www.ijecs.in
International Journal Of Engineering And Computer Science ISSN:2319-7242
Volume 2 Issue 3 March 2013 Page No. 687-691

Modeling and Simulation of Non-Grid-Connected Wind Energy Conversion System

K.Shravankumar, D.R.K.Mahesh, K.Ravishanker

PG Scholar, Department of EEE, CMR College of engineering and technology, Hyderabad ,
Andhra Pradesh, India.
E.mail:kotagirishravankumar@gmail.com

Assistant professor, Department of EEE, CMR College of engineering and technology,
Hyderabad, Andhra Pradesh, India.
E.mail:drkmahesh515@gmail.com

Assistant professor, Department of EEE, CMR College of engineering and technology,
Hyderabad, Andhra Pradesh, India.
E.mail:sravs.boby@gmail.com

Abstract Method for wind turbine controller design and test in laboratory still remains a problem. This paper presents a real time simulator of non-grid-connected wind energy conversion system suitable for controller design and test. The simulation model, which is composed of a fixed-pitch wind turbine, a permanent magnet synchronous generator with PWM voltage source vector control and DC-DC converter with peak current control, is especially suitable for electrochemical industries. High energy efficiency can be achieved by adjusting the rotor speed according to the wind speed. Simulation results show the validity of system modeling and control strategy.

***Keywords*—Wind power; non-grid-connected; simulation model; HIL real-time simulation**

I. INTRODUCTION

The terminal loads of non-grid-connected wind energy conversion system are no longer the conventional power grid, the characteristic of it lies in that power can be applied to single unit immediately, which makes it quite suitable for high energy consuming electrochemical industries such as electrolytic aluminum and seawater desalination. Cancellation of auxiliary appliances that needed for grid connection introduces simplicity of configuration to the plants which helps to reduce the manufacturing cost of the system and the price of wind power energy can also be cut down [1].

With the fast development of wind power technology, the need for rapid prototyping and testing of wind power apparatus is also increasing. The traditional way of testing, integration and validation of complex controlled consists on systematic analysis of the behavior of individual components, mostly by simulation, before complete integration on real apparatus. A more advanced testing/integration approach is needed to diminish the probability of damage, personal injuries and time to market.

With rapid advances in computer technologies, it is increasingly advantageous to make a more efficient approach to system prototyping using Hardware-in-the-Loop (HIL) digital simulation, where one or more devices (wind turbine controllers) are tested while connected to a real-time dynamic equivalent of plant. If the system is correctly modeled, the wind generator controllers under test will behave as if they were connected to the real system. The tested controllers can therefore be tested over a wide range of parameters without risk to the main system.

in this paper, a non-grid-connected direct drive fixed-pitch variable speed wind energy conversion system real-time simulator with advanced hardware-in-the-loop capabilities is discussed. First, the mathematical model of the key components is presented, then the simulation platform based on RT-LAB will follow, the last section presents the experimental results made with the simulator to demonstrate the validity of system modeling and control strategy.

II. SYSTEM MODELING

Topology of non-grid-connected wind energy conversion system this paper discussed is shown in Fig.1. PMSG that with PWM voltage source vector control which can enable a high energy efficiency by adjusting the rotational speed, is directly driven by a fixed pitch wind turbine, DC bus voltage is constant under the control of Boost converter which ensures the power balance of the system, Buck converter is introduced to maintain the output voltage a constant. The basic control strategy is to achieve maximum peak power tracking of wind turbine while operating in below rated power condition and to limit the power while operating in the above rated power condition.

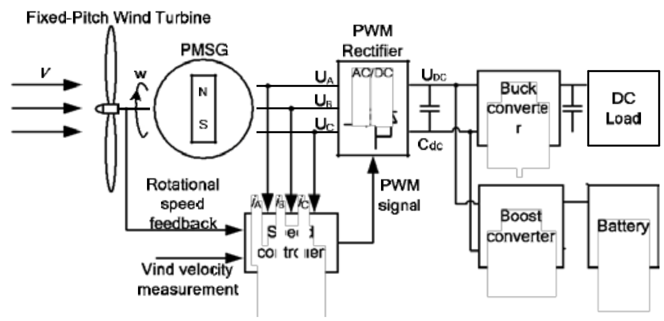

Figure 1. Topology of non-grid-connected wind energy conversion system.

A. *Fixed- pitch wind turbine model* [2]

Ignore the complex aerodynamic equations, fixed-pitch wind turbine model is determined by the following simple equations:

$$\begin{cases} P_m = 0.5\rho\pi R^2 v^3 C_p(\lambda) \\ T_m = P_m / \omega_m \end{cases} \quad (1)$$

where T_m and P_m represent the aerodynamic torque and aerodynamic power of wind turbine, Z_m the rotational speed, Y the air density, R the blade radius, v the wind velocity, O the tip ratio speed, which is defined as: $O = Z_m R/v$, C_p the power coefficient which is a function of O. Parameters used in simulation are all from a real wind turbine, for example, C_{pmax} equals 0.37, blade radius of wind turbine is 4 meters, O_{opt} is 6.75, v_{cut-in} and $v_{cut-out}$ is 4.5m/s and 25m/s respectively , v_{rated} is 12m/s, air density equals 1.25kg/m^3, and the rated output power of the wind turbine is 10kW.

The mathematical equation to model the driving train consist of aerodynamic torque and electromagnetic torque is shown in equation (2):

$$T_m - T_e = J\frac{d\omega}{dt} + B\omega \qquad (2)$$

When the aerodynamic torque T_m is not equal to the electromagnetic torque, rotational speed is about to change, which means the rotational speed can be adjusted by means of adjusting the electromagnetic torque of PMSG.

B. Permanent magnet synchronous generator model

The PMSG is modeled under the following simplifying assumptions: sinusoidal distribution of stator winding, electric and magnetic symmetry, negligible iron losses and unsaturated magnetic circuit. Under these assumptions, the generator model in the so-called steady-state (or stator) coordinates is first obtained. Another simpler model can be obtained in (d,q) rotor coordinates, conversion between (a,b,c) and (d,q) coordinates can be realized by means of the Park Transform. Then, after neglecting the homopolar voltage, u_0, by virtue of symmetry, the (d,q) PMSG model becomes [3]

$$\begin{cases} u_d = Ri_d + L\frac{di_d}{dt} - p\omega i_q \\ u_q = Ri_q + L\frac{di_q}{dt} + p\omega i_d + p\psi_f\omega \\ T_e = \frac{3}{2}p\psi_f i_q \end{cases} \qquad (3)$$

where R is the stator resistance, u_d, u_q are d and q stator voltages, i_d, i_q are d and q stator currents, p is the number of pole pairs, ∴f is the flux that is constant due to permanent magnets, as the permanent magnets are mounted on the rotor surface, d, q inductances are equal, they are represented as L. By introducing the coordinate transformation, electromagnetic torque is only determined by i_q, which highly simplifies the controller design of PMSG.

C. Model of DC-DC converters [4]

DC-DC converters applied in wind power system have special characteristics, for example, they are not only used to perform voltage transformation, but are also used to accomplish MPPT of wind power. In order to finish such tasks feedback variables including normal output voltages, input voltages, currents, or even output power. Besides that, comparing with the analog control of conventional DC-DC converters, complex digital control using DSP is a must in order to finish the desired functions.

Boost converter discussed in this paper is used to maintain the DC bus voltage a constant, so as to assure the power flow of the whole system is balanced. When the wind speed is under the rated value, power generated from PMSG is less than the amount acquired by load, then the boost converter behaves like a “generator”, extra power can be absorbed from battery through boost converter in order to maintain the energy balance, on the contrary, if the power needed is less than that of generated, the excess part of it is stored in battery through boost converter. As mentioned above, the boost converter is required to handle the bidirectional power flow, this is achieved by replacing the diode with MOSFET, and while one MOSFET is on, the other is off. Models of Boost and Buck converter can be established by means of circuit averaging technique, their equivalent small signal circuits are shown in Fig.2&3

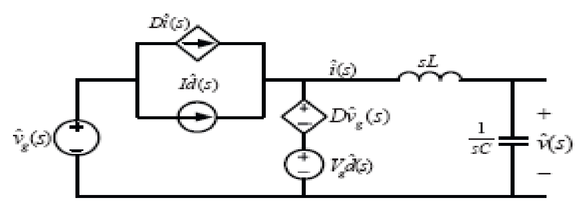

Figure 2. Equivalent small signal circuit of Buck converter.

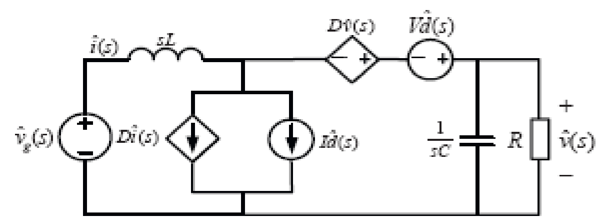

Figure 3. Equivalent small signal circuit of Boost converter.

Then, the transfer function that we are interested in can be easily obtained. The output-to-current and current-to-control transfer functions of the two converters are shown respectively.

Transfer functions of Boost converter:

$$\begin{cases} G_{vi}(s) = \left.\frac{\hat{v}(s)}{\hat{i}(s)}\right|_{\hat{d}(s)=0} = \frac{V}{I}\frac{-\frac{LI}{V(1-D)}+1}{\frac{VC}{I(1-D)}s+1} \\ G_{id}(s) = \left.\frac{\hat{i}(s)}{\hat{d}(s)}\right|_{\hat{v}(s)=0,\hat{v}_g(s)=0} = \frac{V}{Ls} \end{cases} \qquad (4)$$

Transfer functions of Buck converter

$$
\begin{cases}
G_{vi}(s) = \left.\dfrac{\hat{v}(s)}{\hat{i}(s)}\right|_{\hat{d}(s)=0} = \dfrac{1}{sC} \\
G_{id}(s) = \left.\dfrac{\hat{i}(s)}{\hat{d}(s)}\right|_{\hat{v}(s)=0,\hat{v}_g(s)=0} = \dfrac{V_g}{Ls}
\end{cases}
\quad (5)
$$

Average current-mode control is introduced in this paper, transfer functions deduced above can be used to design the voltage and current controller.

III. HIL Real-Time Simulator Of The System

Nowadays, real-time simulation plays an important part in rapid control prototyping, system integration and hardware-in-the-loop testing. Electrical systems have higher bandwidth than mechanical systems and therefore command smaller simulation time steps, the problem gets most when simulating power converters like PWM motor inverters and DC-DC converters because of their high switching frequencies with regards to the simulation sampling frequency. RT-LAB electrical drive simulator proves to be a powerful tool in real-time simulation because of its state-of-the-art hardware and software technique. The PWM signals generated by the real controllers are sampled with a high frequency counter card based on FPGA running at much faster rate than the simulation process, whose frequency

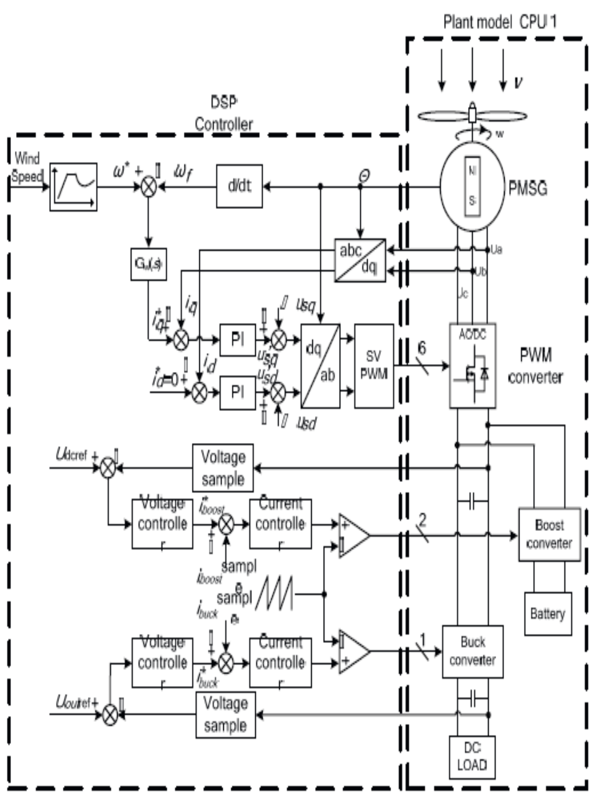

Figure 4. Structure of the direct drive non-grid-connected wind energy conversion system based on RT-LAB

is as high as 100MHz. Along with it, there is a special “time stamp” technique. When some transition occurs on the gate, the counter card stop counting and therefore “stamps” the time of the transition with 10ns resolution. The count is then transferred to the Time stamped bridge as a normalized ratio on the Pentium side of the simulator where the wind generator is simulated. Besides that, ARTIMES solver provides superior simulation efficiency than other solvers. A complex simulation model can be divided into several parts and distributed to different CPU cores, which can shorten the simulation time step greatly [5].

A. *Structure of the real-time simulation model*

Figure 4 represents the structure of the direct drive non-grid-connected wind energy conversion system based on RT-LAB. The virtual plant simulation model, including wind speed, fixed pitch wind turbine, PMSG, PWM converter, Buck converter, Boost converter, Battery and load is distributed to simulator core. Plant speed control, vector control of PMSG, average current-mode control of DC-DC converters are accomplished in real DSP controller. If the control strategy is well designed, the plant will work properly, and the wind generator controllers under test behave as if they were connected to the real system, the tested controller can therefore be tested over a wide range of parameters without risk to the main system [6].

B. *Design of PMSG vector controller*

Equation (3) can be transformed into the following equivalent form, which is used to design the inner current loop controller.

$$
\begin{cases}
Ri_d + L\dfrac{di_d}{dt} = u_d + p\omega i_q \\
Ri_q + L\dfrac{di_q}{dt} = u_q - p\omega i_d - p\psi_f \omega
\end{cases}
\quad (6)
$$

It is obvious that there are coupling terms p_Zi_q and p_Zi_d, which are unwanted in controller design. Feed forward method is applied to eliminate the coupling effect. Redefine two variables in equation(7):

$$
\begin{cases}
v_d = u_d + p\omega i_q \\
v_q = u_q - p\omega i_d
\end{cases}
\quad (7)
$$

current controller can be designed respectively. Take controller of i_q as an example, the control block diagram, which takes sampling delay of current and inertia property of PWM converter into account, is illustrated in Figure 5.

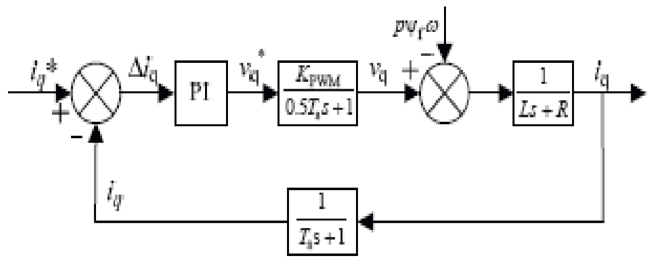

Figure 5. Current control block diagram of PMSG

The set point of i_q is derived from the equation: $i_q^* = T_e^* / 1.5 p\psi_f$. T_s is PWM switching period, K_{PWM} is PWM equivalent gain. Controller designed by PI method has the following form:

$$G_c(s) = \frac{K_{ip}(\tau s+1)}{s} \qquad (8)$$

Omit the perturbation effects of $p\psi_f\omega$ temporarily, and combine the time constant together, a simplified block diagram can be obtained as Figure 6 showed:

q

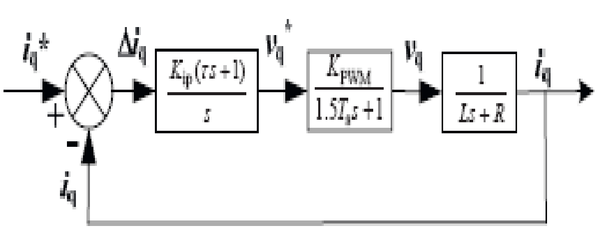

Figure 6. Simpler equivalent current control block diagram of PMSG

Let the zero point of $G_c(s)$ compensate the pole point of the plant, which requires $\tau = L/R$, then we can get the open-loop transfer function of the system:

$$G(s) = \frac{K_{ip}K_{PWM}}{R}\frac{1}{s(1.5T_s s+1)} \qquad (9)$$

Set the parameters as type I required, consider the damping ratio to be 0.707, which yields:

$$\frac{K_{ip}K_{PWM}}{R} \times 1.5T_s = \frac{1}{2} \qquad (10)$$

Till then, the two parameters, τ and K_{ip} , can be calculated by the following equations:

$$\begin{cases} K_{ip} = \dfrac{R}{3K_{PWM}} f_s \\ \tau = \dfrac{L}{R} \end{cases} \qquad (11)$$

At last, the closed loop transfer function of current loop can also be obtained:

$$\Phi_i(S) = \frac{i_q(s)}{i_q^*(s)} = \frac{G(s)}{1+G(s)} = \frac{1}{4.5T_S^2 s^2 + 3T_S s + 1} \qquad (12)$$

IV.EXPERMENTAL RESULTS

Several tests have been carried out to study the performance of a 10kW non-grid-connected wind energy conversion system based on RT-LAB. DSP controller based on TMS320x2407 is connected with RT-LAB through the I/O port. All the information the controller need ,for example, the rotational speed of PMSG, stator voltage, stator current are first transformed into analog signals using the DAC in RT-LAB, then they are transmitted to DSP controller. PWM signals produced by DSP which are used to control the virtual plant simulation model are sent to ADC port of RT-LAB, the wind generator controllers under test behave as if they were connected to a real system.

A. Simulation below the rated wind speed

The initial wind speed is 4m/s, at the moment t=20s, it begins to increase at a constant slope, 0.1s later, it reaches a new steady value of 9m/s. Variables we concerned about are captured by oscilloscope and are used to analyze the working condition of the plant.

It can been seen from Fig.7 (a) (C_p vs v plot) that C_p remains its maximum value near 0.37 during the whole process, which means the MPPT algorithm works properly. This is accomplished by adjusting rotational speed linearly with respect to wind speed, which can be seen from Fig.7 (b

(Z_{m} vs v plot). The initial steady value of Z_{m} is 8 rad/s, when wind speed begins to rise, there is an increase in Z_{m} accordingly, as wind speed reaches a new steady value, Z_{m} remains at a final value of 16m/s. Changes of wind speed and rotational speed will definitely cause the output power of wind turbine vary accordingly. As we can see from Fig.7 (c) (P_{m} vs v plot), P_{m} varies from 740W to 8400W during the dynamic process, simulation value well matches theoretical values calculated in equation (1).

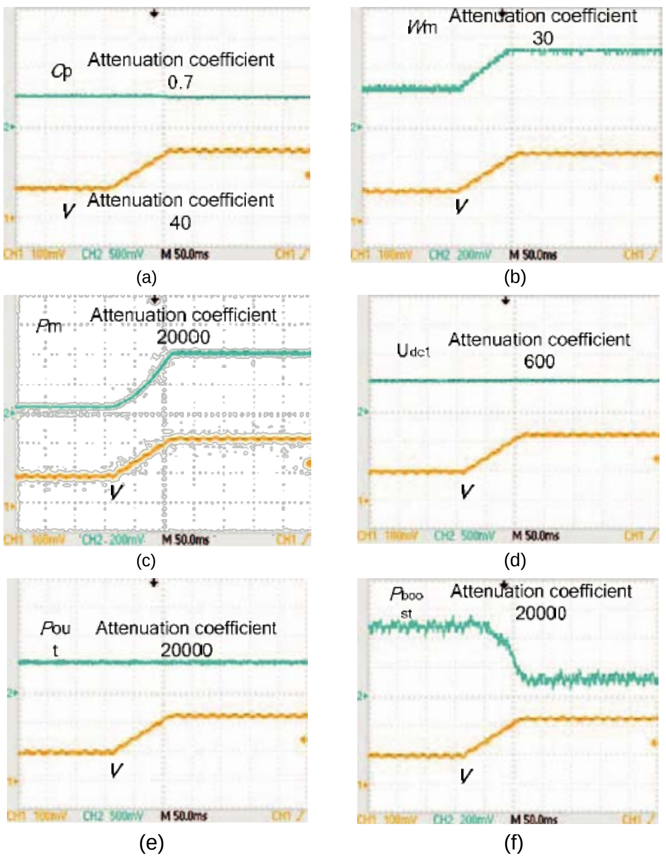

Figure 7. Experimental result in low wind condition

Load of the plant absorbs a constant power of 10kW, as can be seen in Fig.7 (e) (P_{out} vs v plot). The maximum power the wind turbine can provide is only 8400W in the setting low wind condition, the extra power is provided by battery through Boost converter. Power flow is balanced because P_{m} plus P_{boost} equals P_{out}, and when P_{m} increases, P_{boost} decreases accordingly. Besides that, the voltage of DC bus remains at a constant value of 300V, there is no change of it when wind speed varies, which also proves the power flow is balanced.

V. Conclusion

The modeling of non -grid-connected wind energy conversion system has been discussed, and HIL real-time simulation platform has been established on basis of that. Simulation results on different wind speed conditions prove the validity of system modeling and speed controller design, MPPT on low wind condition and constant output power of wind turbine on high wind condition are realized, which improves working efficiency of the plant. DC-DC converters maintain the balance of energy flow by keep the DC bus voltage a constant. Besides that, MAT-LAB proves to be a powerful tool which is suitable for the design and test of wind turbine apparatus and controllers. The experimental results also show that the accuracy of the real-time simulation based on MAT-LAB is as good as general variable-step simulation but much less time consuming.

References

[1] W. Gu, "Development and Application of Large-scale Non-grid-connected Wind Power System," *Automation of Electric Power Systems*, Automation of Electric Power Systems Press, P.O. Box 323, Nanjing, 210003, China, October 2008, vol. 32, no. 19, pp. 1-9.

[2] I. Munteanu, *Optimal Control of Wind Energy System*, Springer London, 2008.

[3] P. Q. Nguyen, *Vector Control of Three-Phase AC Machines*, German: Springer Berlin Heidelberg, 2008.

[4] R. W. Ericson, *Fundamentals of Power Electronics*, 2nd ed, Springer US, 2004.

[5] C. Dufour, J. Belanger, "Real-Time Simulation of Doubly Fed Induction Generator for Wind Turbine Applications," *Proceedings of the 11th International Power Electronics and Motion Control Conference*, Riga, Latvia 2004.