Setup and Performance of the Real-Time Simulator used for Hardware-in-Loop-Tests of a VSC-Based HVDC scheme for Offshore Applications

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***Abstract*-- This paper describes the setup and demonstrates the performance of a real time simulator, used for Hardware-In-the-Loop (HIL) testing of the control and protection systems of VSC-based HVDC schemes based on Modular Multilevel Converter (MMC) topology. The HVDC scheme referenced in the paper connects offshore wind parks in the North Sea to deliver electric power to the German mainland. The main challenge of the paper is to demonstrate the required balance between the following:**

a) the exact and accurate simulation of the network necessary to thoroughly test and prove the performance of the HVDC controls

b) the acceptable level of detail and complexity for the converter and the wind farm representations to optimize the amount of simulator hardware necessary to conduct the tests

Modular Multilevel Converters (MMC) present a major challenge for real time simulation due to the high number of submodules and the massive I/O requirements for HIL tests. Additionally the detailed representation of the wind farms including individual wind turbines increases the requirements on the simulator within the presented offshore application. Due to these issues it was decided to decrease the demand on computing power by using equivalent circuits and/or simplified models.

***Keywords*: Real-Time Simulator, Hardware in Loop Simulation - HIL, Modular Multilevel Converter - MMC, Offshore Wind Farm**

I. Introduction

IN Germany several offshore wind farms are planned or under construction in the North Sea to support the switch from nuclear to renewable electrical energy sources within the next 10-20 years. For the connection of the wind farms to the German mainland, VSC based converters are used. The VSC based converters have black start capability for the energisation of the offshore station, a compact design and they minimize the energy losses relative to AC cable connections. The VSC based HVDC converters also offer additional benefits compared to conventional HVDC systems such as independent control of active and reactive power [1], [2].

The factory testing of control systems for the VSC-based HVDC schemes employs both offline simulation programs as well as real time simulators. During these tests various fault scenarios and system operating points are tested in the laboratory without any risk of damage and before onsite installation.

Unlike the offline simulations, the real time simulators are connected to the physical control and protection system for Hardware-In-the-Loop (HIL) tests using the actual hardware and software of the HVDC system.

Siemens AG in Erlangen, Germany will deliver several VSC-based HVDC schemes for offshore applications in the next few years. To support these projects a real time simulator facility has been constructed in the Erlangen test center to perform the Functional- and Dynamic Performance Tests (FPT/ DPT). The FPT focuses on the overall functionality of the HVDC scheme including switching sequences, steady state performance as well as active- and reactive power ramps, whereas the aim of the DPT is to analyze the interaction between the AC and DC systems as well as to verify the proper converter control and protection behavior under dynamic and transient conditions.

Within these factory tests the real time simulator is used to run all FPT tests and parts of the DPT tests, while the offline simulations focus on DPT tests. At the start of the DPT tests, comparisons are done to verify the simulation results and the software versions of both the offline and real time simulations. Typically some step responses, steady state operating points and AC faults are compared before the official tests are begun.

The paper will first introduce the software and hardware setup of the real time simulator. Next the paper will discuss suitable simplifications for the converter and wind farm representations for usage in the HIL tests. The paper will address the difficulty of having the model fulfill the different requirements of the individual tests that must be performed by the simulator (e.g. sequences, steady state operation as well as

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Paper submitted to the International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada July 18-20, 2013.

transient faults). The results of the tests will be presented and verified by comparing to offline simulation results. The comparison demonstrates a very good correlation between the real time HIL simulation tests and offline simulation.

It is notable that some parts of the model, for example the wind farm, were simulated in more detail in the offline model. Therefore the close correlation of the results gives a good benchmark, especially for the simplification techniques used in the real time simulation.

Finally the performance of the real time simulation and the quality of the results will be evaluated and summarized. The limitations of the equivalents and simplified models applied will also be discussed.

II. Simulation Setup

The RTDS® Simulator platform from RTDS Technologies Inc. was chosen for the simulation facility. The RTDS Simulator has been successfully used by Siemens for many years to conduct HIL testing of conventional HVDC and FACTS systems.

A. Hardware

The newest hardware generation of RTDS Simulator was used and consisted of two racks, each equipped with six PB5 processor cards. The PB5 card includes two PowerPC RISC processors operating with a clock frequency of 1.7 GHz. Contrary to earlier generations of processor cards the PB5 allows up to 8 communication paths to other PB5 cards for the connection of small timestep subnetworks [3].

The connection of the control and protection system to the simulator is established using digital and analogue input and output signals provided by the GTIO card family. These cards guarantee low latency of the signals and provide a large dynamic range for the analogue signals because of the 16-bit resolution [4].

B. Software

The simulation includes the HVDC PLUS converters and equivalents of the offshore and onshore AC networks. While the onshore network is built up as an AC source with only a series connected short circuit impedance, the offshore network includes the actual high voltage network up to the high-medium voltage transformer. The medium voltage network contains one equivalent transmission line connecting scalable equivalent models of a Doubly Fed Induction Generator (DFIG) or a Full Converter Synchronous Generator (FCSG) according to the project requirements. The representation of the models is discussed in the next chapter. The single line diagram of the simulated system is shown in Fig 1.

In the real time simulation, the converter stations and the connecting DC cable are simulated in three separate small timestep networks [5]. The three subnetworks are connected on the DC side through travelling wave transmission line models with a travel time in the range of the small timestep size (i.e. ~3μs). Both converter stations are interfaced to the AC systems with the help of interfacing transformers connecting the small and the normal timestep areas. The onshore AC system is simulated with a normal timestep in the range of ~60μs, whereas the offshore AC system is simulated partly in the small timestep area and partly in the normal timestep area. Each wind turbine is calculated in its own small timestep subnetwork.

III. Suitable Simplifications

A. Onshore AC Network

In the real time simulation the onshore AC network is built up as an AC source with a series connected short circuit impedance. The performance of the original control and protection hardware and software is verified against the offline simulations using a subset of tests with only an AC source at the onshore station. Results from the real time and offline simulations are compared to prove the performance of the control and protection system is consistent across a wide range of operating points and contingencies. Additional tests with a more detailed AC equivalent are carried out in the offline simulation. The detailed AC equivalent is derived from a network reduction study and verified with the original AC network without the HVDC scheme.

However, if it were necessary to build up a larger AC network representation of the onshore system for the real time tests, it would be relatively easy using additional simulator hardware.

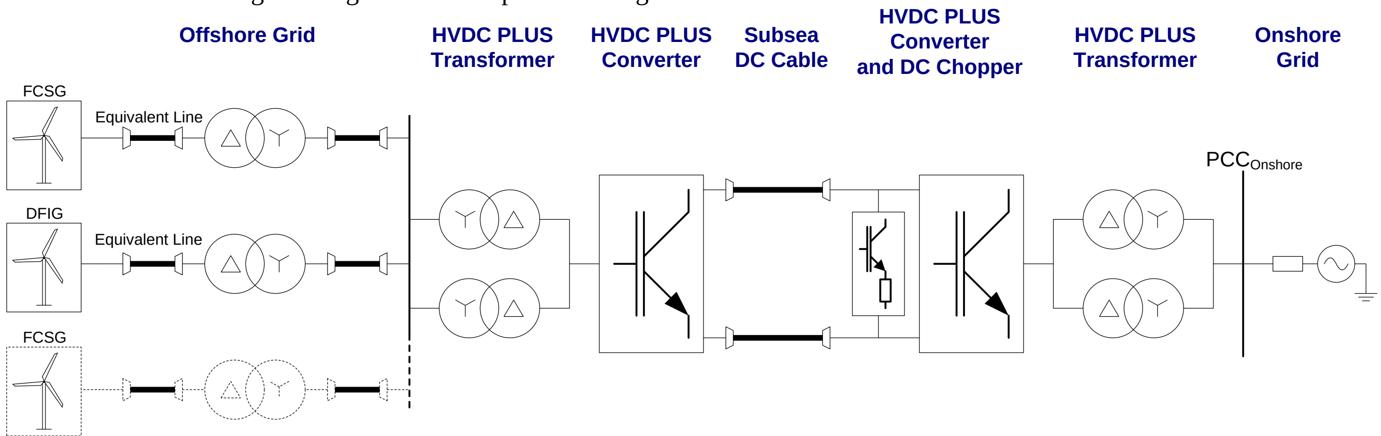

Fig. 1. VSC-based HVDC-Scheme to connect offshore wind parks to the German Mainland

B. MMC Converter

Due to the fact that the detailed simulation of the MMC requires a very high number of submodules and a massive amount of I/O, Siemens reduced the amount of hardware needed by using an equivalent circuit for the converter. The equivalent is used in the real time simulation as well as in the offline simulation and helps to reduce the necessary computing power. Each of the six converter arms per station is simulated by a virtual phase module.

The algorithm used to represent each converter arm within the RTDS simulation (the same is used for the offline simulation) is a simplified version of the series-connected power modules used in the physical HVDC PLUS scheme. The main simplification is that only the average capacitor voltage is calculated by the algorithm, i.e. it is assumed that all sub-modules within each phase module are balanced. In order to save processing power, adopting such a simplification is a definite advantage.

The virtual phase module is comprised of two basic parts; the electrical circuit (Fig. 2) on the one hand and the calculation of the voltages (Fig. 3) for the two phase module sources on the other.

In [2] it is described that the submodules can in principle only have three different states:

i. "Blocked" state (passive load)
ii. "On" state (voltage of capacitor is applied to the submodule terminals)
iii. "Off" state

V_{ON} represents the sum of all capacitor voltages of the submodules in the "On" state, whereas V_{BLK} includes the sum of all Capacitor Voltages in the "Blocked" state. If a module is in the "Off" state it is irrelevant for the simulation and will not be considered because it is electrically disconnected.

Equation (1) summarizes the calculation of the average capacitor voltage of the virtual phase module which is the base for the further calculation of the voltages for the virtual phase module sources.

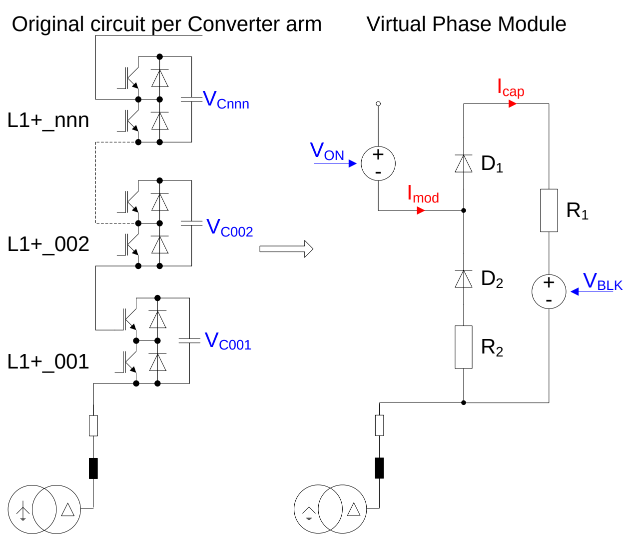

Fig. 2. Original electric circuit and Virtual Phase module electric circuit

$$V_C(t) = \frac{1}{C_{sub} \cdot N_{nominal}} \int \left(N_{blk}(t) \cdot I_{cap}(t) + N_{on}(t) \cdot I_{mod}(t) \right) dt \quad (1)$$

where $N_{nominal}$ is the number of submodules in one converter arm, N_{blk} is the number of submodules in the blocked-state and accordingly N_{on} the number of submodules in on-state. N_{blk} equals 0 if the converter is deblocked and equals $N_{nominal}$ if blocked. The integration time constant is defined as follows

$$T = C_{sub} \cdot N_{nominal} \quad (2)$$

Fig. 3 illustrates the voltage calculation within the phase module.

At this point the next advantage of using the phase module becomes apparent. Instead of receiving the individual firing pulse information for each submodule from the physical control, the simulator receives only the number of submodules in blocked- and on-state which massively reduces the amount of I/O necessary. The information regarding the state of the submodules is sent from the Module Management System (MMS) of the Converter PLUS Control where the information is already available.

The fact that only one average capacitor voltage per converter arm is calculated in the simulation is not a limitation because the individual capacitor voltages are calculated within the MMS for test purposes. From this calculation the maximum and minimum measured capacitor voltages, V_{Cmax} and V_{Cmin}, of each converter arm are selected which is necessary for the testing of some protection functions.

The virtual phase module leads to only one significant limitation regarding the testing of protection functions. Fault scenarios in one individual submodule or within one converter arm are not possible. All other tests are in principle possible.

The solution with the virtual phase module has been verified during the onsite tests of the first commercial HVDC PLUS application, the Transbay Cable project, which has been in commercial operation since 2010.

The braking chopper is simulated in a similar manner, but taking into account the additional resistance of the chopper circuit.

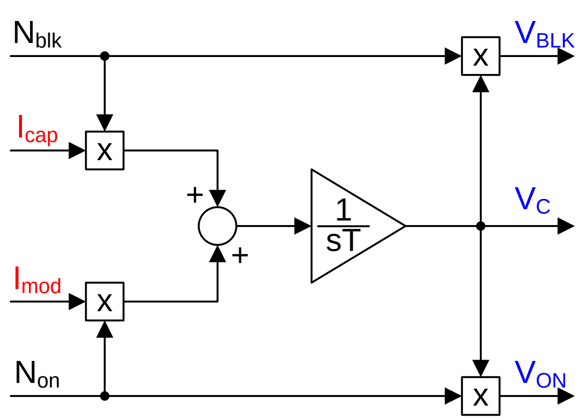

Fig. 3. Capacitor Voltage Calculation

C. Offshore Wind Farm

For the offshore wind farm representation it was decided to build up generic wind turbine models of DFIG as well as FCSG configurations to be independent of any specific wind turbine manufacturer. This approach was adopted because the customization of the wind turbine models from project to project would be highly resource intensive and deliver only a small benefit since all the machines in the current projects are designed to meet the same grid code. Additionally it would be difficult to obtain and maintain detailed information about the wind turbine controls from numerous manufacturers.

Both machines are based on the state of the art principles except for the fact that the converters are controlled by the current reference pulse width modulation (virtual converter) instead of using IGBT based power electronic back-to-back voltage-sourced converters [6], [7]. The equivalent machines comply with the grid code of the system operator and can operate in voltage or in reactive power control mode. The machines are connected through a transformer to the wind farm medium voltage network.

The wind farm representation was simplified in the following manner. The machine transformer current injection on the wind farm medium voltage side is scaled by a factor to simulate a larger number of wind turbines, but only one machine is represented in the simulation. The same type of "scalable" transformer is part of the E-TRAN user library in the offline simulation tool PSCAD [8]. The scale factor only influences the w1 winding current, which is controlled by a dynamically changeable scaling factor (SF). The voltages are defined by the windings turn ratio and not by the SF. The principle is shown in Fig. 4. Iw1 is the un-scaled value of one machine on the primary side of the transformer, whereas Iw1scale includes the number and rating of the turbines included in the equivalent, summarized in the value of SF.

The scalable transformer is used in the offline simulation as well as in the real time simulation. The implementation of one wind turbine requires a minimum of two PB5 processors for the electrical system and up to one processor for the control system depending on its complexity. From this it is clear that only a limited number of these equivalent machines can be simulated to maintain a reasonable balance on the processing requirements. It was decided to combine 40 or 80 machines (depending on the number of wind farms connected) into one equivalent machine for the real time simulations. This meant 3-4 equivalent machines were implemented in the RTDS Simulator for the factory tests.

When simplifying the model it was understood that the simple wind farm model is not suitable to investigate harmonics in the offshore network. The harmonic investigation was left to other studies using suitable tools. Additionally it is not possible to perform realistic tests in the medium voltage wind farm network since it was represented as an equivalent. However this is not of interest for the DPT of the HVDC PLUS scheme. All models have been developed with the purpose of testing the performance of the HVDC system during AC-Faults at the Point of Common Coupling (PCC) of the onshore and offshore grids.

Besides the limitations regarding harmonics and medium voltage network faults, the generic wind turbine models can be used for all FPT/DPT tests including the black start sequence, power limitation by AC network frequency, step responses, AC faults at the PCC's, etc.

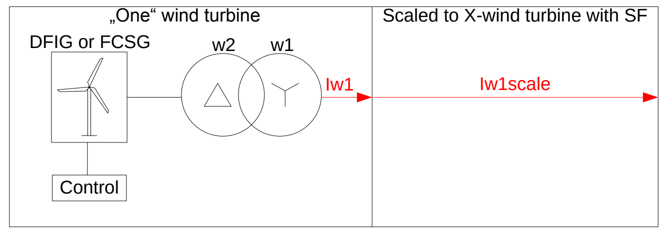

Fig. 4. Position of wind turbine scaling

IV. Validation

Two tests have been selected from the DPT to demonstrate the good correlation between the results in the offline simulation and the RTDS Simulator in combination with the physical control and protection system. Siemens uses the electromagnetic transient simulation program PSCAD® for the offline portion of the DPT tests as well as for the further support of onsite commissioning.

Figure 5 shows the results from both the offline and real time simulation tools for a solid 3-phase to ground fault for 150ms at the $PCC_{Onshore}$. It demonstrates the good correlation between both simulations especially regarding the response of the HVDC converter. The small deviation in the reactive power is caused by a difference in the representation of saturation.

The first graph shows the instantaneous- and the RMS-voltage at the $PCC_{Onshore}$ while the second graph displays the instantaneous- and the RMS-current out of the converter at the same point. The third graph shows the active power at the $PCC_{Onshore}$ as well as the DC-power of the onshore station. The fourth graph displays the reactive power of the HVDC scheme at the $PCC_{Onshore}$. The final two graphs show the converter DC voltage and the DC currents at the onshore station. During loss of connection to the onshore network the braking chopper consumes the power of the wind farms connected. All values are displayed in p.u.

To be sure that the wind farm equivalent in the RTDS Simulator delivered reasonable results it was benchmarked against a project modeled in PSCAD. The PSCAD model was comprised of the HVDC system, a large number of individual machines as well as some combined machines and the wind farm cabling.

The results of the benchmark tests were so encouraging that in subsequent projects the simplified model was also used for the control and protection studies in PSCAD. This optimization resulted in shorter execution times for the offline simulation tests.

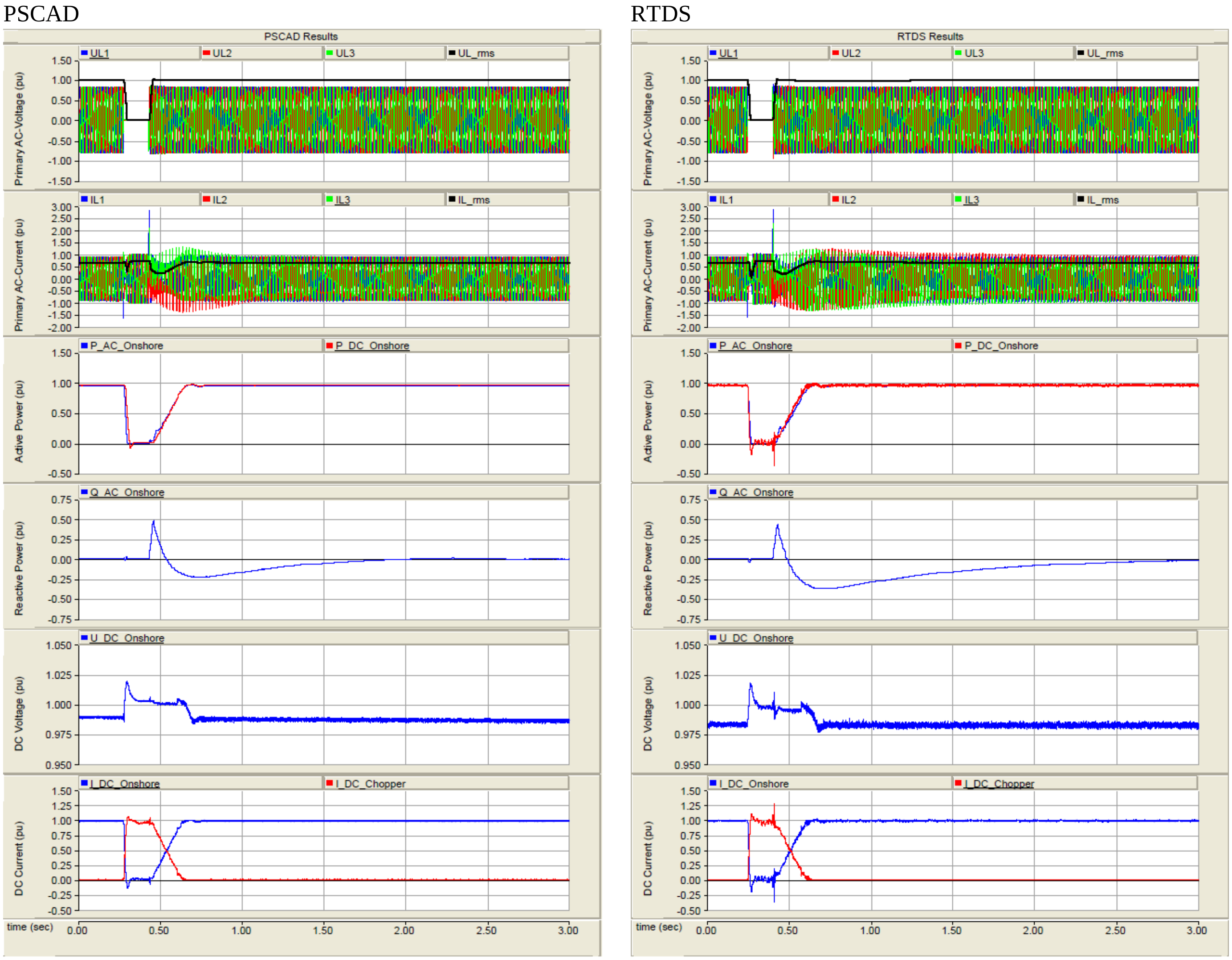

Fig. 5 Comparison of Simulation results from PSCAD and RTDS for a solid 150ms three Phase to Ground fault on the Onshore AC-Bus bar

Figure 6 on the next page displays the results of the benchmark for the wind farm on the basis of a solid 3-Phase to ground fault for 150ms at the offshore station common AC-bus.

The first graph shows the instantaneous- and the RMS-voltage at the offshore station. The second graph displays the instantaneous- and the RMS current into the converter at the same point while the third graph shows the active- and reactive power. All values are again displayed in p.u.

V. Conclusions

The paper demonstrated the required balance between accurate simulation of the VSC-based HVDC scheme and acceptable simplification of the models to optimize the amount of simulator hardware necessary to conduct the FPT/DPT tests using the RTDS Simulator.

Suitable simplifications, particularly of the converter and the wind farms, have been developed and discussed that meet the requirements of the different test groups. The pertinent limitations of the simplified models presented have also been discussed.

As validation of the simplified models, results from two tests have been shown comparing offline simulation using PSCAD with the HIL simulation. The very good correlation of the results demonstrated that the performance of the RTDS Simulator was suitable to perform the factory tests for the physical HVDC control and protection system with only minor limitations. In turn the simplifications applied optimized the amount of hardware required for the real time simulation as well as the complexity of the complete test setup.

PSCAD RTDS

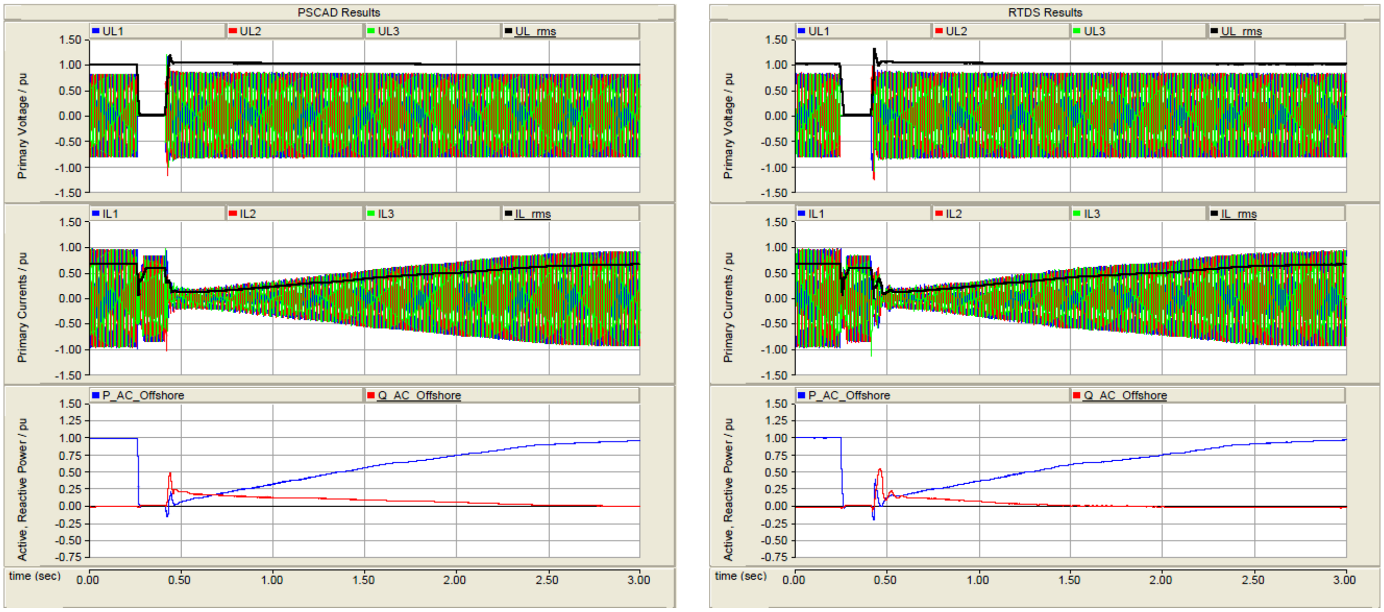

Fig. 6 Comparison of Simulation results from PSCAD and RTDS for a solid 150ms three Phase to Ground fault on the Offshore AC-Busbar with a more simplified Wind farm representation in RTDS.

VI. References

[1] H. Koch, D. Retzmann, "Connecting Large Offshore Wind farms to the Transmission Network", IEEE, T&D Conference, New Orleans 2010

[2] M. Davies, M. Dommaschk, J. Dorn, J. Lang, D. Retzmannn, D. Soerangr "HVDC PLUS – Basics and Principle of Operation" Technical Article publishe by Siemens AG 2011

[3] RTDS Hardware Manual chapter 12 "PB5 Processor Card", April 2010 rev.00

[4] RTDS Hardware Manual chapter 7-10, January 2009 rev.00

[5] T.L. Maguire and W.J. Giesbrecht, "Small Time-Step (<2µsec) VSC Model for the Real Time Digital Simulator" in *Proc. IPST 2005,Montreal Canada, June 2005*, Paper No.IPST05-168-25c

[6] N. Quang, J. A. Dittrich „Vector Control of Three-Phase Ac Machines", Springer publication Berlin Heidelberg 2008

[7] D.M. Brod, D.W. Novotny "Current Control of VSI-PWM Inverters" IEEE Transactions on Industry Applications, Vol. IA-21. No. 4, May/June 1985

[8] E-TRAN User Library: http://www.electranix.com/E-TRAN/

VII. Biographies

Oliver Venjakob received the Dipl.-Ing. degree in Electrical Engineering from the University of applied science Bielefeld, Germany in 2000. After graduating he worked for several years as system engineer in the Real-time simulation department at Siemens AG, Erlangen. His expertise area is the real-time simulation and testing for conventional HVDC systems and modular multilevel converter (MMC) for HVDC PLUS. Currently he is the head of the real-time simulation department.

Sascha Kubera received his Dipl.-Ing. degree in electrical engineering from Kaiserslautern University of Technology, Germany in 2008. After graduating he joined Siemens AG as system engineer for Control & Protection Studies. He is experienced in real-time and offline simulation of HVDC and SVC PLUS systems. Now his focus is on control studies of HVDC PLUS projects and research of control concepts for HVDC VSC technology.

Richard Hibberts-Caswell graduated from the University of Durham in 2005 with an MEng in General Engineering, specializing in Electronic and Computer systems. He joined Siemens in the UK in 2006 and since 2011 has been working in the real-time simulation department at Siemens AG, Erlangen. He is experienced at designing and testing C&P systems for transmission networks and wind farms and has recently been focused on the real-time simulation of HVDC PLUS for offshore wind farm connection.

Trevor Maguire graduated from the University of Manitoba with B.Sc.EE, LL.B., M.Sc.EE and Ph.D. degrees in 1975, 1979, 1986, and 1992 respectively. Relevant employment experience includes time with Manitoba Hydro (1975-76), Manitoba HVDC Research Centre (1986-1994), and RTDS Technologies, Inc. (1994-present). He is a founding principal of RTDS Technologies, Inc. with a special interest in real time simulation model development and also real-time simulation digital hardware development. He participated in creating the world's first commercial real-time digital power system simulator.

Paul Forsyth received his B.Sc. degree in Electrical Engineering from the University of Manitoba, Canada in 1988. After graduating he worked for several years in the area of reactive power compensation and HVDC at ABB Power Systems in Switzerland. He also worked for Haefely-Trench in both Germany and Switzerland before returning to Canada in 1995. Since that time he has been employed by RTDS Technologies where he currently holds the title of Marketing Manager / Simulator Specialist.