Development of a Real Time Wind Turbine Emulator based on RTDS using Advanced Perturbation Methods

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Abstract—This paper presents the development of a fixed speed wind turbine emulator using the Real Time Digital Simulator (RTDS). The wind turbine emulator consists of a wind turbine modeled in an RSCAD software environment. The software model for the wind turbine generates appropriate torque signals based on wind speed profiles using auto-regressive moving average and perturbation methods. These torque signals were fed to a servo motor emulating the wind turbine and were connected to an induction machine that emulated the generator. The response of the emulator shows that it closely matches the performance of the software model under various wind speed profiles. Thus, it can be used as an effective research and experimental tool in several wind energy based renewable energy projects.

Keywords-- wind turbine emulator (WTE), real time simulation, hardware-in-the-loop (HIL), perturbation theory

I. INTRODUCTION

Wind energy is one of the most widely developing and advancing forms of renewable energy. According to a 2011 report by the Global Wind Energy Council on wind statistics, the total installed capacity of wind turbines was 318,137 GW at the end of 2013. This cumulative capacity was projected to reach 596.3 GW in a period of five years in 2018. Therefore, it has deemed necessary to study the behavior of wind turbines under different operational conditions to further develop the wind energy technology and increase the contribution of wind energy in the global energy market.

The performance of wind energy systems which have various configurations, control strategies and operating in either controlled or uncontrolled environments could be tested using real time emulation. For this purpose, researchers have implemented various tools for the steady state and dynamic power studies of wind energy systems. Conventional offline tools such as EMTP-RV, PSCAD, PSS/E, MATLAB/SIMULINK have been used to simulate the behavior of wind generation systems using models of various complexity [1], [2], [3], [4], [5]. However, such offline simulators require a large amount of computation time which may not match the time period of real world events accurately. Also, such simulators could not directly be interfaced with hardware nor can they be tested in real time. On the other hand, real time tools facilitate hardware-in-the-loop simulation. Using such simulation, complex power system models can be simulated in a very short amount of time, which could be as low as tens of microseconds. Hence, real time mechanisms could be used to study systems over a broad range of time, as well as a very narrow range of time.

Using real-time mechanisms, large amount of simulations could be carried out in a short period of time. RT-LAB, Hypersim and dSPACE are some of the real time simulation tools used in literature [6], [7], [8], [9]. Another available tool for a real time simulation study is RTDS. One key advantage of using RTDS over the other simulators is its capability to test hardware or equipment in real time. This is enabled due to its parallel processing architecture that computes system equations in the real world time as specified by its time step. Real-time digital simulator (RTDS) allows conducting power system studies in real time i.e. one hour in the real world equals one hour in the simulator. This enables the study of steady state and transient analysis of test systems. The RTDS hardware utilizes numerous I/O channels to do this. Moreover, links between the software and the hardware simulator could be used to model different types of power systems components.

A hardware emulator based on RTDS could be used to study the performance of actual wind turbines. It also provides a tool to implement new control strategies in an orderly environment. Developing laboratory setups that are scaled versions of actual wind turbines enables to predict the behavior of actual wind energy systems under different scenarios before implementing them in the real world. Also, large number of repetitive experiments could be carried out in a controlled and safe environment. Wind turbine emulators of various configurations, ratings and complexities have been implemented in literature [8], [9], [10], [11], [12], [13]. However, the effectiveness, fidelity and response of such emulators could still be improved using a real time digital simulator (RTDS) based wind turbine emulator and with the help of advanced technical analysis methods.

In this paper, a real time wind turbine emulator was developed using RTDS. As identified in [14], the performance of a grid emulator is largely dependent on the hardware of the wind turbine prototype in addition to the design of the emulator itself. Therefore, the wind turbine was emulated using a standard commercial AC servo motor and its associated drive. This emulator was implemented on a fixed wind turbine

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configuration using an induction generator connected to the utility grid. The servo motor was programmed to run under torque control mode. A capacitor bank was used for power factor correction. Several wind speed profiles were implemented on the emulator. Moreover, for the emulator to operate in environments that resemble a real world scenario, advanced technical analysis methods were implemented. The developed real time wind turbine emulator could be applied as a power systems research and testing tool that could emulate various types of wind turbine systems in the real world.

II. INNOVATIVENESS OF THE APPROACH

The development of wind turbine emulators has been discussed through laboratory setups that are under controlled environments and under conveniently controlled electrical setups in various literature [15], [8], [16], [17], [18]. In other related literature, wind speed was programmed based on historical wind speed data, based on a manual set up and/or based on the Van der Hoven spectrum [19], [20]. Such implementation may not necessarily reflect the time-variable, stochastic environments in which wind turbines are operational. Therefore, the effectiveness, fidelity and response of emulators addressed in previous literature could still be improved with a real time digital simulator (RTDS) based wind turbine emulator and through advanced technical analysis methods such as the perturbation theory as presented in this paper.

III. WIND TURBINE MODEL

A wind turbine is the prime mover of a generator which converts available power in the wind into the mechanical power at its shaft. It can be characterized by its power coefficient and the tip speed ratio. The tip speed ratio (TSR) is the ratio of the hub speed of the turbine to the wind speed given by (1) where \( w_t \) is the speed of the wind turbine in rad/sec, \( R \) is the rotor radius in m and \( V_w \) is the wind speed in m/sec.

\[
\text{TSR} (\lambda) = \frac{\text{Hub Speed}}{\text{Wind Speed}} = \frac{w_t R}{V_w} \tag{1}
\]

The maximum power produced by the wind turbine is limited, due to losses, by the Betz limit [21]. The power coefficient \( C_p \) is described as the ratio of the wind energy converted into mechanical energy to the actual energy in the wind. It is a function of the tip speed ratio \( \lambda \) and pitch angle \( \beta \). The pitch angle is defined as the angle at which the turbine blades can be rotated about its axis. Pitch angle provides a mechanism by which energy in the wind can be cut out when wind reaches dangerously high speeds that might damage the turbine. In this paper, the following values referred from [21] are used to calculate \( C_p \) in (2) where \( C_1 = 0.5176 \), \( C_2 = 116 \), \( C_3 = 0.4 \), \( C_4 = 5 \), \( C_5 = 21 \) and \( C_6 = 0.0068 \).

\[
C_p = C_1 \left( \frac{C_2}{\lambda^2} - \beta C_3 - C_4 \right) e^{-\frac{C_5}{\lambda^2}} + \lambda C_6 \tag{2}
\]

\( \lambda \) is the tip-speed ratio defined by (3) where \( \beta \) is the pitch angle of the rotor blades in degrees.

\[
\lambda = \frac{1}{\lambda + (0.08 + \beta)} - \frac{0.035}{\beta^2 + 1} \tag{3}
\]

The relation between the power coefficient and tip speed ratio at varying pitch angles plotted using equations 3 and 4 is illustrated in Figure 1. The maximum value of \( C_p \) is obtained at \( \beta = 0^\circ \) and \( \lambda = 8.1 \). This particular value of tip speed ratio is defined as optimum TSR (\( \lambda_{\text{opt}} \)).

The mechanical power output of the wind turbine is given in (4) where \( \rho \) is the density of air in kg/m\(^3\), \( C_p \) is the power coefficient, \( A \) is the area covered by the wind turbine blades in \( m^2 \) and \( V_w \) is the wind speed in m/sec.

\[
P_{\text{mech}} = 0.5 \times \rho \times C_p \times A \times V_w^3 \tag{4}
\]

The mechanical torque is given in (5).

\[
T_m = \frac{P_{\text{mech}}}{w_t} \tag{5}
\]

The radius of the wind turbine in the software model was calculated to match the rating of the induction machine used in the experiment which are given in TABLE I. The calculation is given in (6) where \( P \) is the mechanical power input to the induction machine in order to get maximum electrical power output \( P = 484 \text{ W} \), \( C_{\text{opt}} = 0.48 \), \( \rho = 1.224 \text{ kg/m}^3 \), and the rated wind speed = 11 m/s.

\[
R = \sqrt{\frac{P}{0.5 \times \rho \times C_{\text{opt}} \times \pi \times V_w^3}} \tag{6}
\]

The gear ratio is calculated using (7) where \( n_g \) = gear ratio, \( w_{\text{rated}} \) = the rated turbine speed in rad/sec, \( w_{\text{rated}} \) = the rated mechanical rotor speed in rad/sec and is equal to the speed at which rated power is produced by the generator which is 205.879 rad/sec.

\[
n_g = \frac{w_{\text{rated}}}{w_{\text{rated}}} = 1.45 \tag{7}
\]

The rated turbine speed is calculated using (8) where \( \lambda_{\text{opt}} = 8.1 \) is the tip speed ratio at which optimum \( C_p \) is obtained.

\[
w_t = (\lambda_{\text{opt}} \times V_{\text{rated}})/R = 142.173 \text{ rad/sec} \tag{8}
\]

The output power of the turbine for varying wind speeds for the above calculated parameters is shown in Figure 2.

A wind turbine generator starts producing power at a value of wind speed described as the cut-in wind speed. Above the cut-in wind speed, the power output of the turbine goes on increasing until the rated value of wind speed is reached. At this value, the wind turbine produces the rated amount of power.

![Figure 1 Power coefficient vs. tip speed ratio at various pitch angles](image)
Above the rated wind speed, the aerodynamic power needs to be limited to prevent the turbine blades from any kind of damage. The speed at which the turbine is cut-off completely from the wind is called cut-off wind speed. In this paper, a pitch angle controller was designed for aerodynamic power control. For wind speeds above the rated value, the pitch angle controller limited the turbine speed at a set value such that the output of the turbine was maintained at its maximum value. The structure of the pitch angle controller is shown in Figure 3.

IV. SOFTWARE IMPLEMENTATION AND ADVANCED ANALYSIS TECHNIQUES

The implementation performed in RSCAD consisted mainly of four parts namely the wind speed profile, the perturbation methods, the wind turbine model and the induction machine model. Wind speed profiles could be identified based on Van der Hoven spectrum [19] and they could be generated using forecast methods. In this paper, Auto regressive moving average model (ARMA) [22] was used to generate wind speed profiles. A mixed p
\[ \sum \alpha_i Y_{t-i} + \sum \beta_i \varepsilon_{t-i} \]  

where \( Y_t \) = the forecasted generation at time \( t \), \( p \) = the order of the autoregressive process, \( \alpha_i \) = the autoregressive coefficient, \( q \) = the order of the moving average error term, \( \beta_i \) = the moving average coefficient, \( \varepsilon_{t-1} \) = the white noise that gives random uncorrelated variables with zero mean and constant variance.

Such setup often provided profiles that did not necessarily reflect the uncontrolled environment in real-world applications. Therefore, a perturbation method complemented wind speed profiles generated using the ARMA model to account for the effect of stochastic environments. Perturbation theory expresses the study of the effects of small disturbances on a system to obtain practical mathematical solutions to a problem [23]. In literature, perturbation and observation algorithms have been used for estimating rotor speeds without the knowledge of wind turbine and generator parameters in [24]. However, perturbation methods have not been used for analyzing the behavior of wind turbine emulators in real world scenarios. Thus, perturbation methods could be used to represent any stochastic disturbance in the wind turbine system, where \( Y_P \) is the wind turbine including the perturbation \( \varepsilon^t \) at time step \( t \) as given in (10).

\[ Y_P = Y_{t0} + \varepsilon^{1}Y_{t1} + \varepsilon^{2}Y_{t2} + \varepsilon^{3}Y_{t3} + \ldots + \varepsilon^{n}Y_{tn} \]  

(10)

Wind speed profiles were generated based on the ARMA model and the perturbation model as shown in Figure 4 and Figure 5 and were implemented in the modeled system.

The Test Wind Speed profile was created using the RSCAD scheduler component and was implemented to test the system performance for steady state step response. It can be observed from Figure 4, Figure 6 and Figure 7 that above the cut-in speed of 7.5 m/s, the induction machine momentarily behaves as a motor before starting to feed power to the grid. At the rated wind speed, the generator produces maximum power. When wind speed exceeds the rated value, the pitch angle controller controls the speed to a set value such that generator output power is maintained at its maximum value. As the wind speed exceeds the cut off value, the generator is disconnected from the grid.

It can be observed from Figure 7 that the reactive power requirement of the induction machine is fulfilled by the grid without any reactive power support.

\[ W_P^{ref} \]

\[ W_P^r \]

Figure 3 Structure of the pitch angle controller

Figure 2 Rotor speed vs. wind turbine mechanical power output

Figure 4 Test wind profile 1
An experimental test set up of a wind energy conversion system was built using the Real Time Digital Simulator which facilitated the emulation of the wind turbine real time. The hardware implementation consisted of the following distinct parts:

1. RSCAD
2. A standard AC Servo motor
3. An induction machine coupled to the servo motor
4. A capacitor bank connected to the induction machine

The schematic of the entire hardware setup is shown in Figure 8.

The mathematical model of the wind turbine built in RSCAD calculated the reference torque based on the wind speed and rotor speed signals. The rotor speed was measured using an encoder and the corresponding signals were acquired in RSCAD through the Digital Input card of the RTDS. The digital signals were converted back to speed signals in revolutions per minute (rpm). The reference torque signal generated from the model in RSCAD was converted in to an appropriate voltage signal and passed to the servo drive through the Analog Output card of the RTDS. The servo motor was set to operate under torque control mode and followed the reference torque signals.

An induction generator was rigidly coupled to the servo motor and it produced power when the wind speed exceeded the cut-in value. Two capacitor banks of values 18 µF and 20 µF were connected to the generator, through a set of relays, for power factor correction.

Voltage and current divider circuits were used to convert the voltages and currents into permissible limits for the RTDS input/output cards. A PM-800 power meter was used to measure and log the values of active and reactive power.

In the first case study, the Test Wind Speed profile was implemented on the experimental set up. The active output of the generator without the capacitor bank is shown in Figure 9. As can be observed, the results closely match the output of the software system. When the capacitor bank is disconnected from the system, all the required reactive power is supplied by the grid (negative). The active and reactive power with the reactive power support from the capacitor banks are shown in Figure 10.

Since the initial reactive power requirement of the induction generator is very high. some amount is supplied by the grid until the machine is completely excited. The capacitor banks improve the power factor greatly which can be observed in Figure 11.

In the second case study, the Auto-Regressive Moving Average (ARMA) and perturbation method based wind speed profile was implemented to study the system response for dynamic changes in the wind speed. The response of the system to the generated wind speed profile is shown in Figure 12, Figure 13 and Figure 14. The active and reactive power
output with and without reactive power support can be observed. The response also shows that the emulator successfully tracks the wind speed changes and closely emulates a real world wind turbine.

![Figure 9](image9.png)  
**Figure 9** Active power and reactive power with capacitors disconnected

![Figure 10](image10.png)  
**Figure 10** Active power and reactive power with capacitors connected

![Figure 11](image11.png)  
**Figure 11** Power factor

![Figure 12](image12.png)  
**Figure 12** Rotor Speed

VI. CONCLUSION

A real time wind turbine emulator was developed and the response of the hardware system was validated against the software system. The advanced perturbation methods and the computing power of real-time operation enabled hardware-in-the-loop simulation of the wind turbine emulator. The time step of the simulation was around 66 µs thus allowing studying the system response close to actual environments in which wind turbines could operate under. Steady state and dynamic response of the wind energy system demonstrated that the system provides a strong platform for researching and testing complex control topologies and power system studies involving wind turbines.

![Figure 13](image13.png)  
**Figure 13** Real power and reactive power with capacitors disconnected

![Figure 14](image14.png)  
**Figure 14** Real power and reactive power with capacitors connected
VII. APPENDIX

TABLE I. RATING OF THE INDUCTION MACHINE USED IN THE EXPERIMENT

<table>
<thead>
<tr>
<th>Induction Machine Ratings</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power</td>
<td>310 W</td>
</tr>
<tr>
<td>Voltage (L-L)</td>
<td>208 V</td>
</tr>
<tr>
<td>Current (Line)</td>
<td>1.4 A</td>
</tr>
<tr>
<td>Speed (No load)</td>
<td>1725 rpm</td>
</tr>
</tbody>
</table>

REFERENCES


