Real-Time Implementation of BESS to Smooth the Output Power Fluctuation of Variable Speed Wind Turbine Generator

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(Manuscript received Jan. 18, 2013, revised Sep. 25, 2013)

In this paper, a grid connected variable speed wind turbine (VSWT) PMSG integrated with the NaS-type battery energy storage system (BESS) is modeled in the real-time digital simulator (RTDS) to analyze the performance in a real system. This study is also a part of the future power hardware-in-loop (PHIL) test; therefore, individual components are modeled from the practical standpoint. The wind turbine, power grid, and control system are modeled in the large-time-step main network; however, the wind generator (PMSG), frequency converter (FC), and BESS integrated with STATCOM are modeled in the RTDS VSC small-time-step network to take into consideration the higher-switching-frequency phenomena. The interface transformer is used to connect the different-time-step subnetworks. The option of integrating the anemometer is kept open for a future PHIL test. The simulation results are compared with those obtained from the laboratory standard power system software PSCAD/EMTDC to validate the model developed in the RTDS/RSCAD.

Keywords: PMSG, ESS, NaS, STATCOM, RTDS, PSCAD

1. Introduction

Renewable energy sources often produce power and voltage fluctuations with natural conditions (wind speed, solar irradiance, etc). However, electric utility grid systems cannot readily accept connection of new generation plant without strict conditions placed on voltage regulation due to real power fluctuation and reactive power generation or absorption, and on voltage waveform distortion resulting from harmonic currents injected by nonlinear elements of the plant⁽¹⁾. Fluctuating wind speed also causes the system frequency to deviate from the 50 Hz standard, as many protection relays have the frequency margin of 1%, which causes the malfunction of the power system protection equipment⁽²⁾. As a result, it has become the major concern for the Transmission System Operators (TSO) or the utility companies to resolve the wind power smoothing issue⁽³⁾⁽⁴⁾. Energy Storage System (ESS) is needed to smooth the intermittent output power fluctuations of the wind farm. A lot of choices for the ESS are present nowadays in the market, e.g., Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), Flywheel, Super Capacitors Energy Storage (SES), Superconducting Magnetic Energy Storage (SMES), Hydrogen Energy Storage System (HESS), Batteries Energy Storage System (BESS), etc, which are used to overcome the fluctuated wind farm output power⁽⁵⁾.

The choice of the ESS in the electric system network depends upon the desired application. To meet the electric power quality problems, energy storage with fast response rate and ability to charge/discharge many times is needed⁽⁶⁾. For the time scale of seconds-to-minutes, a suitable energy storage system is needed to have a good ramp rates, and, as discussed earlier, flywheel, super capacitors, and batteries might be a good option⁽⁷⁾. Besides that, the chosen energy storage system should be able to provide rated power for longer periods. However, for the longer time scales, the charging/discharging rate becomes less important and the choice of the ESS depends upon the amount of stored energy and the power capacity⁽⁸⁾. Currently, the Pumped Hydro Storage System (PHSS) is the most common storage technology for longer time scales applications⁽⁹⁾.

Different types of batteries are presented as the substantial choice for the ESSs which are Sodium Sulfur (NaS), Lithium-Ion (Li-ion), Nickel-metal, Nickel-cadmium, and Lead-acid batteries. Among different types of batteries, Lead-acid is the most popular and oldest technology. It has low capital investment and has the vast experience of usage. However, lead-acid batteries require frequent maintenance, they have short life (often 3–5 years), risk of explosions and acid leaking, and thus they are not environment friendly. They are majorly used as backup sources nowadays⁽¹⁰⁾. Nickel-cadmium type battery appears as an alternative for the lead-acid battery. They have longer life time, less temperature dependent, and high charge rates. They have a disadvantage of crystallization; it decreases the capacity of the battery when the battery is idled. Nickel-metal type hybrid battery has higher energy density as compared to the lead-acid and nickel-cadmium,

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but they need a special charging control⁽¹¹⁾.

Sodium-Sulfur (NaS) type battery system has a modular structure. It is the most recent technology among other technologies of the batteries. They are manufactured by the NGK insulators Ltd. Japan and are widely used nowadays in renewable applications as the energy storage system. NaS uses the molten metal and operates at temperature above 250°C. They have very high power densities and works good for storing bulk amount of power. They have longer life time i.e. 15 years and they are relatively inexpensive⁽¹²⁾⁽¹³⁾.

The behavior of the Renewable energy sources (RES) are based on the weather conditions, e.g., wind, solar irradiance, temperature; therefore it is not feasible to study and investigate the behavior of the RES through direct implementation as the setup is very expensive. These RES are extensively equipped with modern power electronic inverter/converter. The exact switching behavior of those power electronic converters cannot be mimicked when offline simulation tools are used in simulating the system and therefore, prototype, and control algorithm validation in real-time before integrating with RES is also not possible. Therefore, the necessity of experimental tests and measurements without the direct usage of the RES including power electronic interfacing has increased nowadays. Real-time simulators are a complementary power system analyzing tool to conventional power system offline simulation programs e.g. PSCAD/EMTDC, Simulink, etc., for power system studies. Real-time simulators are able to simulate very complex and large power system models in real-time. The simulation time-step of a real-time simulator is very small as tens of microseconds at the CPU, and tens of nanoseconds at the field-programmable gate array (FPGA). Therefore, real-time simulators can be used to study phenomena over a broad time frame, from less than 1 ms to minutes and hours^{(14)–(17)} and can be used for power hardware-in-loop (PHIL) and control hardware-in-loop (CHIL) testing.

Some work has been carried out in real-time simulators to analyze the different applications of RES. In Refs. (18)–(20), LVRT characteristics of the VSWT-PMSG are analyzed using the RTDS simulator by the controller hardware-in-loop (CHIL) method. Real-time analysis of the enhancement of the transient characteristics of fixed speed wind farms are analyzed by using a reduced scale STATCOM Prototype by using the OPAL-RT simulator⁽²¹⁾. Literatures on power

hardware-in-loop (PHIL) simulations, solar energy, hybrid vehicles, fuel cell in real-time simulators are found in Refs. (22)–(25).

The contribution of this research is to investigate and study the behavior of the variable speed wind farms integrated with the battery energy storage system in real-time using RTDS based on the actual weather conditions, which is wind speed in this case. This work is also a part of the future power hardware-in-loop (PHIL) test and therefore, the component models, especially power electronic converter modules are developed considering the realistic scenario and the developed control scheme can be used for prototype testing purpose. Frequency converter used with PMSG and STATCOM with BESS part are modeled using small-time-step, so that the real power electronic switching behavior is mimicked which is not possible when offline simulation tools are used. A comparative analysis is also carried out with the offline simulation tool, PSCAD to identify the difference from where the necessity of using RTDS can be understood.

2. Modeled System

The model system used in this study is shown in Fig. 1, in which individual wind generators in a wind farm is connected to the grid through the machine-side inverter (MSI), DC link and grid-side converter (GSC). The Permanent magnet synchronous generator (PMSG) is used as wind generator, and battery energy storage system (BESS) is adopted as the ESS. BESS consist of a DC-DC buck-boost converter, DC-AC converter, and a DC link capacitor, connected to the point of common coupling (PCC). Anemometer is considered to measure the wind speed signals from the real world. The wind speed is stored in the file and used in the wind turbine model of the RSCAD by using the scheduler to generate the torque for the wind generator. Hence this is the most accurate way of analyzing the behavior of the wind energy conversion system at different weather conditions.

3. Real-Time Digital Simulator (RTDS)

Real-time digital simulator (RTDS) is a real-time implementation of the electromagnetic type simulation of the power system models. RTDS is based upon the combination of advanced computer hardware and widespread software. RTDS has custom powerful computation platform, used to solve the non-linear differential equations. In this way, the

Fig. 1. Model system

system size to be run is not limited by one processor or one computer, therefore, power system network consisting of hundreds of buses can be simulated in real-time. RTDS hardware is based upon the advanced parallel processing techniques which are based upon the Digital signal processors (DSP) in order to have reduced computation burden for the real-time operation. The RTDS hardware interacts with the RSCAD software during run time and thus performs all the computations in real-time. In order to maintain the real-time operation, different racks can be utilized. Each rack consists of processing cards (triple processor card (3PC), operating at 80 MHz, RISC Processor Card (RPC) operating at 600 MHz, Gigabyte processing card (GPC) operating at 1 MHz and communication card. The most recent and powerful card among all other cards are PB5, it consist of two POWERPC RISC processor operating at 1.7 GHz. Digital and analogue I/O ports are also available with the processing cards. All these cards are connected with each other using the common backplane and hence facilitate the exchange of data between the individual processors and between different racks. The RTDS has a graphical user interface, named RSCAD software, which allows the user's interface with the hardware. It also allows the user to construct the simulation circuit, run, operate and record the results. RSCAD consists of multiple modules like Draft, RunTime, T-LINE, Multiplot, Cable and CBuilder (component builder). The power system modeling can be done in two different approaches. Firstly, the dual-time-step approach and secondly the large-time-step approach. In dual-time-step approach, some parts of the power system and control system which requires high precision (high switching frequency) is modeled in the small-time-step ($< 4\mu s$) and some are modeled in the large-time-step ($50\mu s$) network. Both-time-step network simulated systems are interfaced by the interfaced transformer. While in the large-time-step approach, all the power system components and the control system are modeled in the large-time-step network. The RTDS Simulator (shown in Fig. 2) in the Renewable Energy LAB of The Petroleum Institute contains 4 racks, 3 are mounted in the cubicle frame and one portable

Fig. 2. RTDS Installed at Renewable Energy Lab of The Petroleum Institute, Abu Dhabi, UAE

rack. Each rack has 4 3PC cards including 1 DOPTO card, 2 GPC card, 1 IRC and 1 WIF card.

4. Real-time Modeling of the Battery Energy Storage System

The battery is represented by a simple model consisting of a constant internal resistance in series with a variable internal electromotive force. The battery operation is limited from fully charged to 70% depth of discharge in order to preserve the battery lifetime. A 2 MW 2.86 MWh battery with an open circuit voltage of 0.472 kV (at 35% discharge) is used.

The battery internal electromotive force is assumed to vary linearly with the discharge energy level E . As shown in Fig. 3, when the battery is discharged at the rated power for one hour,

$$2[MW] * 3600[sec] = 7200[MJ] \dots \dots \dots (1)$$

The stored energy drops by 70% while the internal electromotive force only drops by 10% to $0.9 V_0$. V_0 is the internal electromotive force when the battery is fully charged. The internal electromotive force V_{int} can then be expressed as in (2). Given the open circuit voltage at 35% discharge, V_0 is equal to 0.497 kV. The battery is considered to be initially charged to 65% of its total capacity.

$$V_{int} = \left(1 - \frac{E}{72000}\right) V_0 \dots \dots \dots (2)$$

The internal resistance of the battery R_{NaS} is taken to cause a voltage drop equal to 5% of the internal electromotive force when the battery is delivering rated power at 35% discharge level. The battery terminal voltage V_{NaS} at such condition is then equal to 0.449 kV as obtained from (3).

$$\begin{aligned} V_{NaS}|_{35\%} &= 0.95V_0 - I_{NaS}R_{NaS} = (1 - 0.05) \cdot 0.95V_0 \\ &= 0.9025V_0 \dots \dots \dots (3) \end{aligned}$$

Given the battery rated power of 2 MW, the current I_{NaS} can be determined from (4). R_{NaS} is then at 0.0053Ω , as obtained from the voltage drop expression in (3),

$$P_{nas} = V_{NaS} * I_{NaS} \dots \dots \dots (4)$$

The battery internal electromotive force at 35% discharge is known, at 0.472 kV. The internal force V_{int} variation is assumed to vary linearly with the discharge energy level, as

Fig. 3. Characteristic of the NaS type battery

Fig. 7. Block diagram of the Grid Side Converter

generated by the PMSG is fed into the grid. The second is to control the terminal voltage through the reactive power fed to or absorbed from the grid. The GSC is controlled in the synchronous reference frame. The transformation angle is calculated from the three phase voltages at the high voltage side of the transformer connected at the grid side by using the PLL.

6. Switching Scheme in RTDS

A Pulse width modulation (PWM) scheme is used to generate the switching pulses for the frequency converters and STATCOM. RTDS large-time-step is used to generate the carrier and modulation signals. These signals are then transferred to the VSC small-time-step network to generate the triangular wave by using the triangular wave generator module. VSC small-time-step firing pulse generator module is used to generate the high resolution firing pulses in the small-time-step environment by comparing the carrier wave and reference voltage signals. The GTO valves can get the firing pulse by selecting the option CC_WORD of the GTO Bridge ⁽³⁰⁾⁻⁽³²⁾.

7. Real-time Simulation Setup

In this study, the VSWT-PMSG along with the back to back converters and the BESS integrated with the STATCOM are modeled in the small-time-step of the RSCAD in order to take into consideration the higher switching frequency phenomena. The control models are developed in the large-time-step of the RSCAD. Two VSC small-time-step blocks are used; one consists of the model of the VSWT-PMSG including the MSI, DC Link and GSC, and the other consists of the BESS integrated with the STATCOM. The two VSC small-time-step blocks are solved on the different processors of the GPC cards, where the different time-steps models are interfaced each other through the interface transformers. Wind turbine, transmission line and power grid are modeled in the RTDS large-time-step and are solved on the 3PC card. The control blocks are modeled in the large-time-step and are solved on the GPC card; switching signals for the switches are generated in the small-time-step. The processor assignments used to solve the power network in RTDS are shown in Fig. 8.

8. Simulation Results

In this paper, dynamic characteristic is analyzed when the NaS type battery energy storage system (BESS) integrated with the STATCOM is connected at wind farm terminal to smooth the output power fluctuations. Real wind speed data is measured, stored in data file, and used in RTDS environment using scheduler which will finally be replaced

Fig. 8. Block diagram of the modules and processor assignments

Fig. 9. Real-time wind speed data

with advanced anemometer equipped with remote data logger. Simulation results for the 300 seconds of wind speed data are shown. Switching frequency for the frequency converters, DC-DC converter and STATCOM are chosen to be 1050 Hz, 600 Hz and 1000 Hz respectively. RTDS small-time-step for the VSC network 1 and 2 is $2.4\mu s$ and $2.14\mu s$ respectively and large-time-step is chosen to be $50\mu s$. RTDS simulation results are also compared with those obtained by the PSCAD/EMTDC where time-step is chosen to be $20\mu s$. The PI controller parameters are obtained by the trial and error method to obtain the finest performance.

8.1 RSCAD/RTDS Simulation Results Wind speed data shown in Fig. 9 is used in the wind turbine to generate the torque for the PMSG for 300 seconds. Figure 10 shows the RTDS responses of the VSWT-PMSG output and smooth power to the utility grid along with the reference power signal. Figure 11 shows the response of the DC link bus voltage of the BESS, and response of the terminal voltage at the point of common coupling (PCC) is shown in Fig. 12. The energy level of BESS that is dissipated and absorbed during the operation and real power of the battery are shown in Figs. 13 and 14 respectively. Though the DC link voltage is fluctuating due to the wind farm output fluctuations and switching operation of buck-boost converter, it is kept within $\pm 5\%$ of the rated value. The RMS voltage at PCC is kept almost constant at the rated value.

8.2 PSCAD/EMTDC Simulation Results Figure 15 till 19 shows the PSCAD/EMTDC simulation results of the smooth power supplied to the grid, DC link bus voltage of

Fig. 10. RTDS responses of wind farm output, supplied power to the grid and reference power signal

Fig. 11. RTDS response of DC Link bus voltage of the BESS

Fig. 12. RTDS response of RMS voltage at PCC

Fig. 13. RTDS response of energy level of the BESS

Fig. 14. RTDS response of real power supply/absorption of the BESS

Fig. 15. PSCAD/EMTDC responses of wind farm output, supplied power to the grid and reference power signal

Fig. 16. PSCAD/EMTDC response of DC Link bus voltage of the BESS

BESS, RMS voltage at PCC, energy of the BESS and real power supply/absorption by the BESS. The results shows good agreement with the RSCAD results, but the variations in the RMS voltage, DC link bus voltage and power supplied to the grid are different from the RTDS results. This is because, as the RSCAD uses small-time-step for the simulation, the switching phenomena in the power electronic switches can be analyzed accurately and the results are close to the real-time operation.

Comparative analyses have been carried out where dynamic characteristics are analyzed for 300 s of real wind speed data using both PSCAD/EMTDC and RTDS/RSCAD. RTDS required almost the same time of about 310 s to

Fig. 17. PSCAD/EMTDC responses of RMS voltage at PCC

Fig. 18. PSCAD/EMTDC response of energy level of the BESS

Fig. 19. PSCAD/EMTDC response of real power supplied/absorb of the BESS

download and plot the result as the simulation time. However, PSCAD/EMTDC took almost 320 minutes to finish the simulation of 300 s. Therefore, it is quite difficult to perform dynamic analysis including power smoothing, optimum capacity determination for BESS, etc., for longer time in the range of hour or day using offline simulation tools. Hence, RTDS is an effective means to solve these problems.

9. Conclusion

In this study, detailed modeling of the grid connected VSWT-PMSG and the NaS type BESS integrated with STATCOM is carried out in the VSC small-time-step of the RTDS. Simulation results show the effectiveness of the control algorithms developed for controlling the BESS. RTDS simulation results are compared with the laboratory standard offline simulation tool i.e. PSCAD/EMTDC. VSC small-time-step

approach is the most precise method for studying the power system dynamics and power converters operating at higher switching frequencies. For the dynamic characteristics analysis, RTDS is proven as an effective tool due to its high computation capabilities, while the offline simulation tools are accurate but they need very long simulation time, which is not suitable for the dynamic analysis in the range of hours or day.

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