Modelling of the Diode-Rectifier Based HVDC Transmission Solution for Large Offshore Wind Power Plants Grid Access

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Abstract— **This paper presents the detailed and simplified dynamic simulation models of Diode-Rectifier (DR) based HVDC transmission solution which is also known as Siemens New Grid Access (NGA) technology. The new grid access solution was developed mainly to enable an efficient transmission of power produced by large offshore wind power plants that are located more than 100 kilometers away from the mainland. The model of DR HVDC transmission solution is including wind power plant (WPP), diode rectifier units (DRU), DC cable and onshore voltage-source converter (VSC) station. An introductory part describes the full-scale EMT model and its dynamic performance is demonstrated on two study cases showing the power flow initialization and the dynamic behavior during an onshore fault. Based on EMT model, a simplified RMS model was developed and it has been validated by several test cases. The comparison of the EMT and RMS simulation results shows close agreement. Therefore, it could be concluded that the developed RMS model of Diode Rectifier based HVDC grid connection solution could be utilized for large scale dynamic power system studies.**

Keywords- HVDC; Rectifier; Wind Power Plant; Grid Access; Modelling; Dynamic Performance

I. INTRODUCTION

One of the main challenges today is to transmit offshore wind power to the mainland grid as efficiently as possible. Efficiency strongly depends on the type of grid access, which becomes more demanding with the wind power plants moving further and further into the open sea. Siemens has developed a New Grid Access solution depicted in Fig. 1 that enables the efficient transmission of 1.2 GW of power from far shore wind power plants [1]. The New Grid Access approach utilizes offshore AC to high voltage DC (HVDC) conversion by diode rectifiers [2], [3], [4] and a high performance voltage-source converter located onshore. The diode is the simplest and most robust piece of power electronics the engineer can think of. The diodes are encapsulated together with a transformer and a smoothing reactor in a common tank. This so called “diode rectifier unit“ looks like an ordinary AC transformer that is installed and maintained like an ordinary AC transformer. The main benefits lie in the reduction of required space; robustness and low maintenance requirements due to the avoidance of air insulated high voltage equipment and simplified cooling. The wind turbines are assumed to be of type 4, which is the most commonly used wind turbine type in offshore wind power plants. Stable operation in AC and DC mode as well as a smooth transition between operational modes is achieved by implementation of the newly developed wind turbine grid side converter controller functions [5].

II. THE DETAILED SIMULATION MODEL OF DR HVDC GRID ACCESS SOLUTION

The most comprehensive simulations were performed in power system simulation software PSS®NETOMAC featuring 200km cables to shore, 201 independent wind turbine generator (WTG) including detailed controllers models and onshore HVDC converter control. The WTGs are represented in detail by implementing full control algorithm of the line side converter (LSC) including the representation of the DC intermediate link in every single turbine. The models of the generator side converters and mechanical drive trains are simplified. The wind speed during simulation time is assumed to be constant. The time step is typically 1 microsecond in order to model typical string cable sections properly.

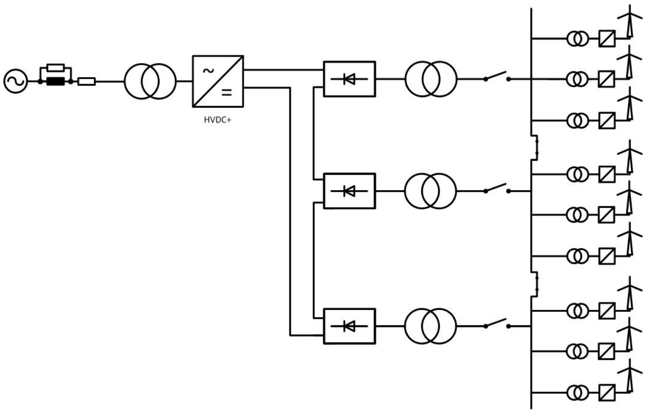

Figure 1. Single line diagram of NGA.

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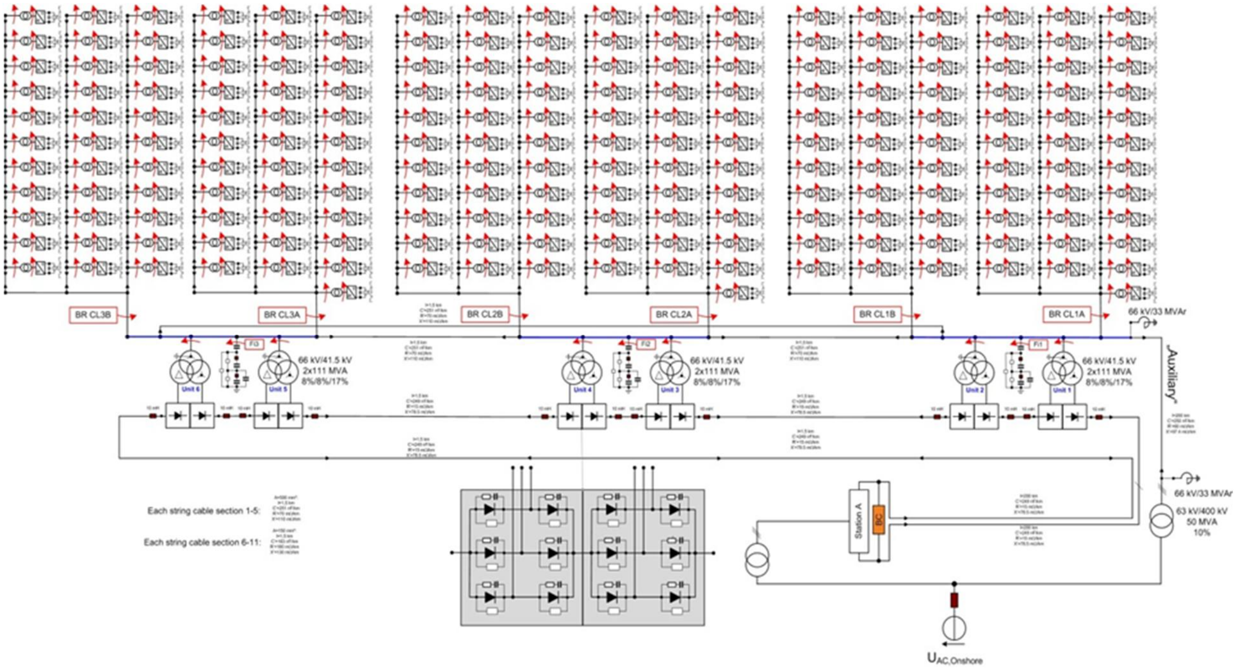

Figure 2. New Grid Access detailed model in PSS®-NETOMAC featuring 200km cables to shore, 201 independent WTG including detailed controllers models and onshore HVDC converter control.

The model of the DR Grid access solution has a modular structure including detailed models of every main component. Initially each element had a generic or even fixed parameter characteristic, which was then followed by further development to a more detailed description. The Figure 2 shows all the main modules of the master model including:

- Onshore network equivalent (with capability of voltage control and various types of faults to be simulated)
- Onshore symmetrical monopolar VSC converter based on HVDC PLUS concept (full bridge submodules)
- DC cable (200 km length)
- Umbilical AC 66 kV cable (200 km length)- Offshore diode rectifiers units (6x DRU's) with filters
- Offshore wind farm – 200 MW sub-clusters with wind generator blocks (6x33 WTG's + 3 WTGs).

III. THE DETAILED MODEL SIMUALTION EVALUATION

Relevant simulation cases describing the dynamic behavior of the entire HVDC transmission solution during an energization and during the onshore networks disturbance were used for the validation.

The initialization of the DR HVDC solution is realized via several phases which are including initial energization, voltage stabilization and establishment of the DC power export after which the umbilical cable is disconnected. For better understanding Figure 3 presents plotted quantities from a simulation run monitored at the one out of 18 wind turbine strings with 12 WTGs. The simulation results in Figure 3 are showing successful energization with the following sequence of events:

1. Energization of string cable
2. WTG transformer energized. WTGs provide reactive power
3. DRU unit energized and connected
4. First WTG starts power production
5. Energization of filter, WTG ramp to 20% of rated power
6. WTGs ramped to full power
7. Umbilical Cable disconnected
8. Frequency operation point adjusted

In this case the active power ramp-up is accelerated and the disconnection of the umbilical cable is delayed to represent a worst case scenario for system stability.

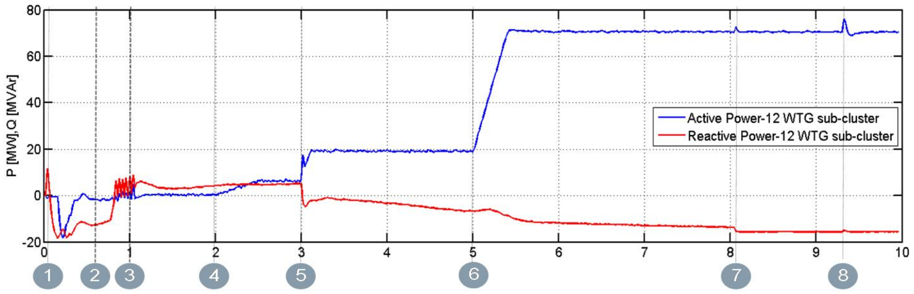

Figure 3. Active and reactive power produced during energization and DC power flow initialization at the single string of 12 WTGs.

The next simulation presents the capability to ride through the symmetrical fault (FRT) introduced at the HV side of the HVDC station transformer. The FRT capability is checked for the UK grid code [6] which requires that the wind farm and the HVDC converter shall remain transiently stable and connected to the system without tripping for a close-up solid three-phase short circuit fault or any unbalanced short circuit fault on the transmission system for a total fault clearance time of up to 140 ms. The wind farm and the HVDC converter shall be designed such that active power output shall be restored to at least 90% of the pre-fault level upon clearance of 140ms fault on the transmission system within 0.5 seconds after the restoration of the voltage at the Interface Point to at least 90% of its nominal value.

Figures 4 and 5 are showing the onshore FRT behavior of the entire DR grid access system where the system voltage is monitored at the offshore connection point as well as at the point onshore where the DR HVDC solution enters the transmission system. Figure 4 depicts the grid voltage during fault and fault recovery. The voltage at the offshore bus bar rises during the fault due to disturbance of the power equilibrium caused by limitation of the onshore HVDC converter to feed the active power into the power system.

Figure 5 depicts the DC power transmitted via the HVDC cable. The FRT test was performed at the reduced power 800 MW which was assumed to be available from wind power plant. After a fault introduction the power over the DC line is reduced to zero but gets back to pre-fault level after the short transient following the fault recovery. The active power post-fault recovery is achieved within 0.4s, which is well within the defined limit of 0.5s for short faults (t<140 ms). The result presented in figures below demonstrate capability of the DR HVDC solution to fault ride through onshore faults and restore active power to pre-fault level as required by UK Grid code.

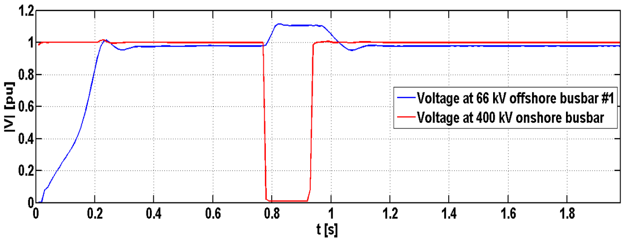

Figure 4. Offshore and onshore AC voltage during and after an onshore grid symmetrical fault event.

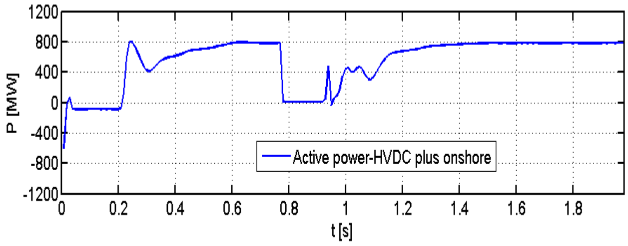

Figure 5. Power export during and after an onshore grid fault event.

IV. DEVELOPMENT OF THE REDUCED ORDER SIMULATION MODEL

In order to facilitate the stability analyses and to perform large scale power system studies that shall include the newly developed DR HVDC solution, the suitable simplified models needs to be developed for EMT and RMS simulations. While the model presented in section III is utilized for the detailed development of the concept the simplified models are intended to be used for setting up a simple meshed HVDC offshore power system model to investigate interoperability of the main equipment in the system and interaction between nearby power systems. The reduced model development is realized in two steps. First the reduced EMT model is formed based on detailed model shown in the previous section by aggregation of the wind park. Further simplification is needed to form RMS level (positive-sequence) simulation model. The both approaches are described more in details in the following subsections.

A. Simplified EMT model

The simplified EMT model shown in Figure 6 includes the simplified model of an aggregated type-4 WPP, connecting transformer, 24-pulse 400MW DRU system, 200km DC cable and the onshore VSC station. For further simplification, the onshore VSC station was represented by a DC voltage source. The 200km DC cable was modeled by 10 cable sections. Each cable section was modeled by a PI model including frequency depended characteristic.

The DRU system includes smoothing reactors, 2x12-pulse diode rectifier system and two three-winding transformers. For harmonic and reactive-power compensation, a filter (type C) was used. The WPP is represented by a connecting transformer, a phase reactor and a line-side converter (LSC) station. The LSC station was represented as a controllable voltage source.

The offshore AC grid typically is a very weak grid (e.g. SCR < 3) with no inertia. In addition, the DRU system has no control capability. Therefore, the control system of the WPP LSC station (aggregated WTG controller) is responsible for controlling both system voltage and frequency. In order to maintain stability of the offshore AC grid, voltage oriented control which possesses grid forming capability was applied. The investigated control system for the WPP LSC station includes:

1. Measuring system (measurement, filter and abc/alpha, beta transformation): estimate the input for the control system

2. Frequency lock loop: dynamically track the system frequency and estimate the frequency deviation

3. Voltage control: support power ramping activity, provide black start function (SVC mode)

4. Active power control: regulate power injection from wind farm through DRU system

5. Reactive power control: control AC voltage to support power flow

6. Frequency control: provide correction for angle of controlled voltage vector

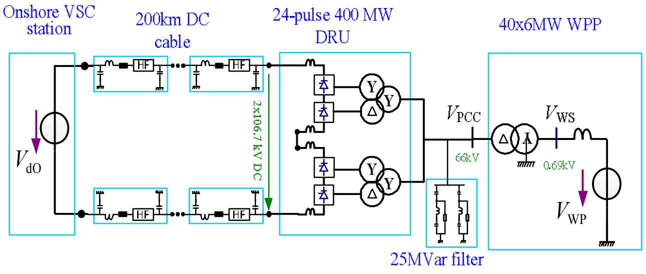

Figure 6. EMT model of investigated DRU+WPP system.

7. Fault-ride-through (FRT) control: limit short circuit current and provide reactive current to support system voltage during faults in offshore AC grid.

8. Fault-ride-through condition detection: provide control coefficients and activating, ramping-down, and deactivating signals for FRT control.

The sampling frequency used for this control system is 2500 Hz. The EMT simulation was carried out with a time step simulation of 1 microsecond.

B. *Equivalent RMS model*

The simplified representation of the DR HVDC grid access solution for RMS simulation (positive- sequence) is modelled by using a voltage-dependent load connected to the point of common coupling (PCC) bus on the AC side and a voltage source connected to the DC cable (see Figure 7). The representation of the converter is based on the following assumptions [7]:

1. The direct current I_d is ripple – free
2. The AC interconnected systems are symmetrical systems with a balanced voltage source.
3. The converter transformers do not saturated.

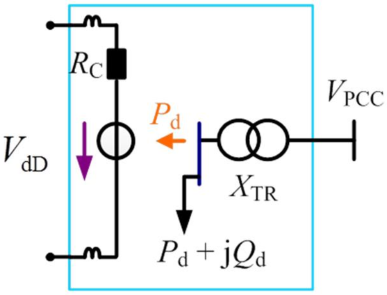

Figure 7. RMS model of investigated DR HVDC system.

The DC voltage V_{dD} can be calculated as:

$$V_{dD} = \frac{3\sqrt{2}}{\Pi} n_{BRD} n_{TR} V_{PCC} \tag{1}$$

where n_{BRD} represents number of DRU bridge, n_{TR} the transformation ratio, X_{TR} the transformer impedance and V_{PCC} is the voltage magnitude at the DRU PCC.

The corresponding commutating resistance is expressed by:

$$R_C = k_C \frac{3}{\Pi} n_{BRD} X_{TR} f_t / f_{REF} \tag{2}$$

where k_C is a correction factor $k_C = f(I_d)$. Ideally, $k_C = 1$. f_t and f_{REF} are the measured and reference frequency at PCC, respectively.

The DC voltage at DRU terminal can be calculated as:

$$V_d = V_{dD} - R_C I_d \tag{3}$$

where V_d and I_d are the DC voltage and DC current at the DC terminal of DRU system.

The active and reactive powers drawn by the DRU system at the secondary side of the DRU transformer can be estimated as:

$$P_d = V_d I_d \tag{4}$$

$$pf_D = \cos\Phi = \frac{V_d}{V_{dD}} \tag{5}$$

$$Q_d = P_d \,.\tan\Phi - \frac{18}{\Pi^2} n_{BRD} X_{TR} I_d^2 \tag{6}$$

Typically the RMS simulation is performed with a longer simulation time step compare to EMT type of simulations that is typically in the range of few milliseconds. Therefore several modifications are needed in the control system of WPP LSC in order to make the WPP model properly performing in RMS simulation. The parts of the WTG LSC control (described in previous subsection) that need to be adapted are:

1. Measuring system and measured signal filtering
2. Frequency lock loop
3. Voltage control
4. Fault-ride-through condition detection

The model adapted as mentioned above could then be utilized for RMS type of simulation which will represent the dynamic behavior of the Wind Power Plant similar to the EMT simplified model.

V. RMS MODEL VALIDATION

A. *Study cases*

To validate the equivalent RMS model of the DR HVDC system and the WPP LSC control system, two study cases were considered.

1. Power ramping case: Initially, the system is not loaded. At the time instant 0.5 s, the active power of WPP is ramped up to set point 0.9 p.u in 200ms. After that, at 1.5s, the active power of WPP is ramped down to zero again within 200 ms.

2. Three-phase short-circuits case (3PSC): A symmetrical fault with zero retained voltage lasting for 150 ms is applied at the AC terminal of DR HVDC.

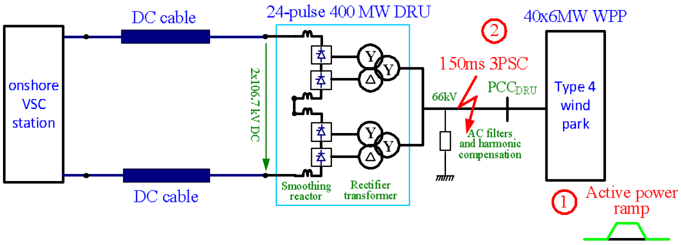

Figure 8. Description of the test cases 1 and 2.

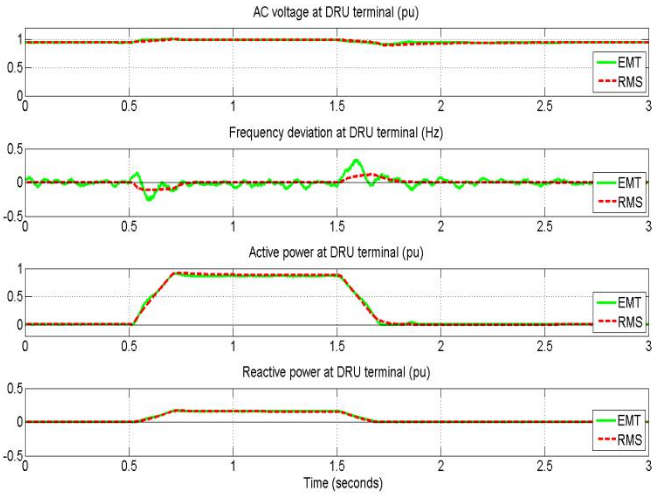

Figure 9. Power set-point change case: results recorded at DRU terminals.

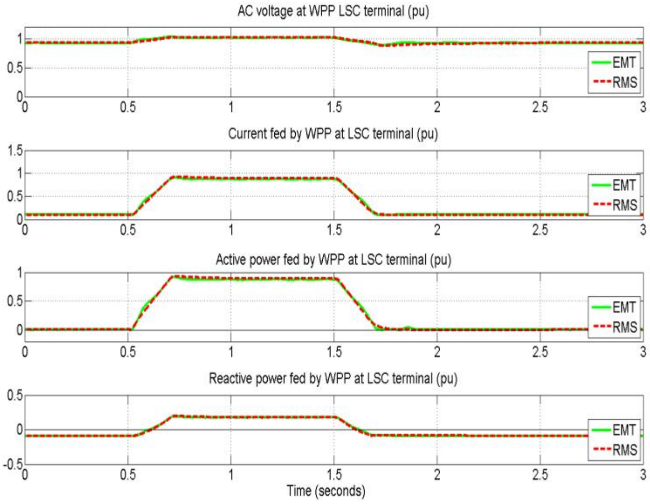

Figure 10. Power set-point change case: results recorded at WPP LSC terminals.

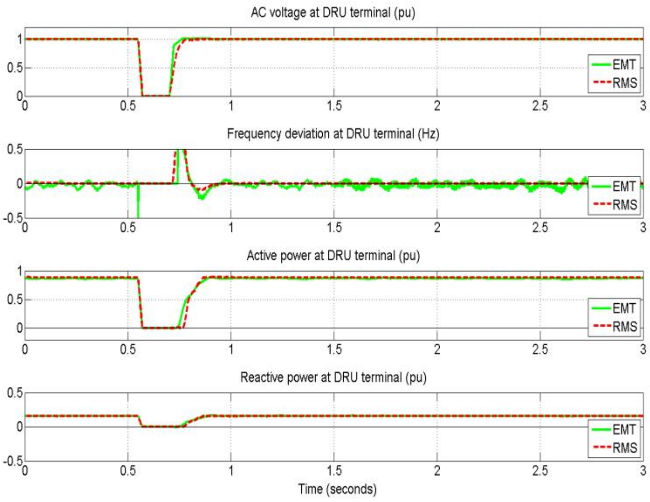

Figure 11. FRT of symmetrical fault - simulation results obtained at DRU terminals.

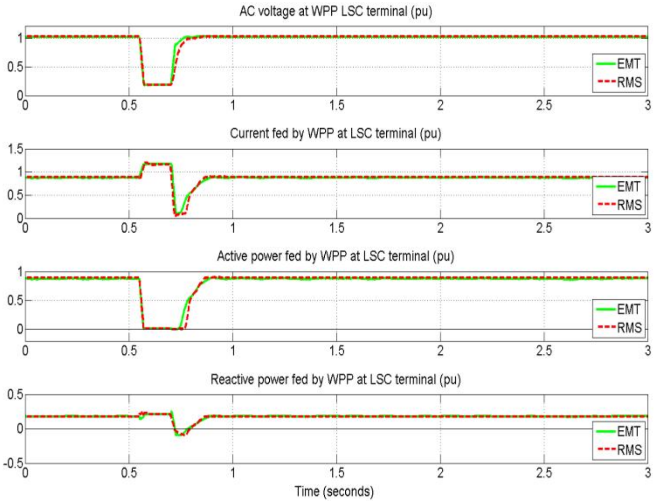

Figure 12. FRT of symmetrical fault - simulation results obtained at WPP LSC terminals.

The simulations with the EMT model were performed with the simulation time step of 0.001ms. The results of EMT (simplified) simulation were used as the reference for validating of the DR HVDC and WPP LSC equivalent RMS model tested by RMS simulations.

The simulation with the equivalent RMS model of DR HVDC system and WPP LSC were carried out using a special set-up. Thanks to a unique simulation capability of NETOMAC, it was possible to run a simulation with different partitions which run either in EMT mode or RMS mode. The RMS simulation was running with the simulation time step of 1 millisecond comprising all AC power system parts.

B. *Simulation results*

The simulation results for the two investigated cases are presented in the Figures 9-12. The system responses, including AC voltage, frequency, active and reactive powers at DRU AC terminal, as well as AC voltage, current, active and reactive powers injected from WPP at the controlled bus. The results obtained from EMT simulation are plotted in green color (solid line) while the results of the RMS simulation are in red (dashed line).

The comparison of the RMS and EMT calculations shows very good match of the simulation results. The equivalent RMS model closely captures the transient excursions of the AC voltage, frequency and active/reactive power drawn by DR system or power flow from WPP LSC station.

VI. CONCLUSIONS

The presented work describes the detailed and simplified EMT level simulation models of the DR HVDC transmission solution which is also known as New Grid Access (NGA) technology. Based on the EMT model, the simplified RMS model has been deployed and validated by several test cases. From the comparison of the EMT and the RMS simulation results could be concluded that RMS model of DR HVDC grid connection solution shows very similar dynamic behavior as EMT domain model and thus it is sufficiently accurate for utilization in large scale dynamic power system studies.

Recommendations for future work on RMS model development:

- The detailed knowledge of the WTG converter control functionality is a prerequisite for the successful RMS model development.

- The reference frame shall be adequately considered including representation of the power system frequency calculation.

- FRT response in RMS domain shall be reconstructed based on RMS monitored quantities.

- Better agreement of the EMT and RMS simulation results can be achieved when the difference (deviation) between nominal and system frequency is small.

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