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Variable Universe Fuzzy Control of Adjustable Hydraulic Torque Converter Based on Multi-Population Genetic Algorithm

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ABSTRACT In order to optimize the control method of guide vane opening in an adjustable hydraulic torque converter, this paper presents a variable universe fuzzy control method for servo system of the adjustable hydraulic torque converter based on the multi-population genetic algorithm. This control method got a kind of adaptive control as optimizing proportional exponential contraction–expansion factors of the current loop with a genetic algorithm, thus transforming the fuzzy variable universe of the current loop. In this method, we designed a variable universe adaptive fuzzy controller with S-function on an adjustable hydraulic torque converter servo system and conducted some simulation experiments. The simulation results showed that the variable universe control based on genetic algorithm improved the anti-interference and robustness of adjustable hydraulic torque converter servo system compared with control methods in the previous literature. This control method could be a desirable way to adjust guide vane opening with the properties of better accuracy, rapidity, and reliability. Thus, the control method we designed will provide an effective, fast, and stable control strategy for the uncertain system with the properties of nonlinearity, strong disturbance, and uncertain time-varying.

INDEX TERMS Adjustable hydraulic torque converter, variable universe fuzzy control, multi-population genetic algorithm, guide vane opening, servo motor.

I. INTRODUCTION

Wind power generation has been vigorously developed as a kind of new energy source with the advantages of large-scale development and commercial development prospects [1]–[5]. At present, two main types of grid-connected wind turbines have been used. One of them is back frequency-stabilized unit represented by doubly-fed and direct-drive, and the other one is front-end speed controlled wind turbine [6]–[8]. However, further development of the back stabilized wind turbine is subjected to many restrictions because it coupled with the power grid via a converter [9]–[11].The front-end speed controlled wind turbine adopted a new transmission form of ''low gear ratio gearbox + hydraulic torque converter + brushless synchronous electric excitation generator''. Previous rigid transmission mode replaced by hydraulic torque flexible transmission mode, and variable frequency feed mode is replaced by synchronous generator direct feed mode. The speed adjustment of wind turbine has adopted hydraulic torque control technology with some advantages such as low voltage ride through, strong reactive power output, good power quality and high reliability. Adjustable hydraulic torque converter is an important part of front-end speed controlled wind turbine. It can realize variable speed input and give constant speed output through reasonable control. Therefore, it is meaningful to research about structure design and adjustment method of adjustable hydraulic torque converter.

As for the combination of hydraulic speed control and wind power generation, a kind of wind power hydraulic speed control device (Windrive) produced by Voith successfully won Hermes Award at Hannover Fair in 2009. It seems that hydraulic speed control system has a broad application prospect [12], [13]. Speed control system of Windrive consists of two rows of planetary gears and one torque converter with adjustable guide vanes. Windrive controls rotational speed with circulating power, thus realize variable-speed input and give constant-speed output. Therefore, the power produced by front-end speed controlled wind turbine can be connected to the power grid. This kind of generating electricity can ensure the stability of generator frequency and avoid using some complex and expensive electrical components like current transformer.

Some researchers have studied hydraulic torque converter with adjustable guide vane in front-end speed controlled wind turbine. Two aspects of study on adjustable hydraulic torque converter were mainly focused on: one was structural design and the other was control method. Zhao and Maißer [14] proposed a new wind power transmission system with circulating power to adjust the output characteristics of system. The circulating power entered the planetary gear train after passing through the servo motor resulted in longer transmission chain and poor efficiency of whole transmission system. As for research about guide vane adjustment rule of torque converter, Du [15] established a mathematical model of wind wheel combined with the speed control system to obtain an operation law of abstract torque converter. However, this system was only statically analyzed in theory. It is necessary to study about dynamic simulation of whole transmission system combined with control system.

In the control system of adjustable hydraulic torque converter, there are two kinds of controllers currently used. One is the double-mode parameter self-tuning fuzzy controller, as used in [16] and [37]. Its advantage is that it can adjust the parameters and alternate the fuzzy control by itself according to the errors and error changes. Its disadvantage is that its dynamic response time is slow relatively. The other one is the two-mode controller based on fuzzy PID, which is adopted in [38]. Its advantages are that: it has a fast response speed and it can restrain overshoot. Its disadvantage is that its control accuracy is low relatively.

In this paper, we presented a variable universe fuzzy control method for servo system of adjustable hydraulic torque converter based on multi-population genetic algorithm. Compared with two kinds of controllers adopt by previous literatures, the advantages of this controller adopted in this paper are that it has a faster response speed and a higher control precision. This controller not only improved the anti-interference and robustness of servo system in adjustable hydraulic torque converter, but also realized an accurate, fast and reliable adjustment of guide vane opening. This control method we designed will provide an effective, fast and stable control strategy for the uncertain system with properties of nonlinearity, strong disturbance and uncertain time-varying.

II. MATHEMATICAL MODEL ESTABLISHMENT OF ADJUSTABLE HYDRAULIC TORQUE CONVERTER AND ANALYSIS OF REGULATING LAW OF GUIDE VANE

A. MATHEMATICAL MODEL ESTABLISHMENT OF ADJUSTABLE HYDRAULIC TORQUE CONVERTER

It is difficult to get an accurate mathematical model because the internal flow field of hydraulic torque converter is complicated. As for the hydraulic torque converter with adjustable guide vane, the parameters of guide vane changes with the change of guide vane, thus it is more difficult and complicated for establishing its mathematical model. Experiments should not be ignored to obtain accurate mathematical model. In the present study, the law of changes of guide vane during the operation of wind power generation was theoretically analyzed. It can be a basis for dynamic analysis and prediction of control system in the future.

TABLE 1. Turbine torque calculated by CFD.

Guide vane relative opening x	Turbine torque at different turbine speed				
	0	300	600	800	1200
1	10003	6630	4329	2858	1630
0.9	9058	6042	3965	2594	1403
0.8	8002	5337	3548	2288	1143
0.73	7299	4926	3271	2089	970
0.6	6050	4102	2645	1752	754
0.53	5376	3742	2460	1453	480
0.47	4716	3264	2193	1323	382
0.4	4056	2787	1926	1194	310
0.2	2734	1946	1292	673	274
0.0	1502	1116	1142	564	182

TABLE 2. Quadratic coefficient of fitting.

Guide vane relative opening x	Quadratic coefficient		
	b0	b1	b2
1	9930	-11.78	0.0041
0.9	9058	-10.5975	0.0035
0.8	7926	-8.988	0.0028
0.73	7299	-8.1525	0.0024
0.6	6001	-6.6601	0.0020
0.53	5376	-5.64	0.0013
0.47	4716	-4.7983	0.0010
0.4	4000	-3.8845	0.0007
0.2	2728	-2.7107	0.0004
0.0	1502	-1.9733	0.0023

At present, there are few studies on the accurate mathematical model of adjustable hydraulic torque converter. Previous study [15] analyzed adjustable hydraulic torque converter with one-dimensional program. The results suggested that the relationship between turbine torque and turbine speed was quadratic function. Afterward, the scholar obtained a mathematical model of adjustable hydraulic torque converter by experimental interpolation.

According to the study of Du, we obtained a mathematical model of adjustable hydraulic torque converter via matched quadratic relationship between quadratic coefficient and guide vane opening with characteristic parameters (Table 1, 2).

It is known that:

$$M_{\mathrm{T}} = b_0 + b_1 n_{\mathrm{T}} + b_2 n_{\mathrm{T}}^2 \tag{1}$$

where: b_0, b_1, b_2 were unknown parameters, they were also functions of guide vane relative opening x; n_{T} was turbine speed.

It is known that the flow field changes intricately when guide vane completely close, and the performance of adjustable hydraulic torque converter is unstable, according

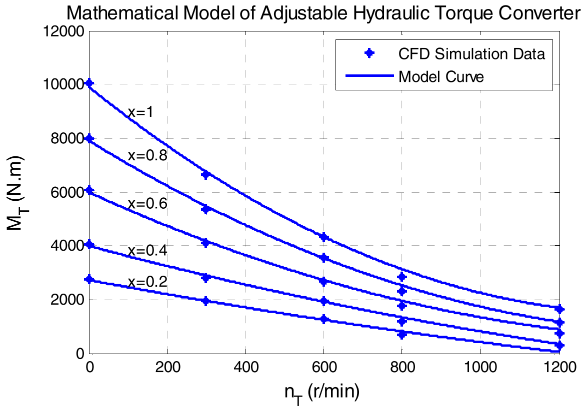

FIGURE 1. Mathematical model curve of hydraulic torque converter with adjustable guide vane.

to the results of flow field simulation and analysis. Therefore, the point with larger opening should be selected when establishing model of adjustable hydraulic torque converter.

Afterwards, we fitted quadratic coefficients (b_0, b_1 and b_2) with a curve to three functions of x.

The fitting result as follows:

$$\begin{cases} b_0 = 9963.86x + 60.4038 \\ b_1 = -13.2480x + 1.3363 \\ b_2 = 0.0027x^2 + 0.0021x - 0.0006 \end{cases} \tag{2}$$

Substituted (2) into (1) then obtained equation (3):

$$\begin{aligned} M_T = &(9963.86x + 60.4038) + (-13.2480x \\ &+1.3363)n_T + (0.0027x^2 + 0.0021x - 0.006)n_T^2 \end{aligned} \tag{3}$$

where: M_{T} was turbine torque; n_{T} was turbine speed.

The mathematical model of hydraulic torque converter with adjustable guide vane we obtained is shown in Figure 1.

B. REGULATING LAW ABOUT GUIDE VANE OF ADJUSTABLE HYDRAULIC TORQUE CONVERTER IN WIND POWER GENERATION SYSTEM

The relationship between guide vane opening and turbine speed in the process of wind turbine operation was obtained (Figure 2 and Functions 4) with fitting method on mathematical model curve of hydraulic torque converter and operating curve of speed control system.

$$\begin{cases} x = -0.00193n_{\mathrm{T}} + 1.4801 & n_{\mathrm{T}} \le 425 \\ x = 7.16 \times 10^{-6}n_{\mathrm{T}}^2 - 0.00838n_{\mathrm{T}} & \\ \quad +2.9256 & 425 < n_{\mathrm{T}} \le 575 \\ x = -0.0001663n_{\mathrm{T}} + 0.57 & n_{\mathrm{T}} \ge 575 \end{cases} \tag{4}$$

The relation between wind wheel speed and torque converter speed ratio suit equation: $i_{TB} = (1 - n_i i_z a_1/n_0)\frac{1+a_2}{1+a_1}$,

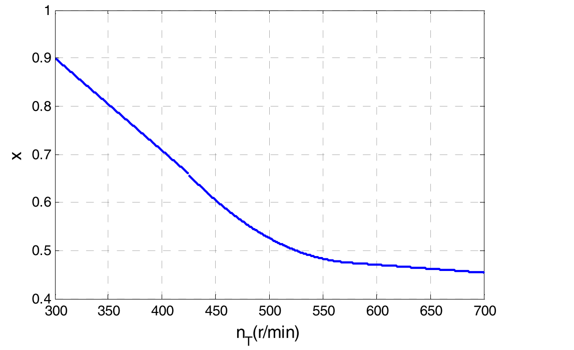

FIGURE 2. Relationship between guide vane relative opening and turbine speed.

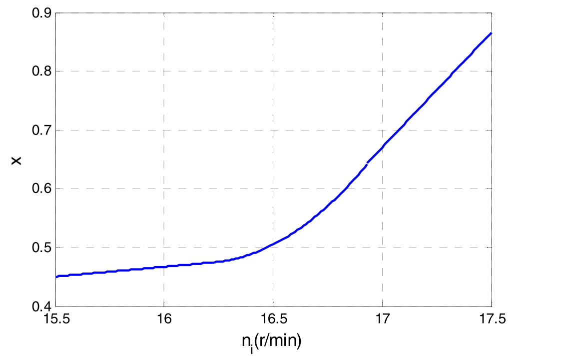

FIGURE 3. Relationship between guide vane relative opening and wind wheel speed.

$i_{TB} = n_T/n_B$, thus obtained three equations:

$$\begin{cases} x = -0.2495 \times \left[(1 - n_i i_Z a_1/n_0)\dfrac{1+a_2}{1+a_1}\right] \\ \quad +0.57 \quad n_i \le 16.23 \\ x = 16.11 \times \left[(1 - n_i i_Z a_1/n_0)\dfrac{1+a_2}{1+a_1}\right]^2 \\ \quad - 12.57 \times (1 - n_i i_Z a_1/n_0)\dfrac{1+a_2}{1+a_1} \\ \quad +2.9256 \quad 16.23 < n_i \le 16.97 \\ x = -2.9037 \times (1 - n_i i_Z a_1/n_0)\dfrac{1+a_2}{1+a_1} \\ \quad +1.4801 \quad n_i > 16.97 \end{cases} \tag{5}$$

where: n_0 was the speed of generator synchronous (n_0 = 1500r/min); n_{B} was the pump wheel speed; i_{z} was transmission ratio of the main rotation gear box; n_{i} was the wind wheel speed, a_1 and a_2 were structural parameters of planetary frame.

Finally, the relationship curve between guide vane relative opening and wind wheel rotational speed was obtained (Figure 3). It suggested that guide vane relative opening had small change at low rotational speed, guide vane relative opening significantly increased with the increase of wind wheel rotational speed. The guide vane relative opening was about 0.85 when wind speed reached the rated wind speed.

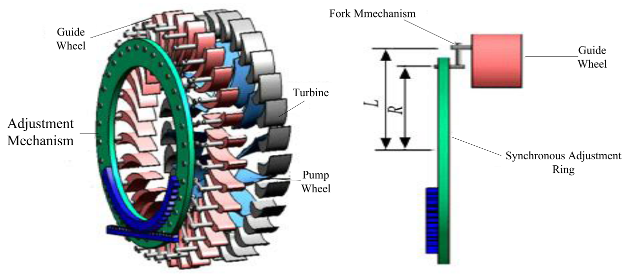

FIGURE 4. Guide vane adjusting mechanism of hydraulic torque converter.

C. WORKING PRINCIPLE OF GUIDE VANE ADJUSTING MECHANISM IN HYDRAULIC TORQUE CONVERTER

The guide vane adjusting mechanism of hydraulic torque converter was shown in Figure 4. Sector gear connected with synchronous adjustment ring; one end of fork adjustment mechanism was installed on synchronous adjustment ring, and the other end was connected with the rotary pin shaft of guide vane. When it will be needed to adjust guide vane opening, the controller will send an angle signal to servo motor, after that the servo motor drives synchronous adjustment ring to rotate at a certain angle through the driving elements such as ball screw, rack and sector gear. The synchronous adjustment ring will drive guide vane to rotate through fork mechanism, thus changing the transmission characteristics of hydraulic speed regulating device [16].

In other words, the control of hydraulic torque converter guide vane opening is actually the control of servo motor rotation angle. The servo motor angle signal was calculated with the given guide vane opening value, which was used as the reference signal of controller. The error and error change rate of actual and reference angle in servo motor were used as the input of guide vane opening controller. The voltage signal working on servo motor was used as the output of guide vane opening controller. Meanwhile, the output signal was converted into the change of hydraulic torque converter guide vane opening through the guide vane adjusting mechanism. Permanent magnet synchronous motor was used in this servo system.

III. VARIABLE UNIVERSE FUZZY CONTROL

A. THEORYOF VARIABLE UNIVERSE

The essence of fuzzy controller is an interpolator [17]–[20]. A better proximity of fuzzy control function obtained by interpolation depends on sufficiently small distance between peaks of these fuzzy sets and control rules. However, it is unrealistic to summarize control rules of fuzzy controller. Therefore, the method of variable universe can be a desirable way to get accurate control function. The variable universe focused on shrinking the initial universe of fuzzy controller with decreasing error or expanding initial universe of fuzzy controller with the increase of error by selecting a serious of appropriate contraction-expansion factors based on a certain fuzzy control rule [21]–[28]. From a local point of view, the contraction of universe is equivalent to more fine division of fuzzy sets in the universe. Increasing control rules and value of fuzzy language variables can get more accurate function thus improving control accuracy.

We assumed the basic universe of input variable $x_i(i = 1, 2, \ldots, n)$ was $X_i = [-E, E](i = 1, 2, \ldots, n)$; the basic universe of output variable y was $Y = [-U, U]$; $\{A_{ij}\}(1 \leq j \leq m)$ was a fuzzy partition in the universe X_i and $\{B_j\}(1 \leq j \leq N)$ was a fuzzy partition in the universe Y, then got a fuzzy rule:

$$\begin{aligned} &\text{IF } x_1 \text{ is } A_{1j} \text{ and } x_2 \text{ is } A_{2j} \text{ and...and } x_n \text{ is } A_{nj} \\ &\text{THEN } y \text{ is } B_j, \quad j = 1, 2, \ldots\ldots m \end{aligned} \tag{6}$$

Set x_i and y_j as the peak values of A_{ij} and B_j, respectively. The theory of variable universe means that X_i and Y can change with the change of x_i and y, respectively. Set universes as followsčž

$$X_i(x_i) = [-\alpha_i(x_i)E_i, \alpha_i(x_i)E_i] \tag{7}$$
$$Y(y) = [-\beta(y)U, \beta(y)U] \tag{8}$$

where: $\alpha_i(x_i)$ $(i = 1, 2, \ldots, n)$ and $\beta(y)$ were contraction-expansion factors of corresponding universe.

B. CONTRACTION-EXPANSION FACTORS OF VARIABLE UNIVERSE

In the process of designing variable universe fuzzy controller, the contraction-expansion factors can be defined as the universe adjustment of control variables according to the current control index because that the system needs to be improved to control the precision with change of contraction-expansion factors.

The contraction-expansion factor $\alpha(x)$ function should meet following conditions: (1) $\alpha(0) = 0$; (2) α is strictly monotonically increasing in the range of $[0, E]$; (3) $x \in X$, $\alpha(x) = \alpha(-x)$; (4) $\alpha(\pm E) = 1$; (5) $x \in X$, $|x| \leq \alpha(x)E$. As for a dual-input single-output fuzzy control system, it is correlated with input variables X and Y. Setting: X was the domain of error (E), Y was the domain of error change rate (EC). Therefore, $\beta(y)$ should be defined on $X \times Y$, that is $\beta = \beta(x, y)$, and the following equations can be chosen as contraction-expansion factors [25], [29]–[35]:

$$\beta(\text{x,y}) = \left(\frac{|x|}{E}\right)^{\tau_1} \left(\frac{|x|}{EC}\right)^{\tau_2} \tag{9}$$
$$\beta(\text{x,y}) = \frac{1}{2}\left[\left(\frac{|x|}{E}\right)^{\tau_1} + \left(\frac{|x|}{EC}\right)^{\tau_2}\right] \tag{10}$$

where: $0 < \tau_1, \tau_2 < 1$.

C. FUZZY CONTROL DESIGN OF CURRENT LOOP IN VARIABLE UNIVERSE

Current loop fuzzy control of servo motor in adjustable hydraulic torque converter was expressed as an N-elements piecewise interpolation function $F(x_1, x_2, \ldots x_n)$ according to

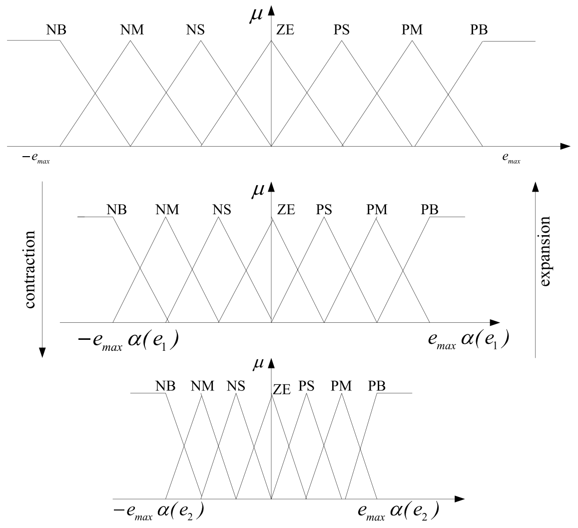

FIGURE 5. The schematic diagram of variable universe.

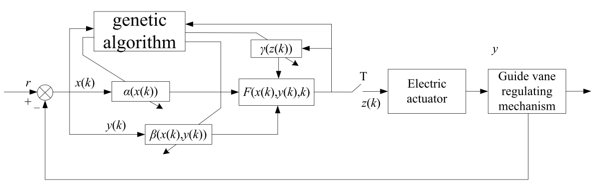

FIGURE 6. Variable universe fuzzy control system optimized by genetic algorithm.

the interpolation mechanism of fuzzy control:

$$F(x_1, x_2, \ldots, x_n) = y(x_1, x_2, \ldots, x_n) = \sum_{j=1}^{m} \prod_{i=1}^{n} A_{ij}(x_i) y_i \quad (11)$$

The expansion or contraction of fuzzy controller depends on corresponding contraction-expansion factors of basic universe. In the initial universe, $\alpha_i(x_i) = \beta(y) = 1$, achieved expansion or contraction of universe via $\alpha_i(x_i)$ and $\beta(y)$ varied with changes of input variable x_i and output variable y, respectively. The schematic diagram of variable universe was shown in Figure 5. Equation (11) could be changed into:

$$y(x(t+1)) = b(t) \sum_{j=1}^{m} \prod_{i=1}^{n} A_{ij}\left(\frac{x_i(t)}{a(x_i(t))}\right) y_i \quad (12)$$

Equation (12) was an N-elements piecewise dynamic interpolation function. The variable universe fuzzy controller is an adaptive controller, its adaptive law is reflected in the contraction-expansion factors α and β. Based on the method of variable universe, the fuzzy control system was designed in a dual-input and single-output fuzzy controller (Figure 6). $x(k)$ and $y(k)$ were input variables of fuzzy controller; $\alpha(x(k))$ and $\beta(x(k), y(k))$ were contraction-expansion factors corresponding to the input variables; $\gamma(z(k))$ was the contraction-expansion factor of output variable and $F(x(k), y(k), k)$ was controller function approximated by fuzzy controller.

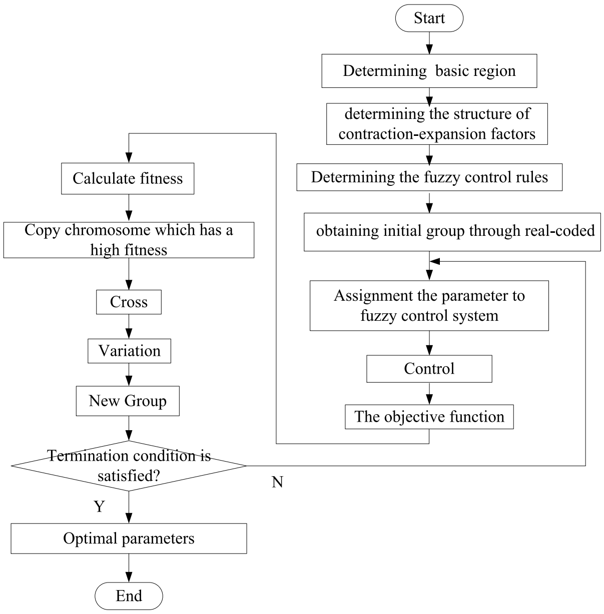

FIGURE 7. Variable universe fuzzy control flow chart optimized by genetic algorithm.

Current loop of servo motor was established with method of variable universe fuzzy control. Error e and change of error de were input; $[-e, e]$ and $[-de, de]$ were universes, respectively; $[-z, z]$ was the universe of output z. The output universe contracted with contraction of input universe. The contraction-expansion factor structure could be established as follows:

$$\begin{aligned} \gamma(e) &= w_1 \left[\frac{|e|}{r_e}\right]^{T_1} \\ \gamma(de) &= \frac{w_2}{2} \left\{ \left[\frac{|e|}{r_e}\right] + \left[\frac{|de|}{r_{de}}\right] \right\}^{T_2} \\ \gamma(z) &= w_3 \left[\frac{|z|}{y_z}\right] \end{aligned} \quad (13)$$

w_1, w_2, w_3, T_1 and T_2 were the five parameters of contraction-expansion factors. The five parameters were assigned to the variable universe fuzzy control system. The variable universe fuzzy control was used to control the system.

The initial population was obtained by random generation. The control flow chart was shown in Figure 7.

The working steps of Figure 7 were as follows. Step1, determining the basic universe of linguistic variable, the structure of contraction-expansion factor, and the rules of fuzzy control. Step2, encoding the five parameters of contraction-expansion factor to be optimized and obtain the initial population. Step3, assigning the parameters of contraction-expansion factor to the designed fuzzy inference system and use of the method of variable universe fuzzy control to control the system. Step4, calculating the fitness according to the objective function. Step5, selecting the chromosome with high fitness for copying, crossover and mutation to obtain a new population. Step6, judging whether the termination condition was satisfied: if it was satisfied, stop obtaining the optimal parameter of contraction-expansion factor; otherwise, gone to step3 to continue.

A structure of contraction-expansion factors was established by objective function (14) to ensure that the adjustment of guide vane opening has a better dynamic performance and the output value was kept within a certain range. The time integral of absolute error was added to the function to improve the transition dynamic performance of the function.

$$J = \int (k_1 |e_\omega(t)| + k_2 u^2(t))dt + k_3 t_u \tag{14}$$

where: $e_\omega(t)$ was the error, $u(t)$ was the control value, t_u was the rise time, k_1, k_2 and k_3 were the weightings of velocity objective function.

The genetic algorithm was used to optimize parameters w_1, w_2, w_3, T_1 and T_2 of contraction-expansion factors. Used real number to encode the five parameters, thus the chromosome length was five ($l = 5$). The fitness function is followed:

$$f = \frac{1}{J} \tag{15}$$

In the process of genetic algorithm optimization, the initial population size was 50, the maximum number of generations was 200, the crossover probability was 0.7, and the mutation probability was 0.1. The fitness value of each individual was calculated by the fitness function (15). In order to obtain the new population, the fitness values were provided to the genetic operator for selection, crossover and mutation. The genetic algorithm searched stopped when the iterations reached 200 times (maximum number of generations). The algorithm converged to the best chromosome and the selected contraction-expansion factor obtained the optimal parameters. The obtained optimal parameters were assigned to the variable universe fuzzy controller, so as to realize the optimal control performance of variable universe fuzzy controller in adjustable hydraulic torque converter servo system.

The operation of basic variables in fuzzy control system depends on the time step k, they were set as $x(k)$, $y(k)$ and $z(k)$. Therefore, the time function can be used to represent the variable universe, they can be denoted as $X(x(k))$, $Y(y(k))$ and $Z(z(k))$. With the progression of optimization, the input and output universes of fuzzy subset were correspondingly changed. Meanwhile, membership functions A_i, B_j and C_{ij} also changed accordingly, which were denoted as $A_i(x(k), k)$, $B_i(y(k), k)$ and $C_{ij}(z(k), k)$. The above genetic algorithm made fuzzy control rules become a set of dynamic rules $R(k)$:

$$\text{R(k): if } x(k) \text{ is } A_i(k) \text{ and } y(k) \text{ is } B_j(k) \text{ then } z(k) \text{ is } C_{ij}(k) \tag{16}$$

where $k = 0$, rule (16) as initial control rule of fuzzy control. As k changes, the control function deforms as the universe changes accordingly, which can be denoted as:

$$F(x(k), y(k), k) = \sum_{i=1}^{p} \sum_{j=1}^{q} A_i(x(k), k) B_j(y(k), k) Z_{ij}(k) \tag{17}$$

It suggested that the monotonicity of $R = R(0)$ guaranteed the monotonicity of $R(k)$ ($k > 0$), thus ensured the validity of control function $F(x(k), y(k), k)$ by rule (16).

The design of fuzzy controller weakened the dependence on prior knowledge in control field with the theory of variable universe. The basic universe will expand or contract with the according change of controller input error according to trend of fuzzy control rules. Therefore, the new fuzzy control rules will be derived from the initial fuzzy rules, thus greatly improving performance of control system.

IV. SIMULATION OF SERVO MOTOR CONTROL SYSTEM IN ADJUSTABLE HYDRAULIC TORQUE CONVERTER

Based on the above theoretical analysis, the corresponding sub-modules were established by MATLAB software, and the simulation of whole system was carried out. In order to verify the effectiveness of variable universe fuzzy control method for adjustable hydraulic torque converter based on multi-population genetic algorithm proposed in this paper, three simulation examples were given and compared with the existing research results.

A. SIMULATION UNDER CONSTANT WIND SPEED

In [16], a two-mode parameter self-tuning fuzzy controller for adjustable hydraulic torque converter was designed and simulated under constant wind speed. The simulation time was 5s. The wind speed was constant at 13m/s. From the simulation results in [16], it can be seen that the speed of synchronous generator reached the rated speed at 0.8s and the steady-state error was almost zero after the adjustment of turbine output speed in hydraulic torque converter, which satisfied the condition of grid-connected power generation.

According to the above conditions, the simulation of generator speed under constant wind speed was carried out. The generator speed response under constant wind speed is shown in Figure 8.

From Figure 8, it can be seen that: the dynamic response time of generator speed using the controller we designed was 0.4s, and the steady-state error was almost zero. Compared to the double-mode parameter self-tuning fuzzy control method proposed in [16], our control method is better in dynamic response time.

B. SIMULATION UNDER STEP WIND SPEED

In [36], a fuzzy controller of adjustable hydraulic torque converter was designed and simulated under step wind speed. The simulation time was 20s, and the wind speed was constant to 9m/s within 0 to 10s. At 10s, the wind speed changed from 9m/s to 10m/s and kept (9m/s step wind speed). From the simulation results in [36], it can be seen that the dynamic response time of generator speed was 3.5s, and the variation of synchronous generator speed was less than 1% (15r/min) when the wind speed changed.

According to the above conditions, the simulation of generator speed under 9m/s step wind speed was carried out.

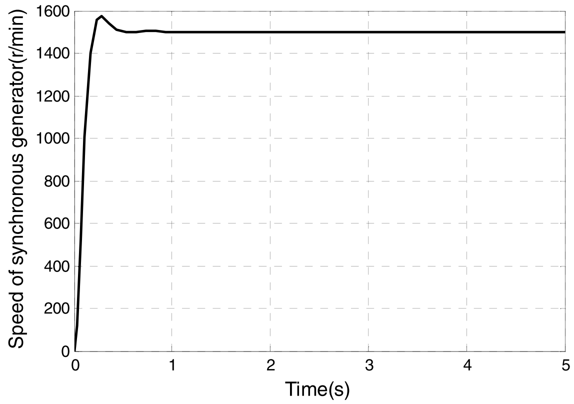

FIGURE 8. Generator speed response under constant wind speed.

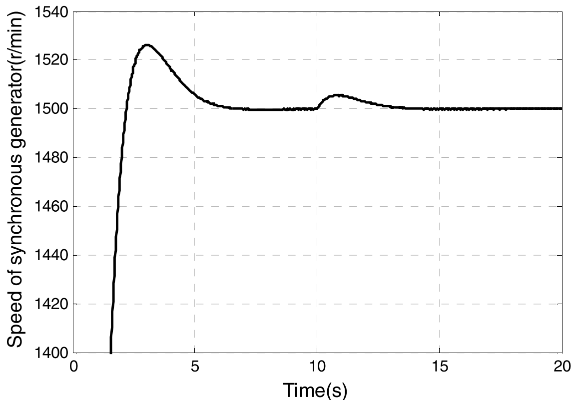

FIGURE 9. Generator speed response under 9m/s step wind speed.

The generator speed response under 9m/s step wind speed is shown in Figure 9.

From Figure 9, it can be seen that: the dynamic response time of generator speed using the controller we designed was 3s. When the wind speed changed, the change of the synchronous generator speed was less than 0.53% (8r/min), compared with the fuzzy control method proposed in [36], the control method we presented has a better control effect.

C. SIMULATION UNDER SINUSOIDAL INPUT SPEED

In [37], a dual-mode controller based on fuzzy PID for adjustable hydraulic torque converter was designed, and the simulation study was carried out when the input speed of hydraulic torque converter changed with sinusoidal law. The simulation time was 200s, and the maximum range of input speed was 420r/min∼500r/min. The input speed includes two kinds of frequencies. The signal frequency changed from 0.05Hz to 0.3Hz at 100s. When the frequency was 0.05Hz, the amplitude of sinusoidal signal change was 40r/min. When the frequency was 0.3Hz, the amplitude of sinusoidal signal change was 20r/min. From the simulation results of [37], it can be seen that: in the fuzzy PID control, the precision of the system was high, the fluctuation range of synchronous generator speed was 1497.3r/min∼1502.3r/min, and the

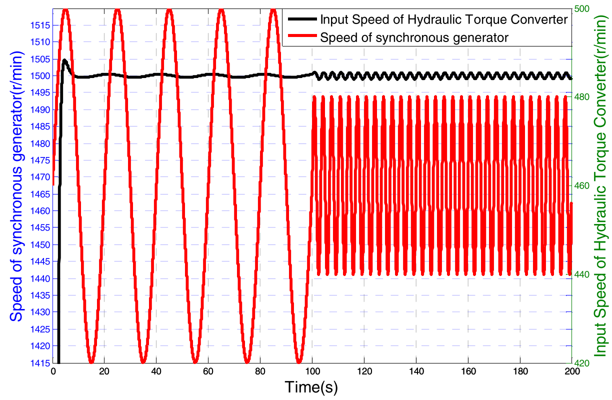

FIGURE 10. Generator speed response under sinusoidal input speed.

frequency range of generator was 49.91Hz∼50.077Hz. In the open-loop control, the response speed of the system was fast relatively, but the fluctuation range of synchronous generator speed increased to 1494.4r/min∼1505.8r/min, and the frequency range of generator was 49.813Hz∼50.193Hz. According to the requirement of GB/T159-2008 (Power quality power system frequency tolerance), the limit value of frequency deviation under normal operation condition of power system was 50 + 0.2Hz. The double-mode control method based on fuzzy PID proposed in [37] can meet the control requirements of hydraulic speed regulating wind turbine and realize the rapid and precise speed control of synchronous generator.

According to the above working conditions, we use the controller designed by us to carry out the simulation of generator speed response when the input speed of hydraulic torque converter changed with sinusoidal law. The generator speed response is shown in Figure 10.

From Figure 10, it can be seen that: when the frequency was 0.05Hz, the fluctuation range of synchronous generator speed was 1498.6r/min∼1501.8r/min, and the frequency range of generator was 49.95Hz∼50.06Hz; when the frequency was 0.3Hz, the fluctuation range of synchronous generator speed was 1495.7r/min∼1503.9r/min, and the frequency range of generator was 49.85Hz∼50.1Hz. Compared with the two-mode control method based on fuzzy PID proposed in [37], the control method we presented achieved a better control result in response speed and control accuracy.

V. CONCLUSION

The present study used variable universe fuzzy control based on multi-population genetic algorithm in current loop control of adjustable hydraulic torque converter servo motor. The controller was programmed with S-function. The simulations of servo system in adjustable hydraulic torque converter were carried out. The simulation results showed that: the controller designed in this paper is superior to the control method adopted in previous literatures; the guide vane opening could be adjusted accurately, quickly and reliably when the wind speed was constant, wind speed was 9m/s step wind speed and the input speed of hydraulic torque converter changed with sinusoidal law.

Through this control method, the optimized control of guide vane opening of adjustable hydraulic torque converter in wind turbine was achieved. By using this control method, the power output quality of wind turbine will be improved. This control method will provide an effective, fast and stable control strategy for the uncertain system with properties of nonlinearity, strong disturbance and uncertain time-varying.

In this paper, the control of guide vane opening in adjustable hydraulic torque converter system has been studied and achieved some results, but there are still some problems that have not been deeply studied, which need to be further considered and perfected: 1) More detailed analysis and more precise modeling of flexible transmission chain in adjustable hydraulic torque converter are needed; 2) Termination conditions of genetic algorithm need to be studied in order to improve the efficiency of genetic algorithm.

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