A REVIEW OF CONTROL STRATEGIES FOR ANALYZING AND DESIGNING MANAGING WIND GENERATORS

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ABSTRACT

Wind energy is currently a fast-growing interdisciplinary field that encompasses many different branches of engineering and science. Modeling and controlling wind energy systems is a difficult and challenging problem. The basic structure of wind turbines and some wind control system methods are briefly reviewed. The need for using advanced theories from fuzzy and intelligent systems in studying wind energy systems is identified and justified. Fuzzy Cognitive Maps are used to model wind energy systems. Simulation studies are performed and obtained results are discussed. Many open problems in the areas of modeling and controlling wind energy systems are outlined.

Keywords: modeling, control, energy systems, wind generators, fuzzy cognitive maps

1. INTRODUCTION

The purpose of modern wind energy conversion systems (WECS) is to extract the aerodynamic power from the wind and convert it to electric power. Today the most wide spread version of WECS is the horizontal axis wind turbine (HAWT) with a 3 blade upwind rotor (Hau 2010; Tong 2010). Before the introduction of variable speed generators, the rotor speed on the HAWT was kept constant. This constraint limited the efficiency of the wind power capture. New wind turbines are able to operate more efficient over a wider range of wind speeds, which has lead to more sophisticated control strategies with the added degrees of freedom. Modern wind turbines are controlled by the pitch of the rotor blades, the electromagnetic torque of the generator and by the yaw of the nacelle. Traditionally wind turbines are placed on land or on solid foundations if placed in the water. This limits their deployment to locations of relatively shallow water because the construction costs of an underwater monopole are too expensive or technically impossible. Modeling and controlling such systems is extremely difficult but absolutely needed.

In this paper an overview of existing advanced modeling and control theories in analyzing and studying wind generators is presented. In Greece lately many wind farms have been installed on mountains. Wind energy production attracts interest as it encompasses many different branches of engineering and science. Standard and Adaptive techniques have been used for modeling and control wind generators. The strong points of these methods are reviewed, studied and presented. So, nowadays there are many methods to generate and control wind energy. However, the wind energy management is a challenging field. The need for development of wind energy will be modeled using Fuzzy Cognitive Maps. An introduction to basic theories of Fuzzy Cognitive Maps is presented. Especially the potential use of Fuzzy Cognitive Maps is investigated and future research directions are proposed.

2. WIND TURBINE THEORIES

A wind turbine (WT) consists of turbine tower, blades, rotor, generator, nacelle, shaft, drive or coupling device, converter and control system.

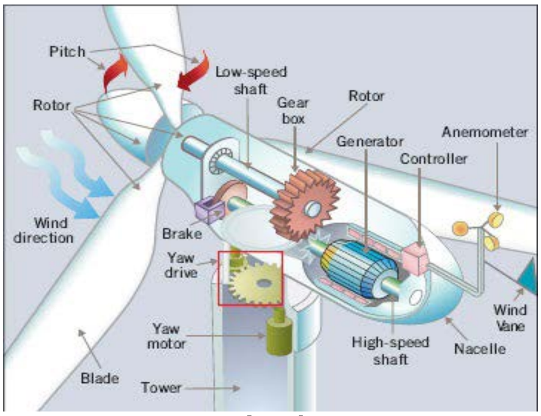

Figure 1: Wind Turbine Structure

The nacelle houses the generator, which is driven by the high-speed shaft. The high-speed shaft is in turn usually driven by a gear box, which steps up the rotational speed from the low-speed shaft. The low-speed shaft is connected to the rotor, which includes the airfoil-shaped blades. These blades capture the kinetic energy in the wind and transform it into the rotational kinetic energy of the wind turbine.

There are two main types of wind turbines: horizontal axis and vertical axis. Horizontal axis turbines, which are more common, have to point into the wind and their axis is horizontal. Because of the angle of their blades, they can collect the maximum amount of wind energy. Vertical axis turbines have axes that are vertically sticking out of the ground and blades that rotate around the axis. They don't need to point into the wind, which makes them more useful in places where the wind direction is unpredictable.

Some wind turbines are designed to operate at a constant speed, while others are built to rotate at variable speeds. The internal components of these two types of turbines are very different. In constant speed machines, the connection between the generator and grid do not allow for much variation in the blade rotation speed. Variable speed turbines use power converters that allow for a wider range in blade rotations. Power converters add to the cost of these machines, but variable speed wind turbines provide significant advantages to a wind farm and engineers continue to research ways to make these turbines more efficient.

The output power of wind turbines varies with wind speed, but is not proportional to it, as the energy that the wind contains increases with the cube of the wind speed. Variable speed wind turbines have four main regions of operation. A stopped turbine or a turbine that is just starting up is considered to be operating in Region 1 in which the wind speed is too low for the turbine to generate power. Region 2 is an operational mode in which it is desirable to capture as much power as possible from the wind and lies between the cut-in speed and rated speed. Here the generator operates at below rated power. In Region 3, in which the wind is sufficient for the turbine to reach its rated output power, the turbine must limit the captured wind power so that safe electrical and mechanical loads are not exceeded. Region 4 is the period of stronger winds, where the power in the wind is so great that it could be detrimental to the turbine, so the turbine shuts down.

3. CONTROL STRATEGIES

Above rated wind speed, the primary objective is to keep power output of the turbine and associated loads on the turbine structure within design limits. Classical techniques such as proportional, integral, and derivative (PID) control of blade pitch (Svensson and Ulen 1982) are typically used to limit power and speed on both the low-speed shaft and high-speed shaft for turbines operating in region 3. In addition, several model-based classical/optimal control design techniques have been used to design controllers to regulate generator speed in high wind speed conditions (Stol and Ballas 2001; Vihriala 2002). Below rated wind speed, the focus is on maximizing power capture. The loads on structure are, generally, small. In this region of operation (region 2), generator torque control (Fingersh and Carlin 1998) is usually used. In (Stol and Ballas 2002) disturbance accommodating control is used to limit power and speed in region 3. The reduction of mechanical loads on the tower and blades is another area of turbine control research (Wright and Balas 2004).

Furthermore, there are many aspects of wind turbine performance that can be improved with more advanced control development. Researchers have developed methods for using adaptive control to compensate for unknown or time-varying parameters in regions 2 and 3 (Bhowmik, Spée and Enslin 1999; Freeman and Balas 1999; Song, Dhinakaran and Bao 2000). A few researchers have also begun to investigate the addition of feedforward control to improve the disturbance rejection performance when the incoming wind profile deviates from that expected (Hand, Wright, Fingersh and Harris 2006). Most of these feedforward controllers use estimates of the disturbance or wind deviation. For instance, lidar sensors can provide quantities representing the wind speed and direction and various wind turbulence and shear parameters (Hand, Wright, Fingersh and Harris 2006). Advanced wind turbine controllers are discussed in (Laks, Pao and Wright 2009).

Other researchers have developed techniques in order to qualify output power and guarantee operation of the wind turbine. Their studies focus on: vector control, optimization control, power smoothing control and voltage control. Vector control is widely applied in the control of induction machines and several types of this control type are discussed in (Cárdenas and Pena 2004; Chowdhury and Chellapilla 2006). Optimization control of wind turbine includes several objectives, such as maximum power output, maximum power efficiency, minimum control input, minimum loss, etc. References (Mihet-Popa, Blaabjerg and Boldea 2004; Munteanu, Cutululis, Bratcu and Ceanga 2005) discuss optimization control methods for maximizing power extraction using algorithms, robust controllers, etc. Power fluctuation is one drawback of wind power which can influence power quality. In (Cárdenas, Peña, Asher and Clare 2004; Senjyu, Sakamoto, Urasaki, Funabashi, Fujita and Sekine 2006) control strategies pointing to power smoothing are presented. Voltage control of wind turbine or wind farm is not indispensable for itself, but also plays a great role in voltage stability of grid. In (Tapia, Tapia and Ostolaza 2004; Hatziargyriou, Karakatsanis and Lorentzou 2005) the issue of voltage control is discussed.

Modeling and control nonlinear complex systems, with new system theories, have always been fruitful challenges. Many approaches have been developed. Some of them had good success in applying them to wind energy while some others had some “problems”. However, a question as to how much wind energy should be produced on a given geographical region has not yet found a realistic and acceptable solution. Although FCMs have been used for wind modeling there still is the question of optimal and cost effective generation.

4. INTRODUCTION TO FUZZY COGNITIVE MAPS

Fuzzy cognitive map (FCM) is a soft computing technique, which is capable of dealing with complex systems. FCM is a promising modeling method for describing particular domains showing the concepts (variables) and the relationships between them (weights) while it encompasses advantageous features. FCM model represents the whole system by a signed directed graph with feedbacks, which indicate cause and effect among the concepts. It models a system as a collection of concepts and causal links between them. The concepts are represented by nodes in this graph and each concept represents a particular characteristic of the system. In the FCM model cause and effect relationships among these concepts is indicated by interconnected weighted links which have either positive or negative signs and different weights. Each link gets a weight Wij according to the strength of the causal relationship between the concepts Ci and Cj.

Some experts understand potential influences and interactions between concepts. So, the expert's knowledge is transformed into a dynamic weighted graph. Experts describe the existing relationship between the concepts as a degree of influence using a linguistic variable, such as "low", "medium", "high", etc. More specifically, the causal interrelationships among concepts are declared using the variable influence which is interpreted as a linguistic variable taking values in the universe of discourse [-1, 1]. A detailed description of the development of FCM model is given in (Stylios and Groumpos 2004).

The value of each concept at every simulation step is calculated by applying the following calculation rule (Groumpos and Stylios 2000):

$$A_i^t = f\left(\sum_{\substack{j=1 \\ j \neq i}}^{N} A_j^{t-1} \cdot W_{ji} + A_i^{t-1}\right) \qquad (1)$$

where A_i^{t-1} is the value of the concept Ci at iteration step t-1 and A_i^t is the value of the concept Ci at iteration step t.

Usually the f function is:

$$f(x) = \frac{1}{1 + e^{-\lambda x}} \qquad (2)$$

which is the unipolar sigmoid function, where $\lambda > 0$ determines the steepness of the continuous function f(x).

5. THE CONSTRUCTION OF A WIND GENERATOR SYSTEM USING FCM THEORIES

In this section a Fuzzy Cognitive Map will be constructed for a simple wind generator system. An expert proposed us a system with four inputs (C1, C2, C3, C4) and one output which is the development of wind energy (C5). So, the concepts are:

- C1: Energy demand
- C2: Fossil fuel reserves
- C3: Wind technologies / equipment / cost
- C4: Energy cost (from conventional sources)
- C5: Development of wind energy

Concepts stand in the interval [0, 1]. The closer to the 1 the value of the output concept is getting, the higher the need wind energy production is. An expert gave his opinion about the interaction between the concepts and informed us about how much "energy demand" (concept 1), "fossil fuel reserves" (concept 2), "wind technologies / equipment / cost" (concept 3) and "energy cost (from conventional sources only)" (concept 4) influence the production of wind energy (output: concept 5). So the weights between concepts are:

Table 1: Weights between Concepts

Weights					
	C1	C2	C3	C4	C5
C1	0	-0.25	0	+0.6	+0.3
C2	0	0	0	-0.55	-0.3
C3	0	0	0	0	-0.3
C4	0	0	+0.25	0	+0.3
C5	0	0	-0.15	-0.15	0

The weight matrix is presented below:

Table 2: Weight matrix

$$W = \begin{bmatrix} 0 & -0.25 & 0 & +0.6 & +0.3 \\ 0 & 0 & 0 & -0.55 & -0.3 \\ 0 & 0 & 0 & 0 & -0.3 \\ 0 & 0 & +0.25 & 0 & +0.3 \\ 0 & 0 & -0.15 & -0.15 & 0 \end{bmatrix}$$

The initial Fuzzy Cognitive Map with the first values of concepts will be as follows:

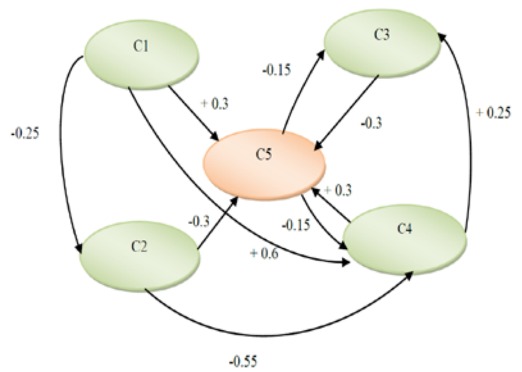

Figure 2: The FCM Model

The model shown in Figure 2 will be used in the next section in order to predict the wind energy production.

6. SIMULATION, RESULTS AND DISCUSSION

Three different scenarios will be simulated in order to decide how much wind energy production is necessary. As it was mentioned above the values of the concepts are between [0, 1].

1st Scenario: Suppose that the expert decided as initial values of the inputs the following which correspond to a situation where the need for wind energy production is low:

Table 3: Initial Values of Inputs (1st scenario)

Initial values		
C1	0.25/1	Very low
C2	0.5/1	Medium
C3	0.75/1	High
C4	0.4/1	Medium

The FCM simulation for the 1st scenario has the following results:

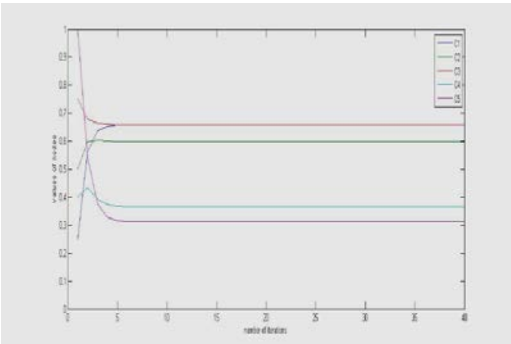

Figure 3: Subsequent Values of Concepts

where the output value is C5=0.3129. This value, according to our expert, is satisfactory enough if we take into account that the development of wind energy production should be low when the inputs (C1, C2, C3, C4) have these initial values.

2nd scenario: Suppose that the expert decided as initial values of the inputs the following which correspond to a situation where the need for wind energy production is medium:

Table 4: Initial Values of Inputs (2nd scenario)

Initial values		
C1	0.5/1	Medium
C2	0.45/1	Medium
C3	0.6/1	High
C4	0.55/1	Medium

The FCM simulation for the 2nd scenario has the following results:

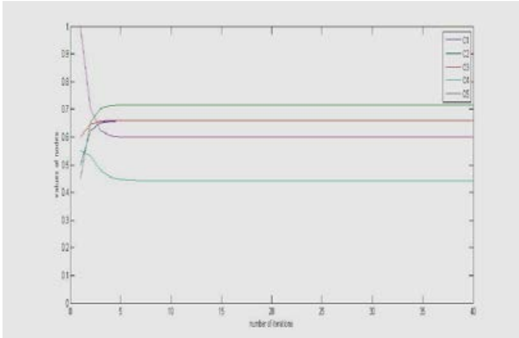

Figure 4: Subsequent Values of Concepts

where the output value is C5=0.5994. This value, according to our expert, is satisfactory enough if we take into account that the development of wind energy production should be medium when the inputs (C1, C2, C3, C4) have these initial values.

3rd scenario: Suppose that the expert decided as initial values of the inputs the following which correspond to a situation where the need for wind energy production is high:

Table 5: Initial Values of Inputs (3rd scenario)

Initial values		
C1	0.75/1	High
C2	0.25/1	Very low
C3	0.35/1	Low
C4	0.65/1	High

The FCM simulation for the 3rd scenario has the following results:

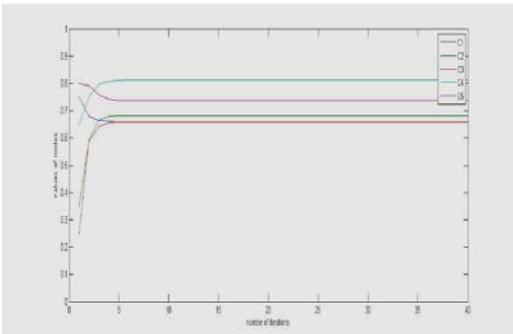

Figure 5: Subsequent Values of Concepts

where the output value is C5=0.7358. This value, according to our expert, is satisfactory enough if we take into account that the development of wind energy production should be high when the inputs (C1, C2, C3, C4) have these initial values.

7. CONCLUSIONS AND FUTURE RESEARCH

In this paper, we first reviewed the basic structure of wind turbines and then describe wind turbine control systems and control loops. We have seen that the generator torque and blade pitch control systems are very important in wind energy system design. Significant performance improvements are achievable with more advanced systems and control research. The new method of Fuzzy Cognitive Maps for modeling and controlling nonlinear systems is used for first time to model wind energy conversion systems. The proposed model is very simple in which only one expert is used. However the simulation studies show that the use of FCMs does provide a new promising methodology approach in modeling and controlling wind energy systems.

Some interesting challenging research topics include: 1) the validation of the proposed model 2) include additional concepts in modeling wind energy conversion systems especially for different geographical regions 3) use more than the one expert 4) conduct simulation studies using real data for various applications and 5) use learning algorithms to train the experts.

8. REFERENCES

Bhowmik, S., Spée, R., Enslin, J. 1999. Performance optimization for doubly-fed wind power generation systems. *IEEE Trans. Ind. Applicat.* vol. 35:949–958.

Cárdenas, R., Pena, R., 2004. Sensorless vector control of induction machines for variable-speed wind energy applications. *IEEE Trans. Energy Conversion* vol. 19:196-205.

Cárdenas, R., Peña, R., Asher, G., Clare, J., 2004. Power Smoothing in Wind Generation Systems Using a Sensorless Vector Controlled Induction Machine Driving a Flywheel. *IEEE Trans. Energy Conversion* vol. 19:206-216.

Chowdhury, H. B., Chellapilla, S., 2006. Double-fed induction generator control for variable speed wind power generation. *Electric Power Systems Research* vol. 76:786–800.

Fingersh, L., Carlin, P., 1998. Results from the NREL variable-speed test bed. *in Proc. 17th ASME Wind Energy Symp.*, pp .233–237. January 12-15, Reno, NV.

Freeman, J., Balas, M., 1999. An investigation of variable speed horizontal axis wind turbines using direct model-reference adaptive control. *in Proc. 18th ASME Wind Energy Symp.*, pp. 66–76. January 11-14, Reno, NV.

Groumpos, P.P., Stylios, D.C., 2000. Modeling supervisory control systems using fuzzy cognitive maps. *Chaos Solit Fract.*, 11(3), 329–336.

Hand, M. M., Wright, D. A., Fingersh, J. L., Harris, M., 2006. Advanced wind turbine controllers attenuate loads when upwind velocity measurements are inputs. *in Proc. 25th AIAA/ASME Wind Energy Symp.*, Reno, NV.

Hatziargyriou, D. N., Karakatsanis, S. T., Lorentzou, I.M., 2005. Voltage control settings to increase wind power based on probabilistic load flow. *Electrical Power and Energy Systems* vol. 27:656–661.

Hau, E., 2010. *Wind Turbines: Fundamentals, Technologies, Application, Economics.* Berlin, New York : Springer.

Laks, H. J., Pao, Y.L., Wright, A., 2009. Control of wind turbines: Past, present, and future. *in Proc. American Control Conf.* June 2009, St. Louis, MO.

Mihet-Popa, L., Blaabjerg, F., Boldea, I., 2004. Wind Turbine Generator Modeling and Simulation Where Rotational Speed is the Controlled Variable. *IEEE Trans. Industry applications* vol. 40:3-10.

Munteanu, I., Cutululis, A. N., Bratcu, I. A., Ceanga, E., 2005. Optimization of variable speed wind power systems based on a LQG approach. *Control Engineering Practice* vol. 13:903–912

Senjyu, T., Sakamoto, R., Urasaki, N., Funabashi, T., Fujita, H., Sekine, H., 2006. Output Power Leveling of Wind Turbine Generator for All Operating Regions by Pitch Angle Control. *IEEE Trans. Energy Conversion* vol. 21:467- 475.

Song, Y., Dhinakaran, B., Bao, X., 2000. Variable speed control of wind turbines using nonlinear and adaptive algorithms. *J. Wind Eng. Ind. Aerodyn.* vol. 85:293–308.

Stol, K., Ballas, M., 2001. Full-State Feedback Control of a Variable-Speed Wind Turbine: A Comparison of Periodic and Constant Gains. *Journal of Solar Energy Engineering* vol 123:319-326.

Stol, K., Ballas, M., 2002. Periodic disturbance accommodating control for speed regulation of wind turbines. *in Proc. 21st ASME Wind Energy Symp.*, pp. 310–320. January 14-17, Reno, NV.

Stylios, D. C., Groumpos, P. P., 2004. Modeling complex systems using fuzzy cognitive maps. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 34, 155–162.

Svensson, J., Ulen, E., 1982. The control system of WTS-3 instrumentation and testing. *in Proc. 4th Int. Symp. Wind Energy Systems*, pp. 195–215. September 21-24, Stockholm, Sweden.

Tapia, A., Tapia, G., Ostolaza X. J., 2004. Reactive power control of wind farms for voltage control applications. *Renewable Energy* vol. 29:377– 392.

Tong, W., 2010. *Wind Power Generation and Wind Turbine Design.* USA, Canada, Mexico:WIT Press.

Vihriala, H., 2002. Control of variable speed wind turbines. Thesis (PhD). Tampere University of Technology.

Wright, A., Balas, M., 2004. Design of controls to attenuate loads in the Controls Advanced Research Turbine. *J. Solar Energy Eng.* vol. 126:1083–1091.