Copyright © 2002 IFAC
15th Triennial World Congress, Barcelona, Spain

NONLINEAR CONTROL OF VARIABLE-SPEED WIND ENERGY CONVERSION SYSTEM

Sun yaojie, Kang longyun, Cao binggang, Yang zhongqing, Shi weixiang

Department of Mechatronical Engineering School of Mechanical Engineering
Xi'an Jiaotong University Xi'an,P.R.China 710049
Myway Labs Co., Ltd

Abstract: This paper discusses the nonlinear control problem for variable-speed wind energy conversion system. Due to the stochastic operating conditions and the inevitable uncertainties inherent in the system, linear control method comes at the price of poor system performance and low reliability. So, it first develops a detailed model of variable-speed wind energy conversion system, which incorporated a distributed generation and then applies the Multiple Sliding Surface designing controller for robust performance of optimizing the generator converter system efficiency. *Copyright © 2002 IFAC*

Keywords: Wind, Energy *control*, Nonlinear *control system*

1.INTRODUCTION

Wind electrical power systems are recently getting more interest, because they are environmentally clean and safe renewable power sources, compared to fossil fuel and nuclear power generation. Many manufactures have developed variable-speed machine ever the last few decades. There have been many production machines and even greater number of prototypes or proofs of concept for variable-speed wind turbines that have the potential for increased energy capture. (P.W. Carlin, *et al* 2000; R.Chedid 1999). The small turbines have been used to provide electricity in places that do not have access to a power grid. The distributed generation is a type application of small turbines, for instance, the distributed generation systems powering mini-grid in remote villages often incorporate wind turbines, with photo-voltaic (PV) or other renewable components. The variable and intermittent character of renewable resources requires the system to have energy storage, the latter usually a battery bank. The controller design for these applications of small VWECS has become an area of increasing attentions. Variable-speed power regulation provides means for initiating rotation, varying rotational speed to extract power at low wind speeds, maintaining power production at a maximum level, and Alleviating the transient loads throughout the wind turbine. Controllers must be designed to meet each of these objectives (P.W. Carlin *et al* 2000). The role of the control system is summarized by the following general goal: (D.J. Leith and W.E. Leithead 1997).

(1) alleviating the transient load throughout the wind turbine;
(2) regulating and smoothing the power generated;
(3) ensuring that the power-train has the appropriate dynamic, particularly damping of the power-train ;
(4) maximizing the energy capture;

All four general performance goals are relevant to the specific case of variable speed wind turbines. First, both the drive-train loads and the structural loads are dependent on both the choice of control strategy and the effectiveness of the associated controller whose objective is to realize it. Second, power smoothing is achieved by alleviating the transient drive-train loads. Third, the control system may be required to provide damping (S.A. Salle *et al*1990). Fourth, the energy capture is a function of speed in above rated wind speed is achieved, as in below rated wind speed, by varying the generator reaction torque. Wind energy conversion systems have strong nonlinear characteristics with many uncertain factors, such as meteorological condition and the continuously varying system loading .The wind turbine system has multiple control inputs: the switching ratio of the rectifier, the torque of the synchronous generator (R.Chedid *et al* 1999). Therefore, a robust nonlinear control system studying under nonlinear and random conditions is requited in order to fully exploit the potential of a variable speed wind energy conversion system. Great stride have been made in the past several decades in the area of controller design for nonlinear uncertain systems. Tremendous strides have been made in the past 25 years in the area of controller design for nonlinear systems. Variable structure control or sliding mode control uses a discontinuous control structure to guarantee perfect tracking for a class of systems satisfying "matching" conditions. Retaining the concept of an "attractive" surface but eliminating the control discontinuities, the method of sliding control is currently being applied in many different applications. A novel sliding mode control, Multiple Surface Sliding control (MSS), a procedure similar to back- stepping methodology, was applied to control the nonlinear systems (J. K. Hedrick and P. P. Yip2000). In the proposed paper, two aims are set forth: the first aim is to develop a detailed model of variable-speed wind energy conversion system (VWECS), which incorporated a distributed generation. And the second is to apply MSS designing controller for robust performance of optimizing the generator converter system efficiency.

2. MODEL DESCRIPTION

The VWECS adopted in this study as shown in fig. 1 The VWECS consists of permanent magnet generator (PM), AC input filter, a resonant rectifierand a three-phase pulse-width-modulated inverter. The PM operating at 100rpm----400rpm, produces a three-phase variable AC voltage 200 volts to 400 volts.

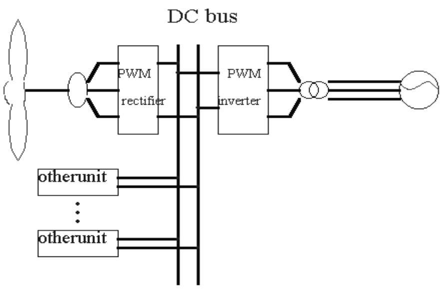

Fig. 1. Schematic VWECS

An input filter is placed between the rectifier and PM generator. The rectifier produces high-frequency pulsed currents, which have high amplitude. This is harmful to the generator. Therefore, the high-frequency currents must be eliminated and the low frequency component of curren should be supply only by the generator. The resonant rectifier is used to convert the three-phase AC voltage of variable amplitude and frequency to a controlled DC voltage, which fed into the battery simulator. The converter produces a nominally constant AC voltage Synchronized with the utility system 50 Hz. The converter is capable of increasing or decreasing the input voltage. Hence increased energy capture will be possible both at the high and the low end of the wind speed range. In this case, using a DC/DC converter is shown in fig. 3. It is well known that DC/DC converter regulate the dc voltage of generator-rectifier unit by varying the switching ratio, so that the optimum dc voltage profile is presented at the rectifier terminal for maximum power capture operation. Also, an appropriate dc voltage is maintained at the dc bus to enable the voltage source inverters to perform the optimal real power transfer and reactive power regulation..

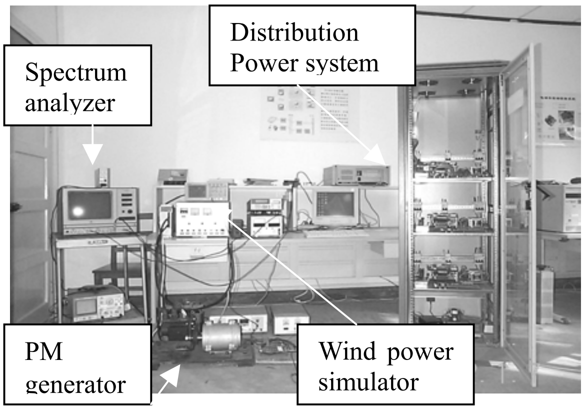

Fig. 2. Photograph of the experiment system

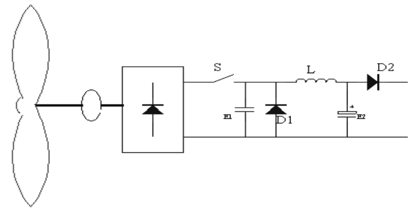

Fig.3. Schematic of PM generator-rectifier unit

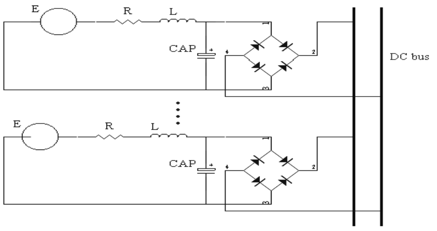

Fig.4. Modular connection of stator and rectifier

2.1 *Wind Modeling*

Wind energy is an intermittent and variable source of energy. The variations in average wind speed using a Weibull distribution, together with short-term fluctuations around this average using a spectral power density model. wind speed varies with many factors and is random in magnitude and direction. In this case, the wind is simulated with four components, namely, base component (V_{base}), ramp component (V_{ramp}), gust component (V_{gust}) and noisy (V_{noise}) component as: (D.J. Leith and W.E. Leithead 1997).

$$V_{wind}=V_{base}+V_{ramp}+V_{gust}+V_{noise} \qquad (1)$$

2.2 Wind Turbine Characteristics

Variable-speed turbines, include a gearbox in the drive train, and they are very compliant at the generator end. Thus, drive-train dynamics may be assumed to be negligible to simplify variable-speed turbine models. So, a simple, rigid, non-linear turbine model developed for the purpose of controller design in this study. The power captured by the wind turbine is calculated as:

$$P = 0.5C_p(\lambda,\beta)\rho V v^2 \qquad (2)$$

where λ is the tip speed ratio (TSR) given by: $\lambda = \frac{\omega_{rm} R}{v}$ and ω_{rm} [rad/s] is the rotor mechanical speed, R [m] is the radius of the blades, v [m/s] is the average wind velocity, A[㎡] is the rotor cross-section, and ρ [kg/m^3] is the air density. A typical variable speed operating c_p-λ curve is shown in Fig.5, so that for given rotor and wind speed, the optimum tip speed ratio can be calculated from the relevant c_p-λ curve.

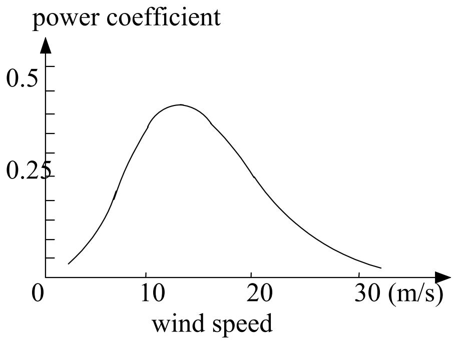

Fig. 5. Power coefficient curve

2.3 PM Generator, Filter and Rectifier System Modeling

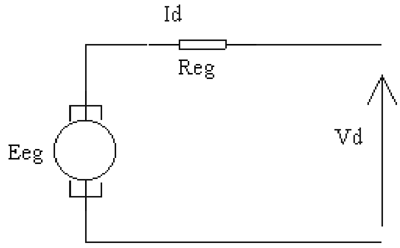

Fig. 6. Circuit model of equivalent DC machine

The circuit configuration of *n* sets of stator and rectifier modules in a modular PM generator system is shown in Fig.4.The multi-phase rectifier system can be seen as an extension of a three phase parallel bridge rectifier circuit reported in 1970s. (R.Ramakumar *et al* 1973) The above circuit model can be simulated in detail, but the simulation of a circuit model would be very time consuming. With such a large number of phases, the generator-rectifier system produces a smooth dc link voltage and current, therefore, in the steady state, the electrical characteristics as viewed from the dc side may be described by an equivalent DC machine. The dc system characteristics within the normal operating region are shown in Fig. 6. The dc link voltage *Vd* and current *Id* are related by (Z.Chen *et al* 2001)

$$V_d = E_{eq} - R_{eq} I_d \qquad (3)$$

The parameters (*Eeq, Req*)_of the equivalent DC machine can be expressed as functions of frequency and dc current. These functions can be established by fitting a suitable analytic curve to data obtained by test or numerical simulation

2.4 Pitch Angle Actuator Modeling

At wind gusts above rated, the incoming power should be bounded by adjust the pitch angle β. The pitch angle is controlled by an electro-mechanical actuator, which is modeled as a first order system with time constant τ_{β}.

$$\dot{\beta} = \frac{1}{\tau_\beta}(\beta_r - \beta) \qquad (4)$$

where β_r is the reference input and β is the pitch angle.

2.5 Measurer of Generator Shaft Angular Speed Modeling

Measurer of generator shaft angular speed, which is modeled as a first order system with time constant with τ_ω, is expressed ω_{gm}.

$$\dot{\omega} = \frac{1}{\tau_\omega}(\omega_g - \omega_{gm}) \qquad (5)$$

It is known that the power coefficient curves $C_p(\lambda, ß)$ are some discrete values of ß. It used to the neural network to produce power coefficient for any value of tip speed ratio λ in the rang [0….40] and for any continuous pitch value in range [0…20]. The neuron model used is the orthogonal progression (R.Chedid *et al* 1999; Shi zhongke 1997).

3. CONTROLLER DESIGN

As noted by several researchers, to electively extract wind power while at the same time maintaining safe operation, the wind turbine should be driven according to the following three fundamental modes associated with wind speed, maximum allowable rotor speed and rated power, i.e. (Y.D.Song,*et al* 2000)

Mode 1 operating at variable speed/optimum tip-speed ratio:

$$Uc \leq U \leq Ub \tag{6}$$

Mode 2 operating at constant speed/variable tip-speed ratio:

$$Ub \leq U \leq Ur \tag{7}$$

Mode 3 operating at variable speed/constant power:

$$Ur \leq U \leq Uf \tag{8}$$

Where Uc is the *cut-in* wind speed, Ub denotes the wind speed at which the maximum allowable rotor speed is reached, Ur is the *rated* wind speed and Uf is the furling wind speed at which the turbine needs to be shut down for protection. It is seen that if high-power efficiency is to be achieved at lower wind speeds, the rotor speed of the wind turbine must be adjusted continuously against wind speed. The linearization method allows the linear system theory to be applied in control design and analysis. However, due to the stochastic operating conditions and the inevitable uncertainties inherent in the system, such a control method comes at the price of poor system performance and low reliability (Y.D.Song,*et al* 2000).

In this work, a method is presented for variable speed control of wind turbines. The objective is to make the rotor speed track the desired speed that is specified according to the three fundamental operating modes as described earlier. Auto-adjusting the DC voltage of the generator through the developed nonlinear and adaptive control algorithms achieve this. Such a control scheme leads to more energy output without involving additional mechanical complexity to the system.

3.1 Turbine Speed Controller

A procedure similar to back-stepping, called Multiple Surface Sliding control (MSS) (J. K. Hedrick and P. P. Yip 2000), was developed along the line of sliding control to simplify controller design of systems where model differentiation was difficult. Numerical differencing schemes are used in MSS control to obtain time derivatives of system nonlinearities. Let us apply MSS control to the previous example.
Define:

$$\begin{aligned} s_1 &:= z_1 = x_1 \\ s_2 &:= z_2 = x_2 - x_{2d} \\ &\Rightarrow \dot{s}_1 = f_1 + x_2 + \Delta f_1(s_1) \end{aligned} \tag{9}$$

Now choosing x_{2d} to make $s_1 s_1 < 0$ assuming s_2 will be driven to zero. A reasonable choice for x_{2d} is

$$x_{2d} = -f_1 - KS_1 - \rho_1 \mathrm{sgn}(S_1) \tag{10}$$

The dynamics of s_1 is then given by:

$$\dot{s} = s_2 - KS_1 + \Delta f_1(s_1) - p_1 \operatorname{sgn}(s_1). \tag{11}$$

However, there have a problem getting the dynamics of s_2, because It cannot differentiate x_{2d} . Differentiation of x_{2d} involves differentiation of the discontinuous function sign(s_1) and s_1 involves $\triangle f_1(s_1)$, which is uncertain. The problem with the discontinuity has been dealt with by dropping the sign (s_1) term in the choice of x_{2d} together with a sufficiently large K, while numerical differentiation is used to solve the problem with the uncertainty on s1,i.e.

$$\dot{x}_{2d} \approx \frac{x_{2d}(n\Delta T) - x_{2d}((n-1)\Delta T)}{\Delta T} \tag{12}$$

where $\triangle T$ is the sampling time interval for a discrete time implementation.

The model of small variable-speed wind energy

$$T_{aero} = \frac{1}{2} P C_{po} \pi R^5 \frac{1}{\lambda_o^{3}} \omega^2 = k\omega \tag{13}$$

conversion system can be given below. The error between ω_{ref} and ω is used to control generator torque to move the rotor speed toward the optimal value.

$$\omega = \sqrt{\frac{T_{aero}}{k}} \tag{14}$$

$$I\dot{\omega} = T_{aero} - T_{gen} \tag{15}$$

The desired output is chosen as ω_{ref} ; the first sliding s_1 is defined as $s_1 = \omega - \omega_{ref}$. So, the controller can be got by procedure of MSS.

3.2. Simulation Study

This system (MWINV-4R222) is tested in conjunction with a variable speed permanent generator and a alternate servo-motor simulator which rated capacity is 2 kW. The inverter was for experiments and research and development of the power electronics that rated capacity is 2 kW. Lead-acid battery bank is the DC loading. The block diagram in Fig 8 illustrates the simulation logic.

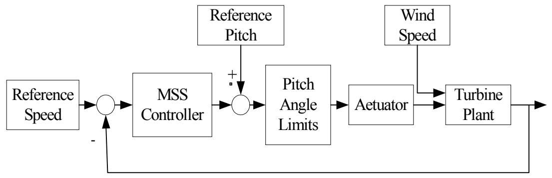

Fig. 8. Simulation block diagram

Actual wind data sample at 1 Hz is the input to the non-linear plant model. The rotor-speed error is input to the controller which commands a change in blade-pitch angle. The pitch is physically limited to angle between 1° and 15°. The simulation conducted was the tracking of the following desired trajectory

$$\omega^{*} = 2 + \sin(t) \tag{16}$$

The tracking error is depicted in Fig.8. It is seen that nonlinear control schemes lead to good tracking performance.

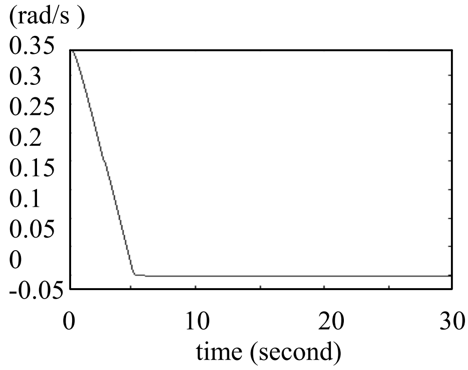

Fig. 9. Tracking process

3.3. Experiment Study

Test of the proposed method based on MWINV-4R222 simulation system is conducted. The results are shown in Fig.10 and Fig.11.

The algorithm of capturing maximum power can be summarized as follows: The power regulation regime is entered when the turbine reaches the design rotor speed for maximum power production. Under these conditions, rotational speed is constrained to a specified maximum value through blade-pitch regulation. Fluctuations in wind speed are accommodated to prevent large excursions from the desired rotational speed. Thus the power production is also constrained to a relatively constant level. In addition to maintaining a constant rotational speed, actuator movement must be restrained to prevent fatigue and overheating. The combination of maintaining a constant rotational speed and minimizing actuator motion are the control objectives specified for the power regulation regime, which auto-adjusts the DC voltage of the generator through load. Together with the measured wind speed wind speed v and sensed shaft speed ω, the tip-speed radio can be maintained by adjusting Pitch angle and DC loading.

The simulation and experiment of pilot study indicate that the control regime is correctly. It could get more power if the wind turbine is operated at variable speed mode by the proposed scheme. The turbine can get maximum power under the rated power, and maintain a constant power at the point of rated power. The advanced study is carrying through now.

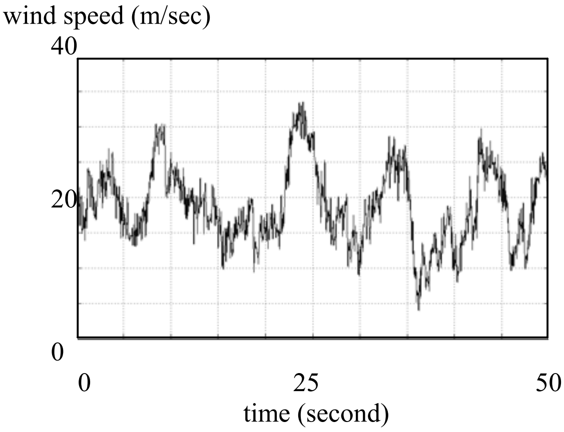

Fig. 10. Wind speed data for case study

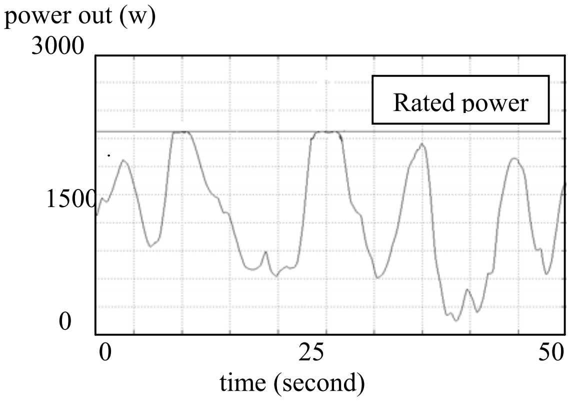

Fig. 11. Output electrical power

4. CONCLUSION

Variable speed operation of wind turbine is necessary to increase power generation efficiency. The Multiple Sliding Surface wind turbine control method is explored in is paper.

This method is based on the regulation of excitation DC voltage of the PM generator and the Pitch angle. Analysis and experiment show that the method is able achieve smooth and satisfactory rotor speed tracking. In addition, a comparison study have been carried out between the proposed method and the tradition Variable speed operation control method that adjust the Pitch angle only. It is found that the proposed method could diminish fatigue of mechanism.

5. ACKNOWLEDGEMENTS

Supported by the Doctorate Foundation of Xi'an Jiaotong University.

REFERENCES

Deniz Yildirim.(1999) .Commissioning of 30KVA Variable-speed, Direct-drive Wind Power Plant. In: *Thesis of doctor degree*, University of Colorado, USA.

D.J. Leith and W.E. Leithead (1997). Implementation of wind turbine controllers. *Int. J. control* ,**Vol 66 (3)**, pp 349-380.

J. K. Hedrick and P. P. Yip (2000) . Multiple Sliding Surface Control, *Theory and Application. Transaction on ASME*, **Vol. 122**, pp. 586-592.

K S, Narendra , K Parthasarsthy (1992) . Identification and Control of Dynamic Systems using neural networks. *IEEE Trans. On Neural Networks*, March 1992, **Vol 1**, pp. 14-37.

P.W. Carlin, A.S. Laxson, E.B. Muljadi (2000). History and State of the Art of Variable-Speed Wind Turbine technology, *Report of National Renewable Energy Laboratory*. USA.

R.Chedid, F. Mrad, M.Basma (1999) . Intelligent control of a class of wind energy conversion systems. *IEEE Transaction on Energy Conversion,* **Vol 14 (4)**, pp. 1597-1604.

R.Ramakumar, H.J.Allison , W.L.Hughes(1973), Analysis of the parallel bridge rectifer system. IEEE Trans. On Industry Application. Vol IA-9, no. 4, pp. 425-436.

S.A. Salle, D. Reardon, W.E. Leithead, M.J. Grimble (1990). Review of wind turbine control. *Int. J. Control* ,**Vol 52 (6)**, pp. 1295- 1310.

Shi zhongke (1997) . *Theory of neural networks control.* Northwest Production University Press.

Xiao jinsong(1996) Dynamic Modeing and Robust Control of Wind Energy Conversion System, *Thesis of doctor degree.* Tsinghua University ,China.

V. I. Utkin(1991). *Sliding Modes in Control and Optimization*, Springer-Verlag,. Berlin.

Y.D.Song, B.Dhinakaran, X.Y.Bao (2000) Varable speed control of wind turbines using nonlinear and adaptive algorithms , *Journal of Wind Engineering and Industrial Aerodynamics* , **Vol 85**, pp 293-308.