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Design and Implementation of Power Electronic Load Used to Test Tidal Current Energy Generator Sets

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***Abstract*—Tidal current energy receives increasing interest as a green renewable energy. Power electronic load is a useful tool to test and evaluate the performance of tidal current energy generator sets. In this paper, a novel power electronic load scheme is proposed. There are four control mode, such as constant power, constant voltage, constant current and constant resistance. It is flexible and can be used to evaluate the power parameters, realize the Maximum Power Point Tracking etc.. An three-stage load control technology is applied to improves the system response speed and control precision. The controller is developed based on STM32. The core control algorithm is Generalized Fuzzy Hyperbolic Model (GFHM) PID algorithm. The real time data may be monitored remotely via GPRS. The simulation and field testing results verified the significations of this scheme. Some valuable experience and data are obtained, and indicate that it is very useful for the further investigate tidal current energy power generation.**

Keywords—Tidal current energy power generation system; power electronic load; simulation verification; field test

I. INTRODUCTION

In the face of the impending problems of energy shortage, tidal current energy that has not been produced on a large scale receives more and more interest as green renewable energy [1]. Tidal current energy has many characteristics including intermittent changes, periodical changes, and continuous changes. How to better develop, use and test the tidal current energy is one of key research areas. The power electronic load was designed in order to test, evaluate the tidal current energy and monitor the operation status for the Tidal Stream Turbine. With the development of the power electronics and power supply technique, power electronic load plays more and more important role in testing and evaluation [2]. Traditional testing methods via resistance box has many shortcomings, such as constant resistance, poor control accuracy, slow response speed and inflexible, which have been abandoned gradually. A power electronic load which has advantages with high accuracy, fast response speed, and simple operation is researched. Such kind of power electronic load should be able to feedback of the power into the power networks [3]. The power electronic load uses AC/DC as main circuit topology structure. Because the system is off-grid power system, we do not design grid-connected parts. Through uncontrolled rectifier, the unstability tidal current energy is switched to steady power energy. Pulse Width Modulation (PWM) is used to control Insulated Gate Bipolar Transistor (IGBT) [4]. As a result, launch loads can be realized in a stepless adjustment way. The power electronic load which has high accuracy and fast response speed can test and evaluate tidal current energy. Also more energy is got from ocean with the help of the power electronic load.

The control algorithm is the core to ensure that the system works in four modes. And here we adopt the Generalized Fuzzy Hyperbolic Model PID (GFHM) as the control algorithm. It has been proved to be a Universal approximator in references [5]. References [6] and [7] made a comprehensive analysis for the control performance of GFHM-PID, and proved that the GFHM-PID controller has better control performance than the traditional PID controller from the theoretical analysis. This paper uses GFHM-PID as the core controller, effectively improved the control performance of the system.

II. SYSTEM COMPOSITION AND WORKING PRINCIPLE

A. Main Circuit Topology Structure of the Power Electronic Load

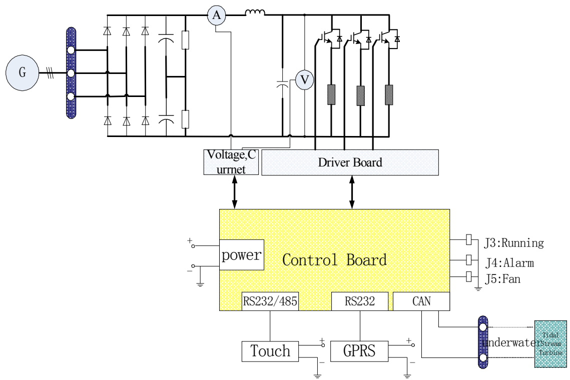

Fig. 1. Circuit of the power electronic load.

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Main circuit topology structure of the power electronic load is shown in Fig. 1. The uncontrolled rectifier circuits are made by six power diodes. When Tidal Stream Turbine works in generating electricity, only two power diodes turn on. In order to make the wave form of the rectified DC voltage smoother, filter circuit consisting of inductance and DC capacitor were added into DC side of the main circuit.

Load module consists of high-frequency power electronic switches and power resistance. Power electronic load adopt electronic power-switching technique, controlling in three parts, to ensure a large dynamic adjustment range. The load apartment adopts modular design, which can achieve larger power load via using modules in parallel or cabinets in parallel, and this made power extend easily. Rectification module uses Semikron SKD110/12, in which the rated voltage is 1200V, and rated current is 110A. Power electronic switch uses Infineon Corporation's BSM 100 GB 170 DLC. This IGBT can tolerate 1700V voltage and 160A current. The parameter of inductance is 100uH/110A, and that of capacitance is 10000μf/450V. Because single capacitance cannot tolerate such high voltage, two capacitance connected were made in series to share the voltage together. The load resistances were chosen according to the power and rectification voltage. The rated voltage of the generator is 400V, which is 540.4V~565.8V after rectification, and we take it as 600V for easily calculating. We take the first part power as 1.25kW and the calculated resistance as 288Ω, but the real largest power of this part is 1.13kW. Therefore, the 1.25kW resistance can meet the system requirements. Herein, we choose 288Ω, 1.25kW resistance as the first part power resistance. The selection of three part power resistance is shown in Table I. The regulation accuracy of load resistance is high. For example, the power of first part is 1.25kW, and the duty ratio changes from 0.01 to 0.99, so the accuracy can reach 12.5W.

TABLE I. PARAMETER LIST OF THE THREE SEGMENTS POWER RESISTANCE

Power (kW)	Calculated Voltage (V)	Calculated Resistance (Ω)	Real Voltage (V)	Rated Power (kW)
1.25	600	288	570	1.128125
5	600	72	570	4.5125
20	600	18	570	18.05

B. *Control System Design*

Power electronic load controlling circuit utilizes STM32F207 as the main controller, and supplemented with periphery signal acquisition circuit and protection circuit. In specific, the controlling circuit consists of communication circuit, detection circuit and controlling unit.

Communication circuit is divided into underwater communication and land communication. Underwater communication transmits the underwater power situation and underwater environment to the land monitor system in real time through CAN. Land communication is divided into local communication and remote communication. Local communication communicates with the touch screen through Modbus agreement, and can issue instructions, displaying and saving data. Remote communication transmits local data to remote laboratory through the wireless GPRS transmission module, which allows us to monitor data and issue instructions conveniently in the laboratory. Data saving function achieves double backup on local touch screen and remote PC, which ensure its safety and reliability.

Detection circuit is divided into voltage detection, current detection and temperature detection. The voltage and current detection through the uncontrollable rectification and the temperature of IGBT is detected. As to failure alarm treatment, considering the failure severity and program execution speed, the main program handles with the over current failure, overvoltage failure and temperature failure in a unified way, and issues IGBT shutdown instruction.

Controlling unit is mainly made up of electrical control and software program control, which is responsible for controlling data detection, controlling alarm, controlling IGBT switch, coordinating the cooperation between each module, to serve the system together. The flow chart of power electronic load controlling system program is shown in Fig. 2.

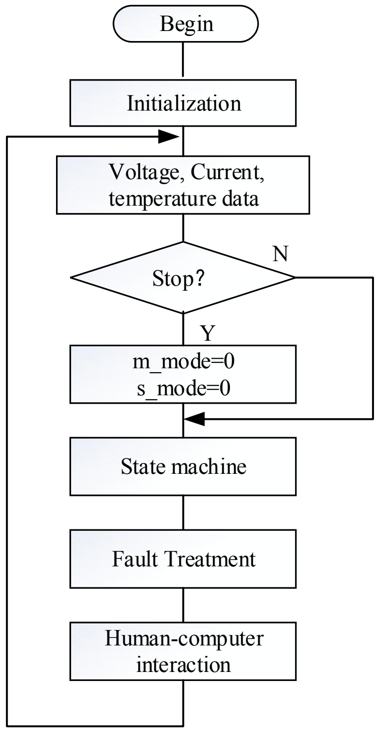

Fig. 2. Program flow chat of control system of power electronic load.

C. *Control Algorithm Design*

The constant power mode is mainly used in this design, not limited to, constant voltage mode, constant current mode and constant resistance mode can be used as well.

In the constant power mode, the power electronic load will consume a constant power. Inner current-loop control and GFHM-PID control algorithm in the constant power mode were used. By setting power P_{cs} and rectifier voltage value $V_{ca,}$ current I_{cs} can be achieved. Compared with feedback value I_c, PWM duty ratio (D) by the GFHM-PID control algorithm can be easily acquired. Duty ratio is used to control the IGBT opening and closing after anti integral saturation and limiting process. Finally, constant power control can be achieved. Through the constant power control, we can get the maximum power of generator when the sea current velocity is constant. We use the inner current-loop control only as well in the constant current mode. Since the control mode is similar to the constant power control mode, it is unnecessary to narrate more here. Principle diagram of control algorithm is shown in Fig.3

Fig. 3. Principle diagram of control system.

Under constant voltage mode, power electronic load can consume enough current so that input voltage can maintain at set voltage. In constant voltage mode, the adopted control algorithm is divided into current inner loop and voltage outer loop. Voltage outer loop controls voltage and the output current is the set value of current inner loop. Current inner loop controls current based on the output of outer loop, which made the system achieve constant current control and constant voltage control simultaneously. Under constant resistance mode, power electronic load can change the current linearly with the change of detected voltage. The control method of constant resistance mode is similar to that of constant voltage mode. Both adopt current inner loop and voltage outer loop control method can achieve constant current control plus constant voltage control simultaneously. The set value of outer loop is equal to the set value of resistance. Via adopting the double closed-loop control method with current inner loop and voltage outer loop, its control algorithm is simple and the control effect is satisfying.

The electricity generated by tidal current energy can be obtained by calculation. Assuming that the resistances of the three parts are R_1、R_2、R_3, the rectifier voltage is U and the duty ratios are D_1、D_2、D_3, then the final power that can be represented as

$$P = \frac{U^2}{D_1 \cdot R_1} + \frac{U^2}{D_2 \cdot R_2} + \frac{U^2}{D_3 \cdot R_3} \qquad (1)$$

If the duty ratio is 0, it indicates the resistance for this part is not used. The control value outputted by the GFHM-PID determines the allocation of duty ratio. Two ways are adopted during duty ratio allocation. Fine regulating is adopted in the first stage power resistance, and the duty ratio changes from 0.01 to 0.99. To ensure stable regulating and reliability of the power, switching coarse regulating is adopted in the second and third stage, and the carry is also adopted in both stages. When the duty ratio of the second stage reaches 75% and the power continues to increase, the system should start the third stage resistance control.

D. GFHM-PID Control Algorithm

Reference [5] proposed a novel fuzzy model named Generalized Fuzzy Hyperbolic Model. The basic structure of GFHM-PID is as Fig.4 [6],[7].

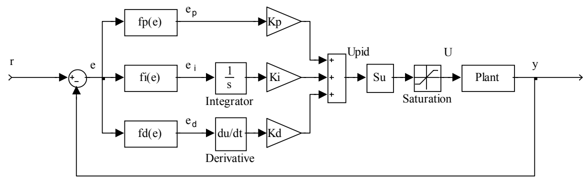

Fig. 4. Control algorithm.

In Fig.4, the functions, $f_p(e)$, $f_i(e)$, $f_d(e)$ are defined by GFHM. The normalized error variable is defined as $\hat{e} = Se \cdot e$, ($|\hat{e}| \le 1$), where $Se > 0$ is normalization factor. Choosing $d \ge 0$, according translational transform, $\hat{e}$ will form three generalized variables:

$$\hat{e}_1 = \hat{e}\,, \quad \hat{e}_2 = \hat{e} + d\,, \quad \hat{e}_3 = \hat{e} - d$$

Defining the membership function for each generalized variables as follows.

$$\hat{e}_1 : \mu_{P_{\hat{e}1}}(\hat{e}_1) = e^{-\frac{1}{2}(\hat{e}_1 - k_1)^2}, \quad \mu_{N_{\hat{e}1}}(\hat{e}_1) = e^{-\frac{1}{2}(\hat{e}_1 + k_1)^2};$$

$$\hat{e}_2 : \mu_{P_{\hat{e}2}}(\hat{e}_2) = e^{-\frac{1}{2}(\hat{e}_2 - k_2)^2}, \quad \mu_{N_{\hat{e}2}}(\hat{e}_2) = e^{-\frac{1}{2}(\hat{e}_2 + k_2)^2};$$

$$\hat{e}_3 : \mu_{P_{\hat{e}3}}(\hat{e}_3) = e^{-\frac{1}{2}(\hat{e}_3 - k_2)^2}, \quad \mu_{N_{\hat{e}3}}(\hat{e}_3) = e^{-\frac{1}{2}(\hat{e}_3 + k_2)^2};$$

where, $k_1, k_2 > 0$.

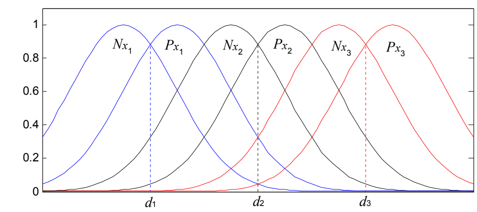

Fig. 5. The membership function curves of generalized input variables.

From the above, $\hat{e}_2$ and $\hat{e}_3$ are symmetric on $\hat{e}_1$, and the shape of their subordinating degree functions are identical.

Choose $c_1, c_2 > 0$ we can describe the control rule with the following 6 rules:

If $\hat{e}_1$ is P then $u = c_1$;
If $\hat{e}_1$ is N then $u = -c_1$;
If $\hat{e}_2$ is P then $u = c_2$;
If $\hat{e}_2$ is N then $u = -c_2$;
If $\hat{e}_3$ is P then $u = c_3$;
If $\hat{e}_3$ is N then $u = -c_3$.

Combine these 6 rules to form 8 (2^3) rules as following:

If $\hat{e}_1$ is P, $\hat{e}_2$ is P, $\hat{e}_3$ is P then $u = c_1 + c_2 + c_2$;
If $\hat{e}_1$ is P, $\hat{e}_2$ is P, $\hat{e}_3$ is N then $u = c_1 + c_2 - c_2$;

If $\widehat{e}_1$ is P, $\widehat{e}_2$ is N, $\widehat{e}_3$ is P then $u = c_1 - c_2 + c_2$;

If $\widehat{e}_1$ is P, $\widehat{e}_2$ is N, $\widehat{e}_3$ is N then $u = c_1 - c_2 - c_2$;

If $\widehat{e}_1$ is N, $\widehat{e}_2$ is P, $\widehat{e}_3$ is P then $u = -c_1 + c_2 + c_2$;

If $\widehat{e}_1$ is N, $\widehat{e}_2$ is P, $\widehat{e}_3$ is N then $u = -c_1 + c_2 - c_2$;

If $\widehat{e}_1$ is N, $\widehat{e}_2$ is N, $\widehat{e}_3$ is P then $u = -c_1 - c_2 + c_2$;

If $\widehat{e}_1$ is N, $\widehat{e}_2$ is N, $\widehat{e}_3$ is N then $u = -c_1 - c_2 - c_2$.

These 8 rules form the rule base of a GFHM, we can get the control output:

$$u = c_1 \tanh\left(k_1 \widehat{e}_1\right) + c_2 \tanh\left(k_2 \widehat{e}_2\right) + c_2 \tanh\left(k_2 \widehat{e}_3\right)$$

$$u = c_1 \tanh\left(k_1 \widehat{e}\right) + c_2 \tanh\left[k_2\left(\widehat{e} - d\right)\right] + c_2 \tanh\left[k_2\left(\widehat{e} + d\right)\right].$$

It has been proved in the references [6] that this fuzzy system is a Guaranteed-PID-Performance fuzzy controller (GPP) system [8]. The controller designed by this system can guarantee the control performance of the conventional linear PID at least

III. Simulation and Test

The software simulation is carried out by Simulink in Matlab. The input voltage is chosen as 400V/50Hz, two capacitors as 10000uf/450V series, and Inductor as 100uH/110A to simulate the constant power control. Fig. 6 shows simulation model of constant power control. Fig. 7 and Fig. 8 show the variable power setpoint curves. The switching frequency of PWM is 5 kHz. According to the current detection, the duty ratio is regulated. According to the simulation we can test the control algorithm and main circuit.

After theoretical analysis and simulation, loading experiment was carried out in order to verify the stability and reliability of the system. Motor is used to drive the turbine simulating the tidal current. Meanwhile, the turbine is connected to the power electronic load though the submarine cables to test the power electronic conversion and study the maximum power point tracking (MPPT). The power electronic conversion test is mainly used to verify the reliability of the system communication and power electronic conversion. MPPT is mainly used to research the max generation power of the Tidal Stream Turbine when the flow speed is constant.

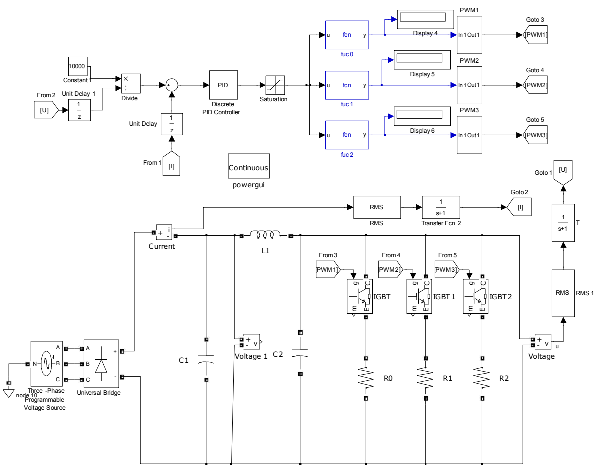

Fig. 6. The simulation model of constant power control.

The rated power, rated speed and rated voltage of the Tidal Stream Turbine are set as 20kW, 375rpm, and 400V respectively. Fig. 9 shows the physical map of the power electronic load. The turbine has an underwater base and a horizontal axis, as shown in Fig.10. Test environment of the Tidal Stream Turbine is shown in Fig.11.

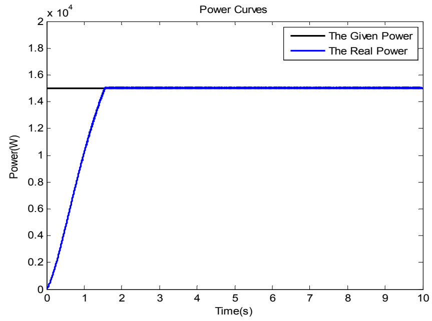

Fig. 7. The simulation curves of 15kW.

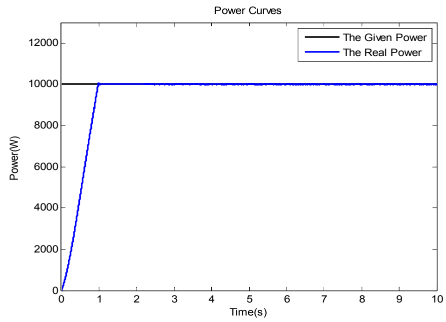

Fig. 8. The simulation curves of 10kW.

Because of restrictions of field conditions, only 2kW could be loaded in the experiments. In the first experiment, the maximum power under different speed was collected. The experimental data and trend are shown in Fig.12. Fig.13 shows the actual operation curves of power electronic load. In the second experiment, the motor speed is set as a constant (the sea current flow speed is constant). Therefore, the relationship between generation speed and the power factor could be observed. When current speed stays as a constant, the motor speed will decline and the power factor will increase via launching more loads. So the power of the Tidal Stream Turbine is related to the launched loads. The experimental data is shown in Table II.

Fig. 9. Internal structure of load.

Fig. 10. Tidal current energy generator sets.

Fig. 11. Test environment of the tidal current energy generator sets.

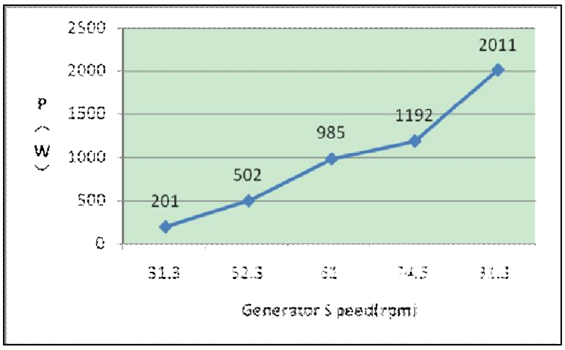

Fig. 12. Maximum power in different rotation speed.

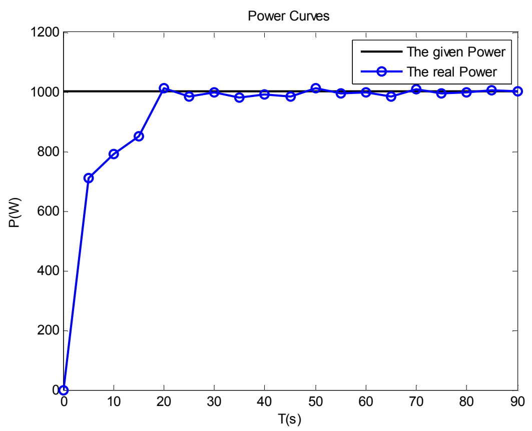

Fig. 13. The actual operation curves of power electronic load.

TABLE II. THE EXPERIMENTAL DATA

No.	Set Power (w)	Power (w)	Generator Speed (rpm)	Power Factor
1	200	196	105	0.23
2	500	491	103.5	0.47
3	800	791	101.7	0.59
4	1000	1007	100.4	0.65
5	1200	1208	99	0.72
6	1500	1507	96.7	0.8
7	1800	1814	93.9	0.85
8	2000	2011	91.3	0.88

IV. CONCLUSION

In this paper, AC/DC is adopted as the main circuit topology structure to research on power electronic load based on actual situation, and the GFHM-PID control algorithm is used. Constant power mode can be achieved with this load. It has been proven by the simulation and field test results that the main circuit, controller, measurement and communication system are with high stability and reliability. The system data of tidal current energy generation system could be recorded in real time. It is very useful to comprehensive evaluate the performance of tidal current energy generation system.

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