Dynamic Characteristics Analysis of Wind Farm Integrated with STATCOM Using RTDS

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Abstract— **This paper concentrates on design and analysis of STATCOM connected at the wind farm terminal in real time environment using Real Time Digital Simulator (RTDS). This work is a part of power hardware-in-loop (PHIL) test required in a future project, and therefore, individual components are models in such a way that is close to real system. For the sake of detail analyses and future study, the system is simulated in two ways. First method is a dual time step approach, where wind turbines and generators of a wind farm, power grid, and control system are realized in the large time-step main network, however, 2-level voltage source converter based STATCOM is modeled in RTDS small time-step environment to adapt with higher switching frequency, where interface transformer is used to link the different time step sub-networks. In the second method, the entire system including the STATCOM is simulated in large time step. Detailed switching scheme for STATCOM and control strategy for both methods are discussed. An option for integrating anemometer for dynamic characteristics analysis is kept open, difficulties of STATCOM switching schemes for control prototype and PHIL testing in RTDS environment are discussed. The merits and demerits of both methods are also presented which is one of the salient features of this study. Results of RTDS are compared with Laboratory standard power system software PSCAD/EMTDC and the features of using RTDS in dynamic characteristics analyses of wind farm are also discussed.**

Keywords- Dual time step approach, RTDS, STATCOM, voltage source converter (VSC), wind energy, PSCAD/EMTDC.

I. INTRODUCTION

Wind is the fastest growing and most widely utilized of the emerging renewable energy technologies in electricity systems at present, with a total of 120.8 GW installed worldwide at the end of 2008 [1]. From recent statistics, it is easily predictable that a large amount of wind power is going to be connected to the power grid, in sooner future. Though variable speed wind generator is becoming popular these days, fixed speed wind turbine generator system which uses induction generator as wind generator has still good market value due to its simple, rugged and maintenance free construction. IG has the stability problem same as synchronous generator [2], which can be overcome using some reactive power compensating devices incorporating at wind farm terminal.

A voltage or current source converter based FACTS devices, such as Solid state transfer switch (SSTS), Dynamic Voltage Restorer (DVR), Unified power flow controller (UPFC), Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) have been used for flexible power flow control, secure loading and damping of power system oscillation [3-5]. Among those, STATCOM is a proven VAR compensating device which can be used to augment the dynamic and transient stability augmentation of wind farm [6-8], though this study is limited to only dynamic analysis.

In the earlier aforementioned studies, offline simulation technique is used to model and simulate the entire system. Typically, when performing offline simulation, the objective is to obtain results as fast as possible. The system solving speed depends on available computation power and the system's mathematical model complexity. Offline simulation technique is not suitable for dynamic characteristics analysis of the system where power converter devices are part of the system, especially when detailed switching model is used to model the power converter using high switching frequency.

This study is conducted in real time digital simulation environment using real time digital simulator (RTDS) to perform dynamic characteristics analysis of wind farm composed of fixed speed wind generator, where STATCOM is considered as VAR compensating tool. This study also aims future control prototype and power hardware-in-loop (PHIL) testing of STATCOM to determining its optimum capacity for stabilizing wind farm under random wind fluctuation or grid fault conditions.

Real time digital simulator (RTDS) is a novel simulation tool for real time simulation, prototype, and hardware-in-loop testing. It can allow physical devices to be connected with it, e.g., in this case study, anemometer for real wind speed measurement, and voltage/current source converters, protection relay, etc. Moreover, it also provides accurate, fast, reliable and cost effective study of power systems with complex High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) [9-12]. In renewable power sector, the RTDS can extensively be used for advance research work due to its bidirectional input/output handling capacity between RTDS simulation and external devices [13-16].

In this study, the entire grid connected wind farm including STATCOM is modeled in two ways for the sake of future study. First one is the dual time-step approach where both small and large time steps are used. STATCOM modeling and control is implemented in the RTDS/RSCAD environment using small time-step which interact with rest of the components in main network running at large time-step using interfacing transformer. In the second method, the entire system including STATCOM is modeled only in large time

step. The cascaded control scheme is used as the control method of the STATCOM in both methods. The switching schemes for STATCOM in both methods are demonstrated in detail, so that those can be used in control prototype and PHIL testing. The results of both methods are compared with the results obtained from laboratory standard power system simulator, PSCAD/EMTDC [17]. The merits and demerits of dual and large time step approaches are investigated and reported, which is one of the salient features of this study. Advantages of using RTDS over offline simulation scheme in dynamic analysis of wind farm are also demonstrated, in this study.

II. Real Time Digital Simulator (RTDS)- A Brief Overview

A. Hardware

Real time digital simulator hardware is based on the parallel processing architecture and has been designed specially to solve the electromagnetic transient simulation algorithm. RTDS simulator consists of multiple RACKs, each of which consist of both communication and processor cards and are linked by a common backplane. To solve a large power system network, it is possible to split the entire power system into parts and these parts can be solved on the different subsystems or even using different racks on the RTDS simulator. Each rack has an Inter Rack Communication (IRC) card which allows the information to be shared between the different racks of RTDS. This study is carried out on RTDS consist of 3 RACKs.

Each rack has also a Workstation Interface (WIF) card which synchronizes the simulation calculations and communicates between different processor cards, as well as communication between different racks of the RTDS simulator. Also WIF card provides Ethernet communication to and from the graphical user interface during real time simulation.

The processors cards are responsible for the calculation of complete network behavior. RTDS uses two different processor card, 3PC (Processor card) and GPC (Gigabyte processor card). GPC contains 2 RISC processors running at 1GHz. Due to their computational power, they are often used in more than one component model calculation at the same time. It is noted that PB5 processor card, the next generation of GPC card is available in market from 2011, which has additional computation power and communication flexibility.

Besides that, RTDS has a family of GT I/O cards. They are used with the GPC cards. GT I/O cards include analogue and digital input and output with 16-bit data converters. Other physical devices can be connected to the RTDS hardware by GT I/O cards [10,12].

B. Software

The graphical user interface between RTDS hardware and user is done by its own software, called RSCAD. It allows simulation circuit to be constructed, run, operated and results to be recorded. The RSCAD has 2 main modules, the Draft and the Run time. In Draft, an extensive library for both power system and control system components is available. The

circuit can be constructed by copying the generic components from the library. After completion of the circuit, it will be complied in order to create the simulation codes required by the RTDS simulator. The simulation can be run using RSCAD Run Time module. Run time, operates on a PC or on workstation, back and forth communication with the WIF card through Ethernet. Simulation result can be plotted and operating condition of the system can be changed in run time by using switches, push buttons, etc., like the real world electric control rooms. A special module exists in RSCAD, so called T-LINE module, facilitate entry of transmission line data. Input information is related to the line geometry and conductor type. Multi-plot is used to analyze the graphical results and also to prepare it in report ready format. Several functions are available e.g, Fourier analysis and Total Harmonic Distortion computation. [9-11].

III. Wind Turbine Modeling

The extracted power from the wind turbine can be expressed by the following equation [18]

$$P_w = 0.5\pi\rho R^2 V_w^3 C_p(\lambda,\beta) \quad [W] \tag{1}$$

Power coefficient, C_p and tip speed ratio, λ can be expressed by the following equations [19],

$$C_p(\lambda,\beta) = 0.5(\Gamma - 0.02\beta^2 - 5.6)e^{-0.17\Gamma} \tag{2}$$

$$\lambda = \frac{\omega_r R}{V_w} \tag{3}$$

$$\Gamma = \frac{R}{\lambda}\frac{3600}{1609} \tag{4}$$

The turbine torque and torque coefficient are expressed by the following equation

$$T_m = 0.5\,\pi\rho R^3 V_w^3 C_t(\lambda) \quad [NM] \tag{5}$$

$$C_t(\lambda) = \frac{C_p(\lambda)}{\lambda} \tag{6}$$

Where ρ is the air density [m], R is the radius of the wind turbine blade [m], V_w is the wind speed in m/sec, β is the pitch angle in degree, ω_r is the rotational speed in rad/sec, and T_m is the wind turbine torque in Nm. The conventional pitch controller has been used in this study, showed in Fig. 1. The principle of the pitch controller is to keep the output power of wind generator at rated level by controlling the blade pitch angle of turbine blade when the wind speed is above than the rated wind speed.
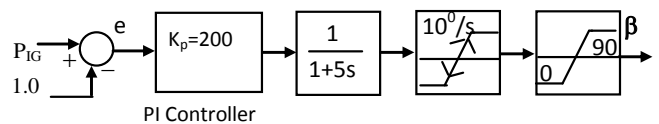

Fig. 1. Conventional Pitch controller

IV. REAL TIME SIMULATION SETUP

Fig. 2 shows the real time simulation setup required for this study. As discussed earlier, RTDS can be connected with other physical devices, an anemometer is considered to measure the wind speed data from the real site which will be sent to the RTDS via GT I/O cards. The wind speed signal will then be sent to RSCAD environment though workstation interfacing card and will be used in wind turbine model to produce torque for wind generator. Hence, this is the most accurate way of analyzing the behavior of wind turbine generator behavior at different operating conditions.
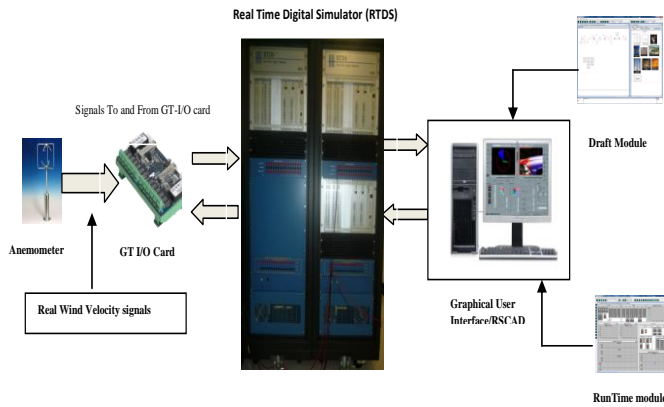
Fig. 2. Simulation block diagram

Fig. 3 shows briefly the different subsystems used to model grid connected wind farm where STATCOM is connected at the wind farm terminal. Grid synchronization using phase locked loop and control system are also modeled as subsystem. The modeling is completely done in RTDS/RSCAD environment.

In Fig. 4, RTDS modules and the processor assignments in dual time-step approach has been shown. Main power system components are solved on the 3PC card. The STATCOM has been modeled in the VSC small time-step network, which are solved on the GPC card. The control part is solved on the 3PC card. Carrier wave signal is generated in the large time-step and are imported in the small time-step after being adapted with small-time step. The carrier wave frequency is chosen 2
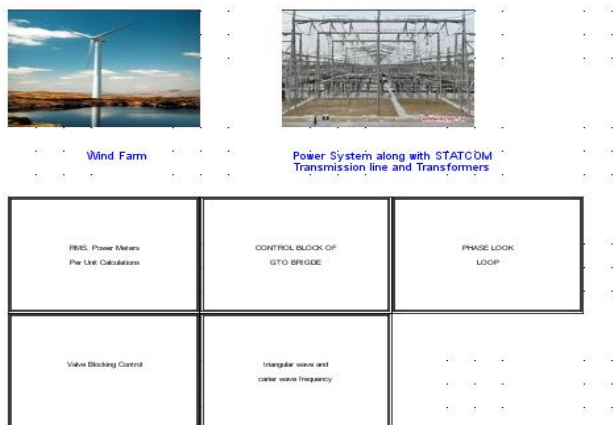

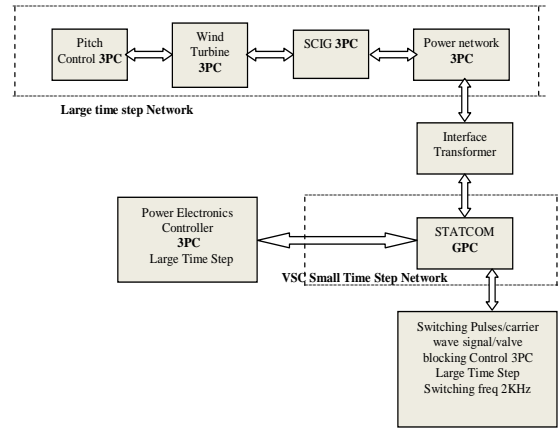Fig. 3. Modeling of the Fixed Speed wind Turbine Induction Generator in RTDS/RSCAD Environment

Fig. 4. RTDS Modules and processor assignments in dual time-step approach

kHz. Large time-step (typically running at 50µs) and small time-step (1µsec – 4µsec) is interfaced via interface transformer.

Fig. 5 shows the RTDS modules and processor assignments in large time-step approach. The power system components are solved on the 3PC card, while the control block is solve on the GPC card. GTO model is computed on the 3PC card. The switching is done on the GPC card. The advantage of using the GPC card is that it will reduce the time-step, while 3PC card requires almost 2 times time-step used in the GPC [12].
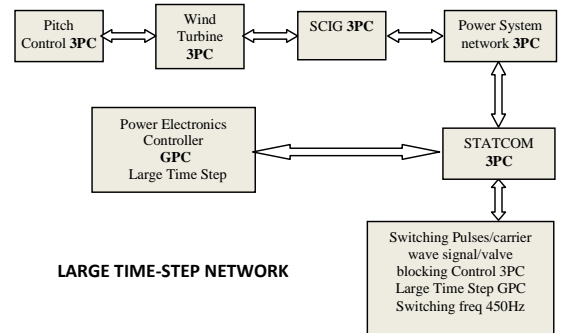

Fig. 5. RTDS Modules and processor in large time-step approach

Wind farm is simulated using aggregated model where many wind generators can be represented with a large wind generator. The parameters of the induction generator used in this study are chosen from [8].

V. STATCOM CONTROL STRATEGY

In this section, control strategy of STATCOM as well as switching scheme for both dual and large time-step approaches are discussed in detail.

A. Control Scheme

The control block diagram of voltage source converter (VSC) based two level STATCOM is shown in Fig. 6 The aim of the control is to maintain desired voltage magnitude at the wind farm terminals during normal operating condition and recover the voltage in shortest possible time after occurrence of grid fault. For the control of voltage source converter (VSC), the well-known cascaded vector control scheme is

used in the control of STATCOM. The dq quantities and three-phase electrical quantities are related to each other by reference frame transformation. The transformation angle is detected from the three phase voltages (V_A, V_B, V_C) at the connection point of STATCOM by using phase locked loop (PLL) system. With suitable adjustment of the magnitude and phase of the VSC output voltage, an efficient control of power exchange between the STATCOM and the ac power system can be obtained. The vector control scheme generates the three-phase reference signals which are used to generate the switching signals for the GTO switched STATCOM. The STATCOM rating has been considered as the same of wind farm rating. The rated DC link voltage is 6.6 kV. The STATCOM is connected to the 66 kV line by a single step down transformer (66 kV/3.6 kV) with 0.1 p.u leakage reactance. The DC-link capacitor value is 50000μF.
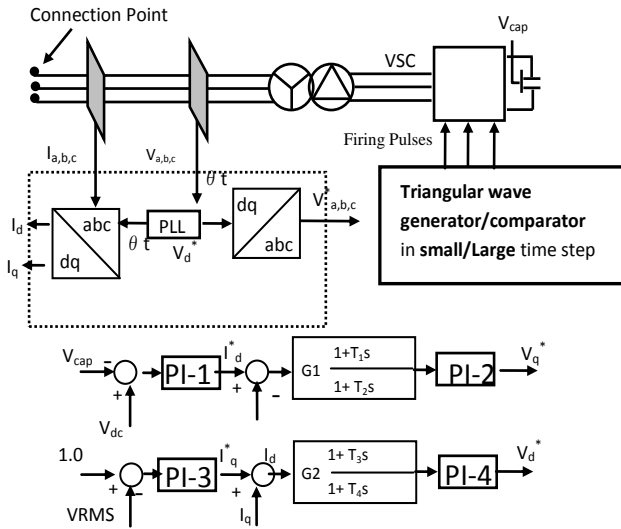

Fig. 6. Control block diagram of VSC based STATCOM

B. Switching Scheme in Dual Time-Step

Dual time-step operates in both small and large time steps. Small time-step VSC sub-network model including switching scheme is shown in Fig. 7. Using the principal of pulse width modulation scheme, the carrier and modulation signals are generated in the RTDS large time-step size environment and then processed to generate high resolution firing pulses using the RTDS firing pulse generator component in the small time-step environment [12]. In order to ensure accurate firing this component requires the transfer of reference phase and frequency from the large time-step environment. This allows the component to extrapolate the phase between large time-steps. The valves of the GTO bridge gets firing pulse input from the comparator by selecting the option CC_WORD of GTO bridge. The valves of the GTO bridge are controlled by the respected bits in a firing pulse word. These consecutive bits are aligned in such a way that the least significant bit (LSB) in the firing pulse coincide with the LSB in the final applied firing pulse word. Hence the first LSB

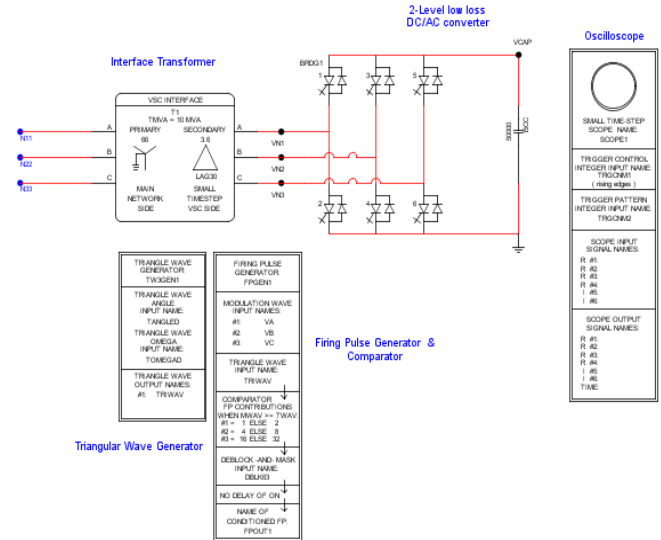controls the valve 1, the second LSB controls the valve 2 and so on. [12]

Fig. 7 Switching scheme for STATCOM in small time-step VSC sub-network (part of dual time step approach)

C. Switching Scheme in Large Time Step

For the large time-step, switching is done by using the pulse width modulation (PWM) technique. For GTO model, switching signal can be generated in two ways either by using one 6P Grp which will generate 6−bit firing pulse integer word (FP), one active bit integer word (FLAST) or by 3 LEG mode. In 3 LG mode there is one 2-bit firing pulse word, one active bit word and one fraction word for each separate leg in the valve group. In this work, switching is done by using 3 LEG mode. The switching diagram is shown in the Fig. 8.
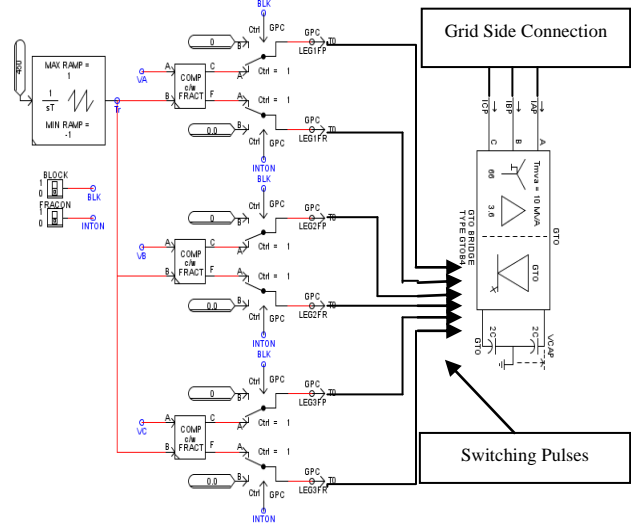

Fig. 8. Switching scheme for STATCOM in Large time-step approach

VI.   SIMULATION RESULTS

In this paper dynamic characteristic is analyzed when STATCOM is considered to be connected at wind farm terminal. Keeping in mind the future control prototype and PHIL testing, STATCOM is modeled in both dual and large time-step environment. Real wind speed data is measured, stored in data file, and used in RTDS environment using scheduler which will finally be replaced with advanced anemometer equipped with remote data logger. Realistic data is used in transmission line calculated from transmission line length which can be changed suitably with any wind farm site data in the next step. Line length is important because STATCOM voltage support set point is considered at the common coupling point. Results are also compared with PSCAD/EMTDC where time step is considered as 20 µsec and switching frequency is considered as 2000Hz. Detailed switching model is considered to model STATACOM in PSCAD/EMTDC environment to perform the time comparison.

A. Dynamic Characteristics Analysis

The analysis is carried out using 50 sec of wind speed data. Interpolation technique is not considered while using real wind speed data in the simulations using PSCAD/EMTDC and RTDS/RSCAD. Longer period can be considered based on the available memory resources. As the wind speed is changing randomly, In Fig. 9, the important responses using offline simulator PSCAD/EMTDC are shown, when STATCOM is considered to be connected at wind farm terminal. The wind farm terminal voltage cannot be maintained at constant value using only the capacitor bank of rated capacity. When STATCOM is used, terminal voltage of wind farm can be maintained at the desired level set by Transmission System Operators (TSOs), as shown in Fig. 9.

Fig. 10 and 11 shows the responses obtained using RTDS in dual and large time-step approaches, respectively. To match the switching frequency used in PSCAD/EMTDC, in dual time-step approach 2000Hz carrier frequency is considered. In Dual time-step approach, VSC sub-network is simulated using 1.5µsec and the other components are simulated in large time-step of 45µsec as it is required to run the simulation higher than the suggested minimum time-step by RTDS resolver. On the other hand, in large time-step approach, the time step chosen is also 45µsec for the sake of time comparison of both approaches. It should be noted that low switching frequency should be used in large time-step approach for generating the switching pulses for switching devices, which is considered as 450Hz in this study. In both figures, the step change around 10 sec represents the change of machine state from constant speed to normal operation. Figures 9 to 11 shows good agreement for IG real power, STATCOM reactive power, DC-link capacitor voltage, wind farm terminal voltage, and IG rotor speed responses, except the initial responses of first few seconds. However, dual time-step approach using RTDS gives smooth responses compared to large time step approach in RTDS and PSCAD/EMTDC, due the exact switching ability in the range of less than 2µsec.
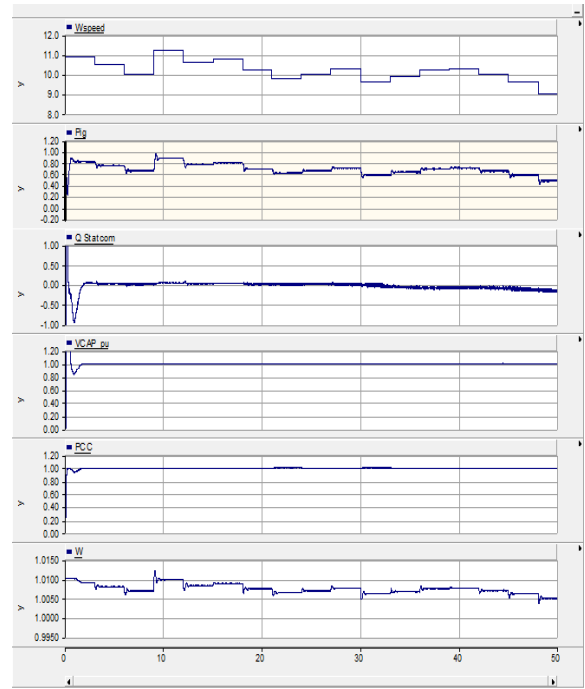

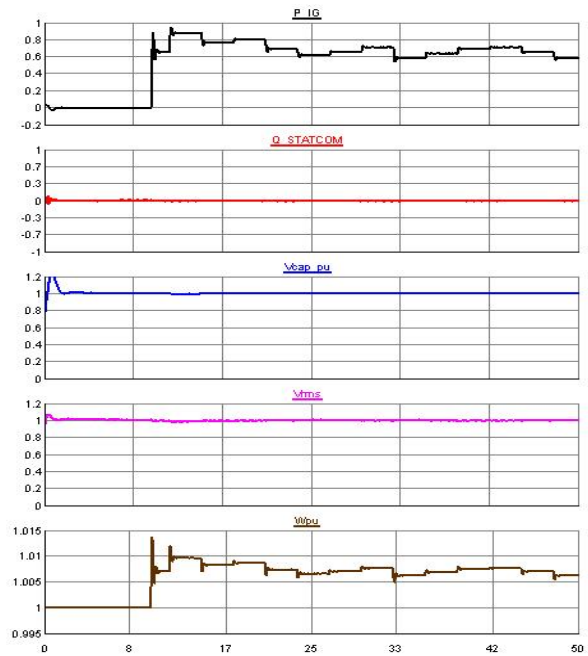Fig. 9. Responses obtained using PSCAD/EMTDC

Fig. 10. Responses obtained using RTDS (dual time-step approach)

A time comparison is carried out while analyzing dynamic characteristics using 50 sec of real wind speed data using both PSCAD/EMTDC and RTDS/RSCAD. Both dual and large time-step approaches require almost the same time of about 51sec to download and plot the result. However, in PSCAD/EMTDC a total time of 720 sec is required to finish the simulation of 50sec, though the program is simulated using 20µsec, which is lower than RTDS large time step. Therefore, it is quite difficult to perform dynamic analysis for longer time in the range of hour or day to determine the optimum capacity of STATCOM suitable for a real wind farm.
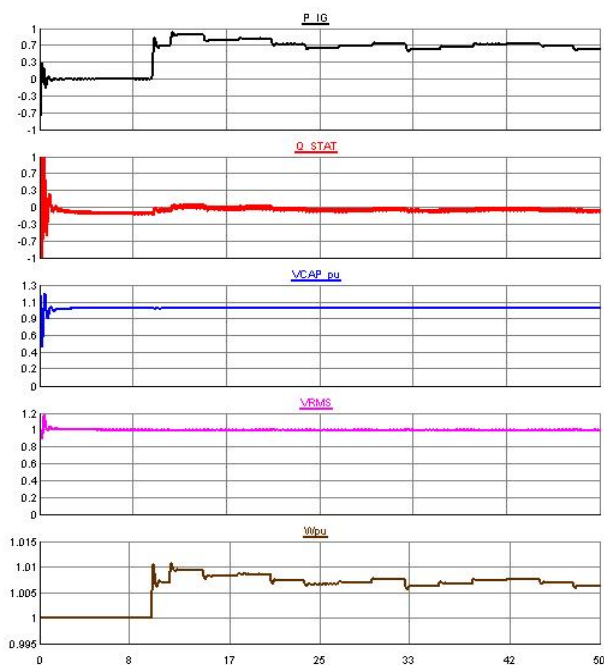
Fig. 11. Responses obtained using RTDS (large time-step approach)

VII. CONCLUSION

In this study, a detail dynamic analysis of grid connected wind farm integrated with STATCOM has been carried out using offline laboratory standard power system simulation tool PSCAD/EMTDC and Real Time Digital Simulator (RTDS). Detailed modeling, control, and switching scheme of STATCOM have been presented, suitable for wind energy conversion system. Dual (small and large) time-step approach and approach using large time step to simulate STATCOM in RTDS environment have been demonstrated. A comparative study has also been performed which are summarized as follows.

Offline simulation technique using PSCAD/EMTDC, MATLAB/Simulink, PSS are precise enough. However, the simulation takes much long time which is practically not feasible for the dynamic analysis in hour or day range, especially when detailed switching model is considered. RTDS is an effective tool for such type of analysis due to fast computation capability.

Dual time step approach is the most accurate method to simulate power converter in RTDS environment.

Dual time step approach is also good to conduct the loss analysis of power converters operated at higher switching frequency.

The system including power converters can even be simulated using large time step, which requires almost the same time of dual time step. The large time step VSC bridge available in RTDS/RSCAD library has Digital Time-Stamp (DITS) feature to handle switching pulses from real world or external DSP/MATLAB based system.

RTDS resources can be used in optimum way simulating power converter using large time-step approach in 3PC card,

when GPC card is fully utilized for dual time-step power converter simulation or other purposes.

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