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Study on Fuzzy Models of Wind Turbine Power Curve

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Abstract: - This paper presents the fuzzy modeling approach to the description of wind turbine power curve. The fuzzy system model is basically a collection of fuzzy IF-THEN rules that are combined via fuzzy reasoning for describing the features of a system under study. The method of fuzzy modeling has been proven to be well-suited for modeling nonlinear industrial processes described by input-output data. In view of the nonlinear characteristic of wind turbine power curve, the method of fuzzy modeling is employed for representing the curve. Based on the Sugeno-type fuzzy model, various models with different numbers of modeling rules are used to describing the power curve which depicts the turbine output power under various wind speeds. It is found that such fuzzy model offers both quantitative and qualitative descriptions for the wind turbine power curve.

Key-Words: - **power system, wind energy, wind turbine, power curve, fuzzy modeling.**

1 Introduction

Electric energy is playing a very important role in our daily life. It offers the motive power of the economic activity and has much influence on the quality of living environment. With increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are made to generate electricity from renewable sources. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and the infinite availability of the prime mover that is converted into electricity [1-5]. One way of generating electricity from renewable sources is to use wind turbines that convert into electricity the energy contained in flowing air.

A fuzzy system model is basically a collection of fuzzy IF-THEN rules that are combined via fuzzy reasoning for describing the features of a systematic behavior [6-12]. The method of fuzzy modeling has been proven to be well-suited for modeling nonlinear industrial processes described by input-output data. The fuzzy model describes the essential features of a system by using linguistic expressions. The fuzzy model not only offers the accurate expression on the quantitative information to the nonlinear system, but also can present the qualitative description for the physical property of study system. Generation of electrical power by a wind turbine generator system at a specific site depends upon the power curve [1-6]. The method of fuzzy modeling has been proven to be well-suited for modeling nonlinear industrial processes described by input-output data. In view of the nonlinear characteristic of wind turbine power curve, the fuzzy model is employed for the purpose of analysis.

This paper aims to report an application of the Sugeno-type fuzzy modeling method [8-10] to the description of power curve for the wind turbine generator. Based on the Sugeno-type fuzzy model, different numbers of modeling rules are adopted and compared in constructing the fuzzy models for representing the output power of a wind turbine generator under different wind speeds which is referred to as the power curve [1-5]. The data points are fitted into the Sugeno-type fuzzy model by employing the algorithm of ANFIS (Adaptive Neuro-Fuzzy Inference System) [10]. It is shown that the model is capable of providing both quantitative and qualitative description for the power curve of a wind turbine generator.

2 Power Curve of Wind Turbine

The output power generated by a wind turbine at a specific site depends upon many factors. Besides the mean wind speed of the site, a much more significant one will be the power curve of the wind turbine which relies on variable wind speeds under different hub heights [1-5]. A typical wind turbine power curve is shown in Figure 1 [13]. Essentially the wind turbine power curve has a nonlinear physical characteristic and the wind speed has significant

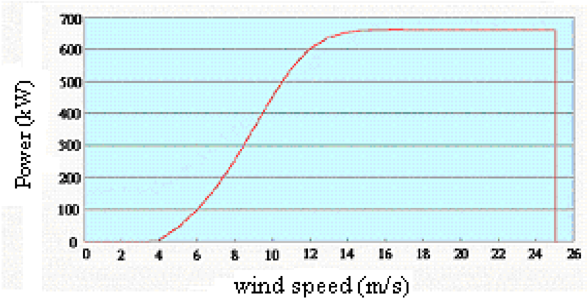

Figure 1. A typical wind turbine power curve [13]

Table 1. The Beaufort scale

Scale	Name	Wind speed (m/s)
0	Calm	Below 0.3
1	Light Air	0.3-1.5
2	Slight Breeze	1.6-3.3
3	Gentle Breeze	3.4-5.4
4	ModerateBreeze	5.5-7.9
5	Fresh Breeze	8.0-10.7
6	Strong Breeze	10.8-13.8
7	Near Gale	13.9-17.1
8	Gale	17.2-20.7
9	Strong Gale	20.8-24.4
10	Storm	24.5-28.4
11	Violent Storm	28.5-32.6
12	Hurricane	32.7-36.9

effect on energy production. In general, the wind turbine starts to generate energy under a wind speed of 3 to 5 m/s which is referred to as the cut-in wind speed. When the wind speed falls between 12 and 15 m/s, the wind turbine electrical power arrives at the rated output, and such wind speed is named the rated wind speed. As the wind speed reaches certain intensity above 25 (m/s), it is necessary to shut down the wind turbine for avoiding damage. This is called the cut-out wind speed or furling.

It is general to designate the scale of wind speed by meter per second (m/s) or according to the Beaufort scale shown as Table 1.

3 Fuzzy Modeling

3.1 Fuzzy Set

The classical set notation strictly assigns each studied object into a relation of membership or non-membership. On the contrary, a set containing elements that have varying degrees of membership in the set is referred to as the fuzzy set [6]. Based on fuzzy set theory, the fuzzy model [7-12], which consists of a number of fuzzy IF-THEN rules, is used for describing the behavior or characteristic of the studied system. It typically expresses an inference such that if we know a premise, then we can infer or derive a conclusion. In a general nonlinear system, each of the fuzzy relational equations can be expressed in rule-based form. In modeling nonlinear systems, various types of fuzzy rule-based system could be described by a collection of fuzzy IF-THEN rules. The objective of this paper is to study an application of the fuzzy model to describe the nonlinear wind turbine power curve.

Among various types of fuzzy models, the Sugeno-type fuzzy model has recently become one of the major topics in theoretical studies and practical applications of fuzzy modeling and control [8-10]. The basic idea of Sugeno-type fuzzy model is to decompose the input space into fuzzy regions and then to approximate the system in every region by a simple linear model. The overall fuzzy model is implemented by combining all the linear relations constructed in each fuzzy region of the input space. The main advantage of the Sugeno-type fuzzy model lies in its capability of smoothly interpolating linear functions in different regions of the system.

3.2 Model Structure

In this study, the single-input-single-output Sugeno-type fuzzy model consisting of n rules, as described in (1), $i = 1, 2, \cdots, n,$ is adopted for describing the wind turbine power curve:

$$R^i: \text{ IF } v \text{ is } A^i \text{ THEN } P_i = a_i v + b_i, \; i = 1, 2, \cdots, n. \quad (1)$$

where v stands for the system input (the wind speed) and P_i (the output power) represents the output in the ith subregion. It is noted that the input domain is partitioned into n fuzzy subregions (wind scales), which is described by a fuzzy set A^i, and the system behavior in each subregion is modeled by a linear equation $P_i = a_i v + b_i$ of which a_i is the coefficient of wind variation and b_i is a constant. Let $m_i(x)$ denote the membership function of the fuzzy set A^i. If the system input v attains a reading v^0 then the overall system output P is obtained by computing a weighted average of all the outputs P_i's from each rule as shown in (2) and (3).

$$P = \left(\sum_{i=1}^{n} w_i P_i\right) / \left(\sum_{i=1}^{n} w_i\right) \quad (2)$$

$$w_i = m_i(v^0), \quad P_i = a_i v^0 + b_i. \quad (3)$$

3.3 Model Identification

Model identification can be defined as a process of recognizing structure in data by comparisons with known structure. The aim of model identification is to figure out all the parameters of the model. The tasks of model identification for the Sugeno-type fuzzy model are usually divided into two categories: structure identification and parameter identification.

(1) Structure identification: Set the number of model rules according to the system characteristics. Different numbers of model rules will yield different ways of description for the power curve.

(2) Parameter identification: First select the type of membership functions depending on the shape described in each fuzzy set. Then the parameters of the linear function in each rule are to be identified. In this study, the Gaussian type membership function in (5) is employed for the fuzzy set in the IF-part of the rule:

$$f(x) = \exp[-\frac{(x-c)^2}{2\sigma^2}] \tag{5}$$

where the parameters c and σ define the shape of each membership function. Then the parameters a_i and b_i in the THEN part of the rule can be identified by the method of ANFIS (Adaptive Neuro-Fuzzy Inference System) [10].

4 Example

The wind turbine power curve shown in Fig. 1[13] is selected for study in this paper. From Figure 1, the wind turbine starts to generate electric energy at this moment of wind speed 4 m/s, i.e. the cut-in wind speed v_{I}. When the wind speed is 13 m/s, namely the rated wind speed v_{R}, the wind turbine output power arrives at the rated output $P_{\max}$ as 660 kW. As the wind speed reaches the intensity around 25 m/s, i.e. cut-out wind speed v_{O} or furling, the wind turbine should be shut down for avoiding damage. The wind turbine power curve can be represented as (6) where v is the wind speed in meter per second and P is the output power of wind turbine in kW.

$$P = \begin{cases} 0, & v < v_{\mathrm{I}} \quad or \quad v > v_{\mathrm{O}} \\ FM(v), & v_{\mathrm{I}} \le v \le v_{\mathrm{R}} \\ P_{\max}, & v_{\mathrm{R}} < v \le v_{\mathrm{O}} \end{cases} \tag{6}$$

As the wind speed falls between the cut-in speed and the rated wind speed, the output power $FM(v)$ is to be describeded by the Sugeno-type fuzzy model. Note that $FM(v)$ is the nonlinear part of the power curve. To better understand the performance of the Sugeno-type fuzzy model, comparative studies are conducted under conditions of different numbers of modeling rules. As an illustration, fuzzy models with two, four, five and six rule are shown as follows. All parameters for models with different numbers of modeling rules are shown in Table 2 to Table 5. The mean-squared errors under different numbers of modeling rules are tabulated as Table 6.

(1) Two-rule model:

R^1 : IF v is slight breeze
THEN P_1=0.12v-5.12 (kW);

R^2 : IF v is fresh breeze
THEN P_2=0.22v+660 (kW).

(2) Four-rule model:

R^1 : IF v is light air
THEN P_1=0.17v-5.32 (kW);

R^2 : IF v is moderate breeze
THEN P_2=0.23v+440 (kW);

R^3 : IF v is fresh breeze
THEN P_3=0.12v+650 (kW);

R^4 : IF v is strong breeze
THEN P_4=0.22v+660 (kW).

(3) Five-rule model:

R^1 : IF v is calm
THEN P_1=-0.23v-3.12 (kW);

R^2 : IF v is slight breeze
THEN P_2=0.17v-5.32 (kW);

R^3 : IF v is moderate breeze
THEN P_3=0.23v+520 (kW);

R^4 : IF v is fresh breeze
THEN P_4=0.12v+660 (kW);

R^5 : IF v is strong breeze
THEN P_5=0.22v+655 (kW).

(4) Six-rule model:

R^1 : IF v is calm
THEN P_1=-0.35v-3.06 (kW);

R^2 : IF v is slight breeze
THEN P_2=0.23v-0.24 (kW);

R^3 : IF v is gentle breeze
THEN P_3=0.17v+520 (kW);

R^4 : IF v is moderate breeze
THEN P_4=0.23v+655 (kW);

R^5 : IF v is fresh breeze
THEN P_5=0.12v+659.5 (kW);

R^6 : IF v is strong breeze
THEN P_6=0.22v+660 (kW).

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Table 2. The parameters of two-rule model

Rule	Parameters (σ_i,c_i) of IF part	Parameters (a_i,b_i) of THEN part
1	(2.468, 3.25)	(0.12, -5.12)
2	(2.44, 8.552)	(0.223, 660)

Table 3. The parameters of four-rule model

Rule	Parameters (σ_i,c_i) of IF part	Parameters (a_i,b_i) of THEN part
1	(2.71, 1.11)	(0.1674, -5.32)
2	(2.14, 6.736)	(0.2284, 440)
3	(2.38, 9.316)	(0.12, 650)
4	(3.019, 13.4)	(0.223, 660)

Table 4. The parameters of five-rule model

Rule	Parameters (σ_i,c_i) of IF part	Parameters (a_i,b_i) of THEN part
1	(3.23, 0)	(-0.234, -3.12)
2	(2.823, 2.489)	(0.1674, -5.32)
3	(2.12, 6.273)	(0.2284, 520)
4	(1.48, 8.343)	(0.12, 660)
5	(2.56, 11.33)	(0.223, 655)

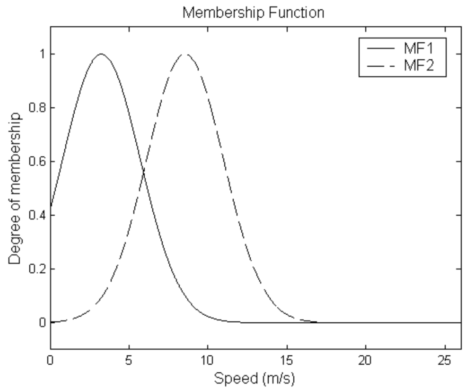
Table 5. The parameters of six-rule model

Rule	Parameters (σ_i,c_i) of IF part	Parameters (a_i,b_i) of THEN part
1	(2.88, 0)	(0.345, -3.057)
2	(2.12, 3.3)	(0.234, 0.24)
3	(1.82, 5.4)	(0.1674, 520)
4	(1.635, 7.9)	(0.2284, 655)
5	(1.53, 8.624)	(0.12, 659.5)
6	(2.13, 10.8)	(0.223, 660)

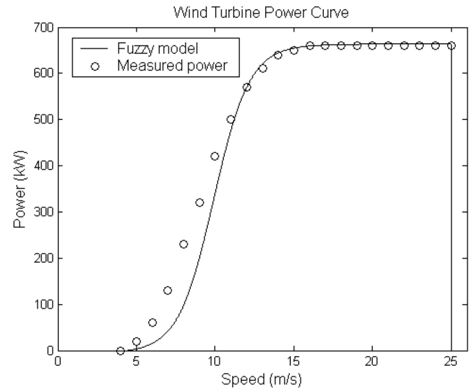
Table 6. The mean-square error under different numbers of modeling rules

Rule numbers	Mean-square error (%)
2	4.7423
4	1.9080
5	1.4456
6	0.4782

The membership functions as well as data points with fuzzy models are drawn in a single figure for the purpose of comparison as shown from Fig. 2 to Fig. 5. From Table 6 and Fig. 2 to Fig. 5, it is observed that more modeling rules will yield a model with higher degree of fitting accuracy.

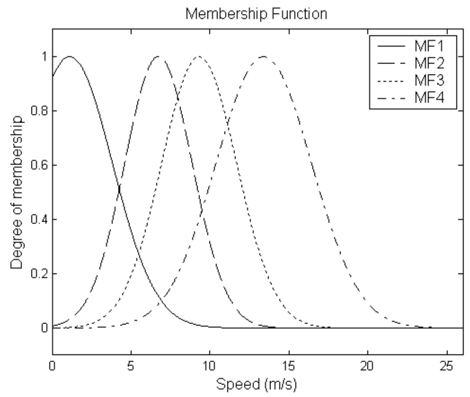


(a) Membership function

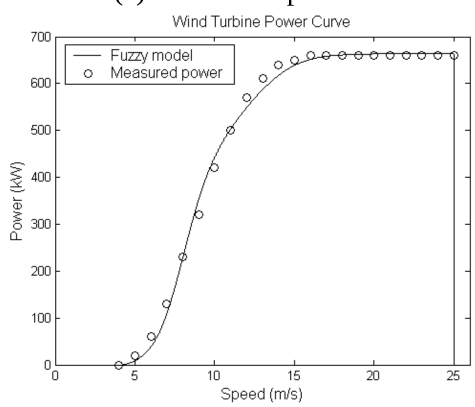


(b) Fuzzy model and measured power data

Figure 2. Two-rule model

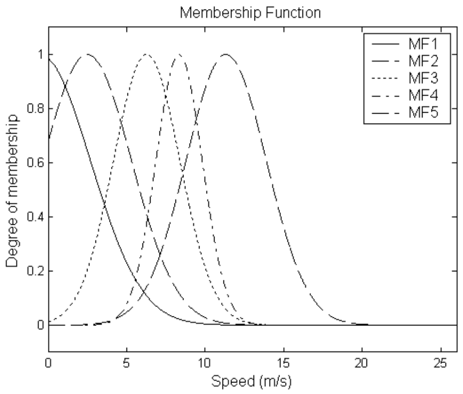


(a) Membership function

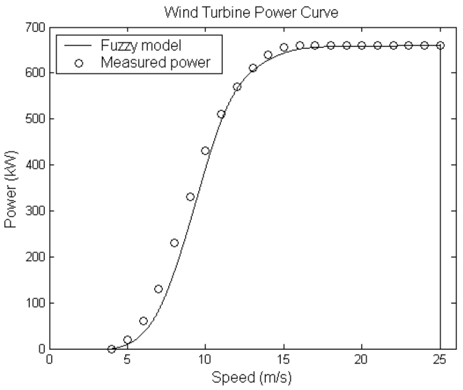


(b) Fuzzy model and measured power data

Figure 3. Four-rule model

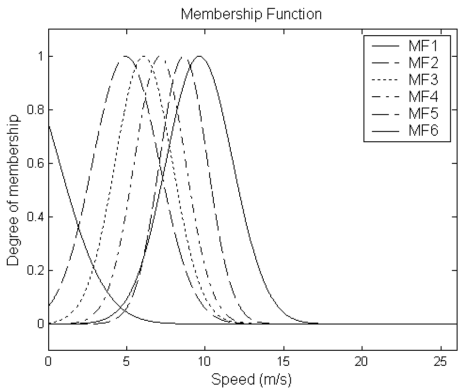


(a) Membership function

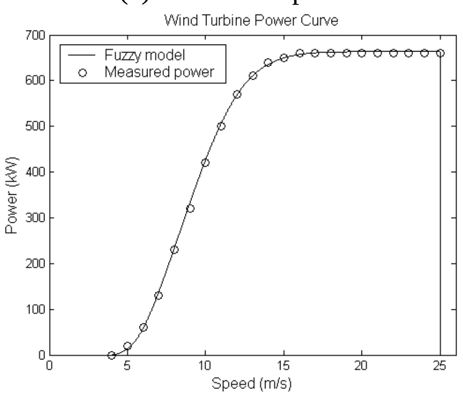


(b) Fuzzy model and measured power data

Figure 4. Five-rule model



(a) Membership function



(b) Fuzzy model and measured power data

Figure 5. Six-rule model

5 Conclusion

The main purpose of this paper is to present the description of wind turbine power curve by fuzzy modeling. In view of the nonlinear characteristic of wind turbine power curve which depicts the turbine output power under various wind speeds, the method of fuzzy modeling is employed for representing the curve. Based on the Sugeno-type fuzzy model, various models with different numbers of modeling rules has been identified to describe the power curve It is found that such fuzzy model offers both quantitative and qualitative descriptions for the wind turbine power curve. The validty of the Sugeno-type fuzzy model in the analysis of wind turbine power curve has been verified in this study.

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