
- Voltage dip with Fault Impedance.
- Fault duration.
- Pre-fault active power at the PoC.
- Pre-fault reactive power at the PoC.

As part of the consistency test, models must support bidirectional translation between simulation tools. This means that OEM's must ensure parametrization can be imported/exported between tools.

3) *Robustness test*

Simulation models provided by 3rd party OEMs must have the following characteristics to guarantee the robustness of the simulation when models are integrated into Vestas modelling environment:

- Voltage, frequency, and active/reactive power flat response with no disturbance are applied.
- Models do not disturb the operation of existing dynamic models.
- Models are numerically robust for dynamic simulation for several minutes.
- Models must show similar response by using different simulation settings (time steps, acceleration factor, etc.)
- Must be numerically stable for a given range of grid SCR and X/R ratio.

V. POWER SYSTEM INTEGRATION OF VESTAS POWER PLANTS

A. *Models of Vestas WTG and PPC*

The technology design of different power suppliers included in an standard hybrid power plant (WTG, PV, STATCOM, etc.) and the tightened performance requirements defined by TSOs across the world in their respective grid codes, makes it impossible to use standard library electrical simulation models to carry out studies for grid code compliance. To overcome this situation, Vestas model design concept is based in a full source code integrated model called Unified Model Framework (UMF). UMF models are created as a digital twin of the original control developed by the different Vestas design teams for both wind turbine and power plant controller. UMF concept allows to integrate a unique control code in any commercial simulation tool regardless of its solver nature as described in Figure 7.

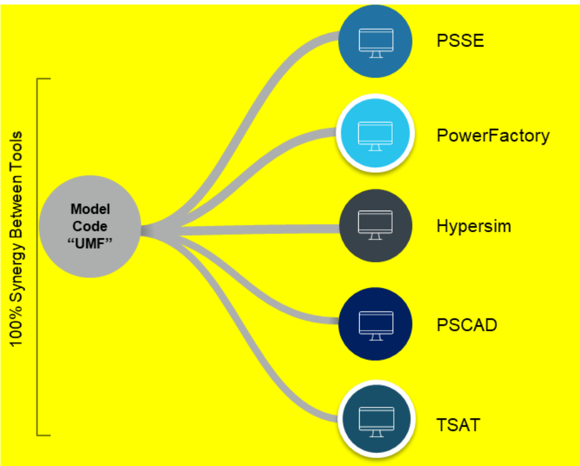

Figure 7. UMF model integration description in various comertial electrical simulation tools

The approach described above gives to all Vestas electrical simulation models a high degree of adaptability in updating models according to the latest source code design. This is a plug and play approach that allows to release model updates on a bi-monthly basis or ad-hoc when a critical update must be pushed to the real product.

Vestas UMF model allows the user to parametrize the model as the real product to obtain a mirror response. This level of alignment between model and product allows a full traceability regarding product parametrization and enable the full translation of product parametrization, from modelling environment to real site. Guaranteeing the performance obtained during the grid code assessment, will resemble the real plant performance on site.

B. Power system integration studies

When designing a hybrid power plant, site-specific EPD studies are performed with the aim to determine dimensioning of the different eBoP components, to make assessment on region specific grid code compliance and to ensure optimal balance of plant design.

As the different countries, regions or even TSOs have different grid codes, the studies always include steady-state analysis and transient stability studies.

In addition, when connecting hybrid power plant to extremely weak grids, problems such as voltage instability, lack of inertia and undesired dynamic behavior arise. Both dynamic stability (RMS) and electromagnetic transient (EMT) studies including N-M contingency studies are conducted to determine the need of additional equipment such as STATCOM or SynCon, their installation location, and the specifications of these components.

In steady state analysis, load flow and short circuit study are conducted. The primary objective of the short circuit analysis is to determine the maximum fault levels at bus locations within the plant to determine the required fault rating of different equipment. Load flow studies are performed with the objectives as follows:

- To assess the effect of grid voltage variations on WTG and PV bus voltage levels
- To assess the loading of the cables in the hybrid power plant and verify the selected cable sizes
- To assess the loading of the transformers in the hybrid power plant and verify the selected transformer sizes
- To determine tap changer range if transformer is On-Load Tap Changer (OLTC) type
- To assess the size of reactive compensation equipment that may be required to meet the given grid code requirements
- To estimate the maximum load current for protection system design
- To plot PQ chart for the complete hybrid power plant based on load flow study results.

The objective of the transient analysis is to investigate the plant response under a defined set of grid disturbances. The performance of the plant will determine whether any additional eBoP equipment is required to meet the specific grid code requirements. The transient stability studies include Low Voltage Ride Though (LVRT) study, High Voltage Ride Through study (HVRT), voltage and reactive power control performance evaluation, frequency control performance evaluation, and sometimes they also include N-M contingency studies to assess plant response to disturbances following contingency events.

In some cases, a STATCOM has to be selected to provide fast voltage regulation and dynamic reactive power support at the grid connection point. In extreme cases [1,2], a SynCon is selected to improve short circuit strength and enhance system inertia if required. The SynCon remains synchronized for close-in faults and extended clearing. It helps post-fault voltage recovery which in turn stabilize the WTG phase-locked loop. Like STATCOM, a SynCon will continuously provide dynamic reactive power support.

By doing EPD studies, we ensure grid code compliance and optimal plant design.

In many countries and regions, commissioning tests are required to demonstrate that the installed plant is fulfilling the performance requirement set out in the connection agreements, e.g. [3] and [4]. In addition, the plant proponent is required to carry out tests to validate the R2 model and its parameters and ensure that the plant models represent the installed system.

To ensure smooth commissioning test, a test plan will be made according to guidance set out in e.g. [3] and [4] and submitted for approval from the relevant authorities before test commencement. Pre-test simulation studies are conducted according to test plan to assess whether the installed plant complies with the performance requirements and to discover the potential issues and implementing the necessary correction measures before test commencement.

As an example, in Australia, the commissioning test must be conducted for several holding points where the plant overall output is constrained to pre-defined megawatt levels. At each Hold Point, a report is required to be submitted to the TSO and the relevant Network Service Provider (NSP) for review and approval, before progressing further with the commissioning activities.

The test results and model overlay results give sufficient confidence in the performance of the hybrid power plant under a variety of system conditions. This confidence leads us to recommend the plant to be allowed to move up to higher level holding points.

Conclusion

By consistently pursuing the four initiatives of 1) Maintain high-quality of Vestas WTG- and PPC-models, 2) Development of Vestas hybrid PPC features and best practice commissioning guidelines, 3) Qualification of third-party OEM dynamic components and 4) Performance of dedicated grid integration studies, Vestas ensure optimal balance of plant design, grid code compliance and smooth plant commissioning.

In the near future it is our plan to have developed a complete set of standardized TPS' for all main dynamic electrical plant components in a hybrid power plant as listed in section IV.A.1). Further we intend to have a limited number of OEMs qualified for delivering each of the listed dynamic components.

The targeted result of above initiatives is to know dynamic performance and mathematical models of all main electrical components of a Vestas hybrid power plant being it Vestas own WTGs and PPC or 3rd party OEM dynamic components. This in order to reduce plant risk to the largest possible degree to the benefit of Vestas and our customers.

References

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