Design of Wind-solar Complementary Power System Based on Progressive Fuzzy Control

Ning Chen
School of Mechanical and Automotive Engineering, Zhejiang University of Science and Technology, Hangzhou, China
Email: nelching@163.com

Xiao Qu
School of Automation and Electrical Engineering, Zhejiang University of Science and Technology, Hangzhou, China
Email: quxiao@zust.edu.cn

Weibing Weng and Xing Xu
School of Mechanical and Automotive Engineering, Zhejiang University of Science and Technology, Hangzhou, China
Email: xuxing1332@163.com

***Abstract*—In order to make a wind-solar complementary power system be a self-intervention controller, a new fuzzy control approach to hybrid power generation in wind and solar co-generation system is developed in this paper. Firstly, a new kind of structure of wind-solar complementary power system is designed. The method of double-fed brushless wind turbine sets is adopted, based on the principle of nonlinear control theory, according to the external excitation caused by the nonlinear changes of wind forces and wind speeds, for the purpose of capturing the wind power in the greatest degree. Meanwhile, the idea of extensional adaptive control on solar cells is adopted, also in order to transform the renewable energy to electrical power to the most degree. Secondly, according to the analysis on the characteristics of the multi-input and multi-output of the distributed wind-solar complementary power system, a progressive fuzzy control algorithm based on fuzzy control method and adaptive control theory is put forward to control the loading and unloading process congruously among the wind turbines, the solar cells and the grid. Finally, the simulation study is carried out. It is shown that the new kind of wind-solar complementary power system can achieve the balance quite well between the supply and the demand of the electrical energy automatically according to the load of system, under the premise of improving the utilization rate of renewable resources as much as possible.**

***Index Terms*—renewable energy, wind-solar complementary power system, nonlinear control, algorithm of progressive fuzzy control, extensional adaptive control, double-fed brushless wind turbine, congruous loading and unloading process, self-intervention controller**

I. INTRODUCTION

With the growing world energy shortage and the requirements of environmental protection, wind power generation technology and solar power generation technology have respectively made considerable development in recent years[1]. More and more wind power and solar power has been applied as the substitute for fossil fuels. But, whether wind power generation technology or solar power generation technology has its great limitation when they are applied independently[2]. Thus, a new power generation style named wind-solar complementary power system has been developed, which can help wind power generation and solar power generation to compensate for each other so as to supply a stable output of electrical power[3,4].

In the future, a wind-solar complementary power system could guarantee a great certain percentage of power supply all the year, reduce the exhaust of diesel fuel, and realize the sufficient use of the natural renewable resources. But nowadays, the technology has not been perfect enough[5,6]. There are several key problems urgently need to be resolved, such as the incongruous loading and unloading process among the wind generators and the solar cells and the grid, the bad stability of the system, the lack of self-intervention and adaptability, and so on.

In order to promote the technology of wind-solar complementary power generation to practical progress, some scientists threw themselves into the relevant studies and researches. Boroyevich D. et al put forward a optimal sizing method for wind-solar-battery hybrid power system[7], Dufo-López R, et al. established a multi-mode energy control and management model for wind-solar hybrid power generation[8], Gelik, A.N. [9] and Billinton R, et al[10] developed respectively a coordination control algorithm for wind-solar hybrid power system, Mingliang Li[11] and Yifeng Wang et al [12] designed a new type wind-solar hybrid generator respectively. Although some technical items about wind-solar complementary power generation system were solved quite well with those researches above, some were left hanging in the air, especially how to control the loading and unloading process congruously. In addition, almost all researches

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Xing Xu is the corresponding author to this work.

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above focus on the off-net household wind-solar complementary power system. The knack about how to achieve the balance between the supply and the demand of the electrical energy automatically according to the load of system and the grid has not been under the scientific exploration yet. It's necessary to develop a new design of wind-solar complementary power system, which is a self-intervention controller according to the supply and the demand of the system and the grid, and can achieve a congruous loading and unloading process among the wind generators and the solar cells and the grid.

A new design of wind-solar complementary power system based on fuzzy control theory combining with extensional adaptive control idea and adaptive control method was established in this paper, so as to achieve the balance between the supply and the demand of the electrical energy automatically according to the load of system, under the premise of improving the utilization rate of renewable resources as much as possible.

II. A New Structure Of Wind-solar Complementary Power System

A typical wind-solar complementary power system consists of wind generator, solar units, batteries, charge controllers, inverters, system monitoring system, etc.[13] Because of no evaluation about the impact of the load on the power output, this type of structure is not smart enough to link into the power grid.

In order to solve the above problems, a new kind of structure of wind-solar complementary power system is designed, shown in Fig.1. The wind generator employs a special design which means a double-fed brushless wind turbine, and the solar units are composed of a group of pollution-free solar panels attached with a certain dry battery groups. Both the rectified currents from solar units and wind turbine paralleled on the side of direct current will pass through a charge-discharge controller to charge the solar battery groups. After that, the rectified currents will go through an inverter to charge or to drive the alternating load linked to the power grid. In this structure, a power quality controller will take its responsibility when the alternating load has a higher requirement about power output, or the power grid need to be charged. Then, the wind-solar complementary power system can not only run independently but also incorporate into the electrical power grid.

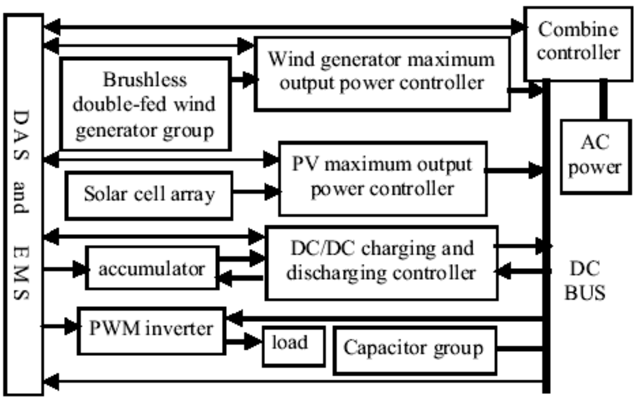

Figure 1. The schematic diagram about the new structure of the wind-solar complementary power system

In order to decrease the costs of electronic components and to eliminate the replacement of the electric brush, the ratio of the *loop-circuit power* to *control loop-circuit power* of double-fed brushless wind turbine in this new structure is set to be at an even/odd number. Furthermore, a lower control loop-circuit power is employed.

For the purpose of controlling the frequency changes dynamically as well as avoiding the occurrence of harmonic, frequency conversion circuit is put to use on controlling the double-fed brushless wind turbine to develop a passive control on frequency error of the wind-solar complementary power system. After that, the nonlinear characters of the external excitation caused by the nonlinear changes of wind forces and wind speeds are inputted into the anti-disturbance controller based on the adaptive theory, which consists of tracking differentiator, extended state observer, and feedback device for nonlinear state error. Tracking differentiator can provide the generalized differential signal without any noise. Extended state observer can take the real-time measurement on the internal systematic state as well as the external disturbance, so that the ascertainment of feedback and linearization of dynamic feedback can be achieved. Feedback device for nonlinear state error can ensure the perfect dynamic performance of the generation system with good robustness, and big swing.

III. Design Of The Progressive Fuzzy Control System

Although it is an exponential relationship between regulation totality and input variables in a general fuzzy controller, the linear relationship can be achieved in a progressive fuzzy controller (PFC) based on fuzzy control method and adaptive control theory. If the nonlinear system has more than one input variable, PFC can effectively reduce the dimensions of fuzzy controlling rules' database and can simplify the instructions of practical operation of the controller.

As shown in Fig.1, the input of the PFC is

$$y = f_3(x_4, f_2(x_3, f_1(x_2, x_1))) \tag{1}$$

In which the i th output is

$$f_i(y_{i-1}, x_{i+1}) = \frac{\sum_{p=1}^{n_i}\sum_{q=1}^{m_i} h_i(y_{i-1}, x_{i+1})[\mu_{ip}(y_{i-1})\mu_{iq}(x_{i+1})]}{\sum_{p=1}^{n_i}\sum_{q=1}^{m_i}[\mu_{ip}(y_{i-1})\mu_{iq}(x_{i+1})]}$$

$$i = 1, 2, 3, 4 \tag{2}$$

Where, n_i is the number of the (i-1)th output fuzzy set titled y_{i-1}, and m_i is the number of ith input fuzzy set titled x_{i+1}. The block diagram of PFC in the wind-solar complementary power system is shown in the Fig. 2.

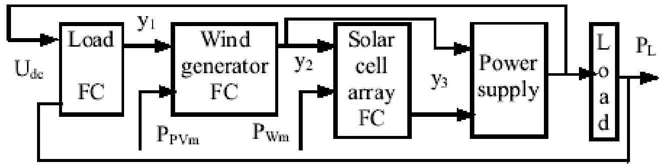

Figure 2. The block diagram of PFC in the wind-solar complementary power system

In our design, the wind generation set is composed of 5 wind turbines on 12kW class, so that the total output power of the generation set ranges from 0kW to 60kW. The solar generator set consists of 5 solar cell units on 6kW class, and the total output power of the solar generator set would swing from 0kW to 30 kW, meanwhile the load power changes from 0kW to 90kW.

The prerequisite of a safe, stable, and efficient power supply system is to keep the balance of the electrical power supply and the demand from the load. Because the load is always powered by DC voltage through inverter, the DC voltage stability will directly determine the quality of the power used to drive the load. The DC generatrix voltage titled U_{dc}, working from 198V to 242V, is taken as passive control variable in the design and its rated voltage is 220V. In order to simplify the structure, the inputs of energy control system are chosen as U_{dc}, P_{Wm} (maximal output power of wind generator set), P_{PVm} (maximal output power of solar generator set), and P_L (the demand of load). The outputs are KW (utilization ratio of wind generator set output power), K_{PV} (utilization ratio of solar generator set output power), and K_S (switch function: when K_S=1, the generation system could be connected into the power grid; when K_S=0, the generation system is disconnected from the power grid). In our design, $KW, K_{PV} \in [0,0.2,0.4,0.6,0.8,1]$.

According to the operation characteristic, system control regulations include fuzzy control rules and precise control rules.

Fuzzy control: It not only monitor the wind turbines, solar units, DC generatrix voltage and the load, but also control the former two components and maintain the balance between the supply and demand of the electric power. When the system can not generate sufficient power, the public grid will compensate the shortfall; once the supplement exceeds, it will break off automatically from the public power grid.

$$D_1(t) = \frac{1}{2}(1 + \frac{u_m}{V_{tri}}) \tag{3}$$

$$K_{\text{PWM}} = \frac{U_i(s)}{U_m(s)} = \frac{E}{V_{tri}} \tag{4}$$

$$G(s) = \frac{U_o(s)}{U_i(s)} = \frac{\frac{1}{Cs}//R}{\frac{1}{Cs}//R + Ls + R_L} = \frac{1}{LCs^2 + (\frac{L}{R} + R_L C)s + \frac{R_L}{R} + 1} \tag{5}$$

$$P(s) = \frac{U_o(s)}{U_m(s)} = \frac{U_o(s)}{U_i(s)}\frac{U_i(s)}{U_m(s)} = \frac{1}{LCs^2 + (\frac{L}{R} + R_L C)s + \frac{R_L}{R} + 1}\frac{E}{V_{\text{tri}}} \tag{6}$$

Precise control:

When U_{dc}<198V, K_S=1; when U_{dc}>220V, K_S=0; and when U_{dc}>242V, cut off the power supply from wind-solar complementary power system, until U_{dc} less than 220V.

$$|\frac{P(s)}{1 + k_f P(s)}\frac{Q(s)}{P(s)}e^{-Ts}| < 1 \tag{7}$$

$$P(s) = \frac{U_o(s)}{U_m(s)} = \frac{U_o(s)}{U_i(s)}\frac{U_i(s)}{U_m(s)} = \frac{1}{LCs^2 + R_L Cs + 1}\frac{E}{V_{\text{tri}}} \tag{8}$$

$$|1 + k_f P(s)| > |Q(s)| \tag{9}$$

In our design, the most influential variables to system are chosen as the first-level rule sets system variables, and the less ones are chosen as the second-level rule sets system variables, and so on. We can set fuzzy subset variables as *Z*(Zero), *S*(Small), *Sr*(Smaller), *M*(Middle), *Br*(Bigger), *B*(Big), *N*(Negative), *L*(Low), *M*(Middle), *H*(High).It is recommended by our research that it is better to reduce the number and complexity of the fuzzy control subsets for keeping higher precision. Besides, when there are some changes of power supply and power demand, each on-off action would not switch frequently, so that the wavy input variable should be designated as a fuzzy subset to avoid the bad fluctuation of controlling output. Based on above principles, U_{dc} would be working from 198V to 242V, and relevant fuzzy subset would be [L, M, H], and P_L would be from 0kW to 75kW, and relevant fuzzy subset would be [Z, S, Sr, M, Br, B], as well as P_{Wm} would be from 0kW to 75kW, and relevant fuzzy subset would be [S, Sr, M, Br, B], and P_{PVm} would be from 0kW to 15kW, and relevant fuzzy subset would be [Z, S, Sr, M, Br, B]

A. Design of the First-step Fuzzy Controller

In the wind-solar complementary power system, DC voltage is the critical factor for system stability. The relationship between DC voltage and load power determines the subsequent controlling of energy management system. Thus, we take P_L and U_{dc} as the first-level inputs, and take energy intensity y_1, which is the load relatively to the system, as the output. The membership's function of the first-step fuzzy controller is shown in Table I, and the control rules are shown in Fig. 3.

The variable set of y_1 is defined as [Z, S, Sr, M, Br, B], and the relevant de-fuzzy precise variable set is deduced out as [0, 0.1, 0.3, 0.5, 0.7, 0.9].

TABLE I.
THE FIRST-STEP FUZZY RULES SET

U_{dc} \ P_L	Z	S	Sr	M	Br	B
L	S	Sr	M	Br	B	B
M	Z	S	Sr	M	Br	B
H	Z	S	Sr	M	Br	B

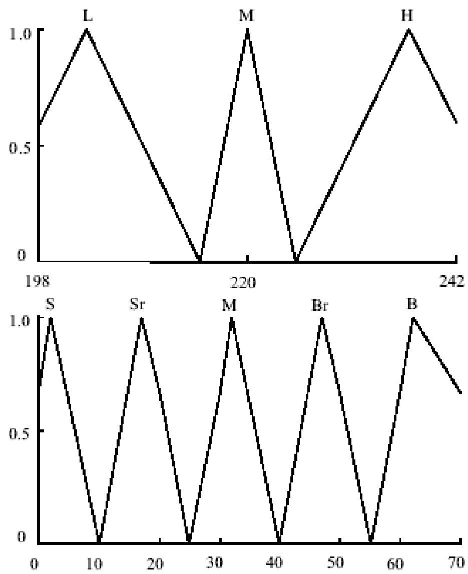

Figure 3. The membership function of P_L and U_{dc}

B. Design of the Second-step Fuzzy Controller

In our research, we take y_1 and P_{Wm} as the inputs, and take y_2, which is defined as the percentage of wind power supplied to system, as output. The memberships function named P_{Wm} is shown in Table 2, and the rules for the second-level control are shown in Fig. 4. The fuzzy variable set of y_2 is defined as [Z, S, Sr, M, Br, B], and the relevant de-fuzzy precise variable set is deduced out as [0, 0.2, 0.4, 0.6, 0.8, 1.0]. Besides, the wind turbines set used is defined as [0,1, 2, 3, 4, 5].

TABLE II.
THE SECOND-STEP FUZZY RULES SET

y1 \ P_{Wm}	S	Sr	M	Br	B
Z	Sr	S	S	Z	Z
S	M	Sr	Sr	S	S
Sr	B	M	M	Sr	Sr
M	B	B	Br	Br	M
Br	B	B	B	B	Br
B	B	B	B	B	B

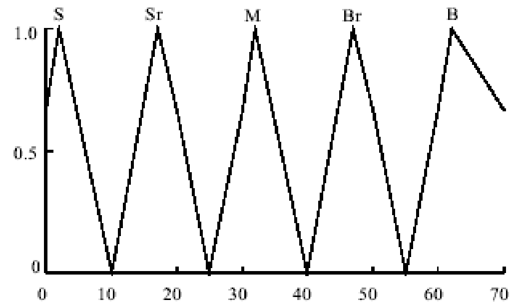

Figure 4. The membership function of P_L (the same as P_{Wm})

C. Design of the Third-step Fuzzy Controller

In our research, we take x_4 and P_{PVm} (x_4=75 y_2- y_3P_{Wm}) as the inputs, and take y_3, which is defined as the percentage of solar power supplied to system, as the output. The memberships function of x_4 and P_{PVm} are shown in Table 3, as well as the second-step control rules are shown in Fig 5.

TABLE III.
THE THIRD-STEP FUZZY RULES SET

P_{PVm} \ x_4	N	S	Sr	M	Br	B
Z	Z	B	B	B	B	B
S	Z	Br	B	B	B	B
Sr	Z	M	B	B	B	B
M	Z	Sr	M	M	B	B
Br	Z	S	Sr	M	Br	B
B	Z	S	Sr	M	Br	B

In our research, we found that the de-fuzzy variable of y_3 equals to y_2. And the terms of $5y_2$ and $5y_3$ separately means the total number of the wind turbines set and the solar units, which supply the power to the system together.

When P_L and U_{dc} are changed, the system would perform the real-time control function automatically, through gradually fuzzy control steps, so as to progressively approach the object function.

IV. SIMULATING RESEARCH AND THE ANALYSES

For the purpose of validating the feasibility of the system, we designed a simulation model of energy management system based on progressive fuzzy control, which is established by the power demand and supply from 8:00 to 20:00 in a certain day.

The power of the entire output of the wind turbines set and the solar units fluctuates in a comparatively large range, as well as the load power does. The output power curves are shown in Fig. 6. Obviously, the electrical power grid will be unstable if there don not have any control.

The relationship between the load power and the maximal output power of hybrid power generation in wind-solar complementary power system is shown in Fig. 7, where the term of (P_{Wm}+P_{PVm}) means the maximal output power, and the term P_L means the load power.

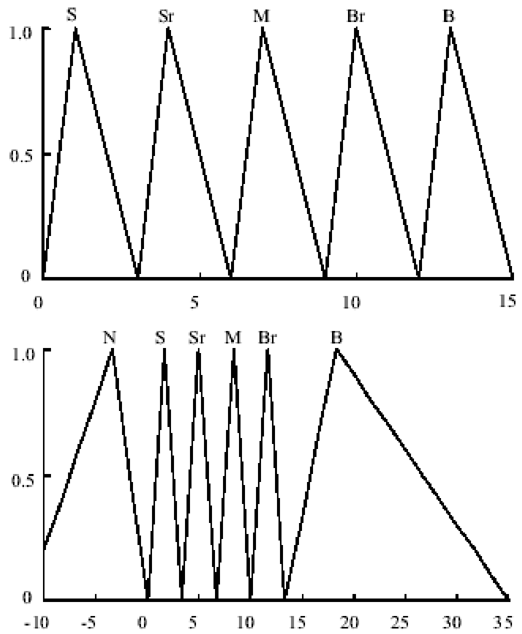

Figure 5. The membership function of x_4 and P_{PVm} (x_4=75y_2-y_3P_{Wm})

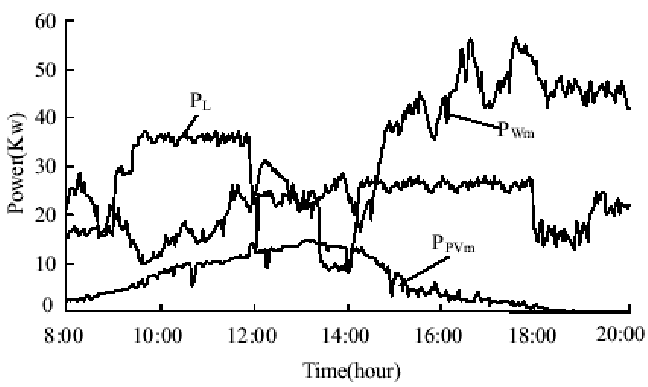

Figure 6. Output power curves of wind turbines unit and solar cells unit as well as the power curve of the load

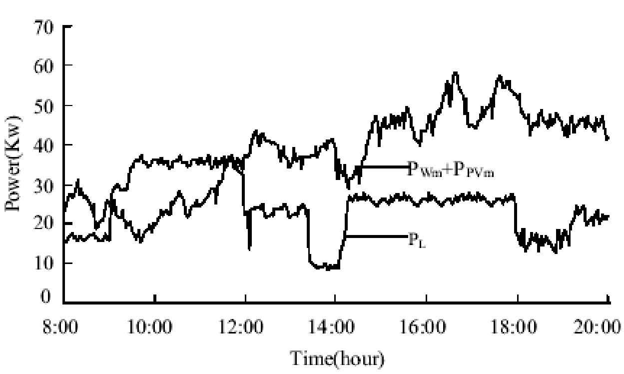

Figure 7. The maximum output power curves of wind turbines unit and solar cells unit as well as the power curve of the load

From Fig.7, it can be seen that the load power sometimes would be away from totally hybrid power, so that the direct current generatrix voltage would like to be fluctuant without control. Thus, the system would not work properly.

Figure 8 gives the relationship curve between load power and real output power of hybrid power generation in wind-solar complementary power system under fuzzy control without connecting into the grid. The term of (P_W+P_{PV}) means the real power supplied by hybrid power generation in wind-solar complementary power system. If the maximal output power of reproducible resources is less than the load power, the output power of reproducible resources would equal the number of (P_{Wm}+P_{PVm}), that is to say that the reproducible resources are adequate enough to use. Otherwise, the output power of reproducible resources would equal the number of the load power, which means that the system can load or unload the solar cells group and wind turbines unit according to the load power.

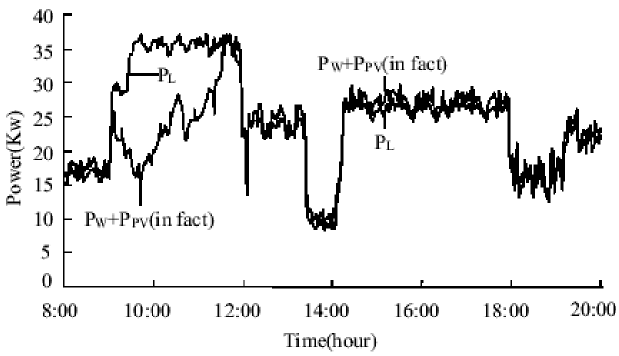

Figure 8. The real output power curves of wind turbines unit and solar cells unit as well as the power curve of the load

When the total output power of the wind-solar complementary power system is less than the load power, leading to that the direct current voltage drops to the threshold value (192V) preset on the system, the grid will supplement the insufficiency on the basis of fully utilizing the output power of the wind-solar complementary power system, in order to maintain the DC voltage at 192V. It is shown in Fig.9

The load power curves compared to the total power supplied after the algorithm of progressive fuzzy control was used on the wind-solar complementary power system

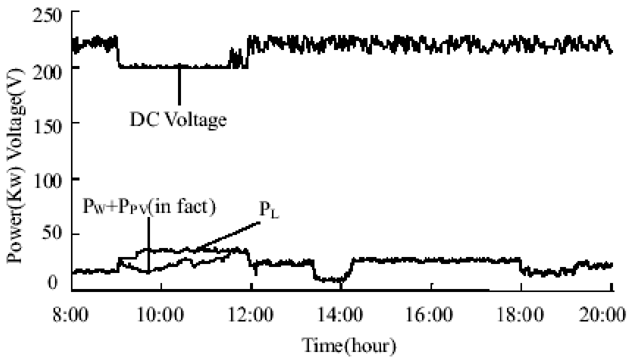

Figure 9. The curves of DC voltage if the load power partly more than the output power of the wind-solar complementary power system

were shown in Fig.10. It is seen that the power supply system can do self-intervention according to its load, so that the balance between supply and demand will be achieved.

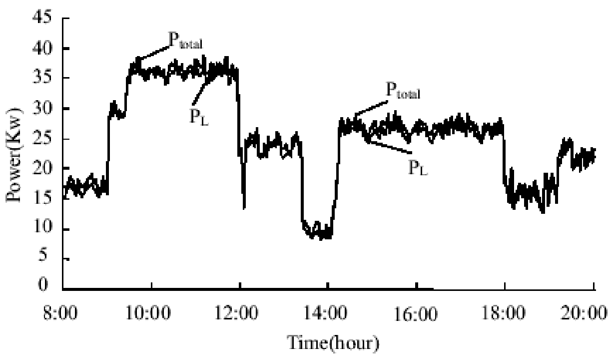

Figure 10. The power curves of the total supply and the load

Some experiments were held and the results indicate that the wind-solar complementary power system based on the progressive fuzzy control can automatically load or unload from the grid according to the load demand. So that the purpose of utilizing wind resources and solar resources efficiently is accomplished.

IV. CONCLUSION

In order to make the wind-solar complementary power system be a self-intervention controller, a new fuzzy control approach to hybrid power generation in wind-solar complementary power system is developed in this paper. Firstly, a new kind of structure of wind-solar complementary power system is designed. The method of double-fed brushless wind turbines set and the idea of extensional adaptive control on solar cells unit are adopted, based on the external excitation caused by the nonlinear changes of wind forces and wind speeds, for the purpose of capturing the wind power and the solar power in the greatest degree. Secondly, according to the analysis on the characteristics of the multi-input and multi-output of the distributed hybrid power system, an algorithm of progressive fuzzy control is put forward to control the loading and unloading process congruously among the distributed wind-solar complementary power system. Finally, the simulation study is carried out. It is shown that the wind-solar complementary power system can achieve the balance between the supply and the demand of the electrical energy automatically according to the load of system, under the premise of improving the utilization rate of renewable resources as much as possible.

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Ning Chen received the Ph.D. degree in mechanical engineering from Zhejiang University in 2004. Currently, he is an Associate Professor at Zhejiang University of Science and Technology, and the fellow of Chinese Association on Mechanical Engineering. His research interests include Intelligent Transport System(ITS) and Logistics Engineering. He has published 33 papers around mechanical engineering, transportation engineering, and logistics engineering. His work has been supported by the National Natural Science Foundation of China as well as other academic originations.

Xiao Qu received the Master degree in automation engineering from Zhejiang University in 1999. Currently, she is an associate professor at Zhejiang University of Science and Technology. Her interests are in urban transportation system control design and information processing.

Xing Xu received the Ph.D. degree in mechanical engineering from Zhejiang Sci-Tech University in 2013. Currently, he is an assistant professor at Zhejiang University of Science and Technology. His interests are in urban transportation system control design and information processing.

Weibing Weng received the Ph.D. degree in Logistics Engineering from Dortmund University of Technology in 2011. Currently, he is an assistant professor at Zhejiang University of Science and Technology. His interests are in logistics technologies and equipments.