Research on the design of the fuzzy control system of full bridge DC converter

Wenda Liu 1*, Shutian Liang 2 and Chuxue Hao 3

1 Wuhan Institute of Marine Electric Propulsion, Wuhan 430064, China
2 Wuhan Institute of Marine Electric Propulsion, Wuhan 430064, China
3 Wuhan Institute of Marine Electric Propulsion, Wuhan 430064, China

*Corresponding author’s e-mail: liu_wenda@163.com

Abstract. It is difficult to build the mathematical model of a full bridge DC converter in a DC zonal electric distribution system. This paper advanced a design method and the specific design steps of the fuzzy control system of full bridge DC converter. A simulation model was built and the simulation results shown that in the aspect of output voltage control of a full bridge DC converter, the fuzzy control system was obviously superior to PID control system in indexes such as overshoot, response time and the times of oscillation.

1. Introduction

The integrated marine power system integrates the propulsion system and the electric power system, which are traditionally mutually independent, into one system. In the form of electric power, it provides power supply to propulsion load, pulsing load, communication systems, navigation systems and hotel load, so the comprehensive use of power source of the whole ship is realized. The application of integrated power system not only provides power supply to marine load, simplifies the marine power system, boosts the efficiency of marine systems, reduces the noise level of ships and the cost of the ship life cycle, it also conforms the trend of informationization and intellectualization and represents the future trend of marine power system.[1]

Currently the AC power system, which is composed of radial power distribution system and AC generators, remains the mainstream marine power system. The energy of the electric power loads are fed back through cables by a few centralized power distribution center, therefore thousands of cables go through cabins of the ship, which causes a problem for the laying of the cables. With the increase of the electric load, the power distribution system has become increasingly huge and complicated, causing trouble to the installation, maintenance and protection of the system and setting a limit for the upgrade of the ships. The centralized power distribution system soon reached an extreme and the power distribution system had become a focus in the design and construction of a ship. In real applications, with the increase of the capacity of the power distribution system, the partial electrical isolation becomes increasingly difficult for the ships adopting traditional radial power distribution. In case of accident and damage, the mechanical breaker is unable to isolate the fault swiftly and effectively. The partial fault may influence the whole system or even cause a power loss of the whole ship[2].

The zonal distribution system differ considerably from the currently adopted radial distribution. The basic component of a zonal distribution system are power transmission bus and zonal distribution...
center. The zonal distribution system provides power supply to the load center of the power supply zones, which obtain power from the main power transmission lines that run through the whole shipboard. From the power electronics conversion devices and power distribution cables, the load of the zones obtain power and the number of the cables that run through the cabins is greatly reduced. By reducing the amount of power cables and power distribution equipments, the cable installation is simplified and the difficulty of the ship construction is reduced, it is also benefit for the modular construction and the reduction of the whole life cost. The modular building enable the electric consuming equipment in a zone to obtain power without having to connect to the other zones during the construction. The installation, commission and test of the marine equipment is much more convenient.

The DC zonal distribution transmit and distribute power with direct current. Comparing to AC system, a DC zonal distribution system can make better use of zonal distribution for the following two reasons, one is that a DC zonal distribution adopts power electronics devices for the system protection, which is more capable of isolating the fault than an electric-magnetic breaker and is better for system reestablishment. Another reason is that a DC zonal distribution system can get rid of the speed coupling between a generator and a load motor, which is benefit for the optimization of the prime movers and the load motors.

2. The control model of a DC converter
The DC converter is the core equipment of a DC zonal distribution system, it converts the voltage of a DC bus to another kind of DC voltage (normally with a voltage drop) to supply power to the DC distribution zones. The DC outputted from the DC converter in the DC distribution zones can be converted into DC or AC of an appropriate voltage class that is suitable to the power consumption equipments. As the main power source in the DC distribution zones, the stability of the voltage output of the DC converter is an important technical index, this paper mainly researched on the control system of the output voltage of a DC converter.

The DC converter can be categorized into direct DC converter and indirect DC converter. A direct DC converter is also named a chopper, which converts a direct current into another direct current without an isolation between the input and output, and an indirect DC converter has an AC link added in the direct DC converter with an isolation by a transformer between the input and output.

One kind of indirect DC converter, the full bridge DC converter, is currently widely used. The basic structure of a full bridge DC converter is shown in figure 1. The inverter circuit, consisting of four switches, converts the DC to AC that connects to the primary winding of the transformer. By changing the duty cycle of the switches, the mean value of the commutating voltage is changed and the output voltage is changed. By changing the frequency of the switches, the frequency of AC at the primary side of the transformer is changed.

![Figure 1. The structure of a full bridge DC converter](image)
When the filter inductance value is great enough, the filter current is continuous, and the output voltage when the circuit is stable is:

\[ U_o = 2naU_i \]  

Where \( U_i \) is the input DC voltage, \( U_o \) is the output DC voltage, \( n \) is the ratio of the isolation transformer and \( \alpha \) is the duty cycle of the inverter switches.

The structure of the control system of a full bridge DC converter is shown in figure 2.

![Figure 2. The basic structure of the control system of a full bridge DC converter](image)

Where \( U_o^* \) is the ideal output voltage, \( U_0 \) is the real output voltage, and \( \varepsilon \) is the error of the voltage.

Equation (1) is the DC voltage output when the circuit is stable, and the transient process of the circuit is related to the parameters of both the full bridge converter and the load. Because the loads in the DC distribution zones include inductive loads, capacitive loads and pure resistive loads, the parameters of the loads vary considerably, meanwhile because the complexity of the running characteristics of the components (i.e. switches and isolation transformers etc) of the full bridge DC converter, it is really difficult to build a precise mathematical model of a full bridge DC converter. Therefore, when engineers adopt the traditional design method based on the precise mathematical model, they use the simplified DC transformer mathematical model, estimate the load values and design the controller by trial-and-error and the control effect is apparently not ideal.

3. The design of fuzzy control system of a DC converter

The fuzzy control system adopts the fuzzy mathematical approach to simulate the way that the fuzzy logic thinking of human works on the control object whose precise mathematical model is unknown. Comparing to the traditional control system, it is independent to precise mathematical model and it is an intelligent control system.

The structure of the control system of a full bridge DC converter is shown in figure 3[7-8].

![Figure 3. The basic structure of the fuzzy control system of a full bridge DC converter](image)
The fuzzy controller modules includes fuzzification, fuzzy rules, fuzzy reasoning and defuzzification [9]. The information processing in a fuzzy controller is shown in figure 4, the error of the system \( e \) and its changing rate \( \dot{e} \) is multiplied by their corresponding scaling factor \( k_e \) and \( k_{ec} \) separately, then we get the domain of error and the change rate of error, which is \( n_e \) and \( n_{ec} \) separately. Then we obtain the fuzzy set \( E \) and \( EC \) from the corresponding membership function \( \mu_E \) and \( \mu_{EC} \). Then we get output fuzzy set \( U \) according to the fuzzy rules, by fuzzy reasoning we get output domain \( n_u \) which is multiplied the scaling factor \( k_u \) and we get real output \( \alpha \).

**Figure 4.** The information processing of a fuzzy controller

In figure 4, the fuzzy control rules simulated the control function that human has for controlled object, it is the core of the fuzzy controller.

The following example demonstrate the design steps of the fuzzy control system of a full bridge DC converter. The basic parameters of a full bridge DC converter are as following: input voltage=5000V, ideal output voltage=1000V, transformer ratio=0.25, according to equation (1), we obtain the duty cycle of the inverter switches = 40% when the circuit is stable.

### 3.1 Structural Design

We set the basic domain for \( e \) and \( \dot{e} \) as [-10, 10], and the basic domain for \( \alpha \) as [0, 0.5].

The fuzzy domain of \( E \) and \( EC \) is \{-5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5\}, and the fuzzy domain of \( U \) is \{-5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5\}.

The fuzzy set of \( E \) and \( EC \) is determined as \{NB, NM, NS, O, PS, PM, PB\} and the fuzzy set of \( U \) is determined as \{O, L1, L2, L3, L4, L5\}.

Hence we determine the scaling factors as \( k_e = k_{ec} = 2 \), \( k_u = 1/10 \).

### 3.2 Fuzzification

The fuzzification is to determine the curves of the each membership function. According to the rules of the membership function and the practical experience we determine the curves as following.
Figure 5. The curves of membership function of $\mu_E$, $\mu_{EC}$

3.3 Design of fuzzy rules
By learning from the human-object control experience, we get the table of fuzzy control rules as shown in the following table 1 and the curved surface of rules as shown in figure 6.

Table 1. The table of fuzzy control rules.

| U   | EC | NB | NM | NS | O  | PS | PM | PB |
|-----|----|----|----|----|----|----|----|----|
| E   |    | O  | O  | L1 | L2 | L3 | L3 | L4 |
| NB  | L1 | L2 | L3 | L3 | L3 | L3 | L4 | L4 |
| NM  | L2 | L3 | L4 | L4 | L4 | L4 | L4 | L5 |
| NS  | L3 | L4 | L4 | L4 | L4 | L4 | L4 | L5 |
| O   | L4 | L5 | L5 | L5 | L5 | L5 | L5 | L5 |
| PS  | L5 | L5 | L5 | L5 | L5 | L5 | L5 | L5 |
| PM  | L6 | L6 | L6 | L6 | L6 | L6 | L6 | L6 |
| PB  | L7 | L7 | L7 | L7 | L7 | L7 | L7 | L7 |

Figure 6. The curved surface of fuzzy control rules

3.4 Defuzzification
We get a fuzzy control variable by the reasoning with fuzzy control rules, which can not be directly used for the control of object. We need to convert the fuzzy variables into precise variables and this conversion process is called defuzzification. Similar to fuzzification, firstly the curves of membership function $\mu_U$ need to be determined, as shown in figure 7. After the membership functions are determined, we obtain the values of the output domain, which are multiplied by the scaling factor $k_u$ and the real control values are obtained.
4. Simulation Validation

We built a simulation model and simulated the full bridge DC converter and its control system. Firstly we built a simulation model of a full bridge DC converter as shown in figure 8, the main parameters of it are listed in table 2.

Table 2. The parameters of the simulation model of a full bridge DC converter.

| Symbols | Names               | parameters |
|---------|---------------------|------------|
| Ui      | DC voltage source   | 5000V      |
| S1-S4   | MOSFET              |            |
| T       | Isolation transformer | Ratio=1:0.25 |
| VD1-VD4 | Diode               |            |
| L       | Filter Inductance   | L=0.001H   |
| C       | Capacitor           | C=0.0002F  |
| R1      | Load                | R=10Ω      |
| R2      | Load                | R=20Ω      |
|         | Gate Drive1-2       | 4KHz       |

The Open-Loop control of a full bridge DC converter, the duty cycle of the inverter switches is 40%, the output voltage curve is shown in figure 9 (load R1 first, then load R2 0.01s after when the system is stable).
From the simulation result we see that the overshoot of the output voltage is obvious \((\sigma \approx 70\%)\), the voltage fluctuation is also obvious when the load changes.

The simulation model after we add fuzzy control system in the full bridge DC converter is shown as in figure 10:

We adopt the close-loop fuzzy control on a full bridge DC converter, the output voltage curve of it is shown as in figure11 and figure 12 (load R1 first, then load R2 0.01s after when the system is stable). The output wave of classic PID control is also drawn in figure 11 for comparison. From the simulation result we see that after the fuzzy control is added in the the full bridge DC converter, the overshoot of the output wave has reduced significantly \((\sigma < 7\%)\), the output wave has less no oscillation, and is more stable during the load changes.
Figure 11. The output voltage curves of a full bridge DC converter (fuzzy control versus PID control)

Figure 12. The partial enlarged curve of the output voltage of a full bridge DC converter (fuzzy control versus PID control)

5. Conclusion
The design of the classic control system is based on the mathematical model of the controlled object, the more precise is the model, the better the control system is designed. Two problems emerge out of it, one is that the precise mathematical model is increasingly difficult to build as the complexity of the controlled object increases. Another problem is that even if the precise model is obtained, the designed control system is not applicable in the real control system because of the enormous calculation quantity. In the real application of control system, a fact is found that an experienced operator only inspect and analyze the controlled object by simple meters without knowing the working principle or the mathematical model of the controlled object, by adjusting the control process through the actuator, the control effect of the complex controlled object is always optimal. The fuzzy control is expressing the operation process of the operator with fuzzy mathematics and using it as a controller. The fuzzy controller do not focus on the mathematical model of the controlled object, and the optimal control of it rely on the “experience of the operator”, i.e. the “fuzzy rules” in this paper. Therefore the focus and difficulty of the designing of a fuzzy control system is the designing of the fuzzy rule, which require further study in the future.
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