Design of a Low Power Consumption Control System of Permanent Magnet Synchronous Motor for Automated Guided Vehicle

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***Abstract*—Permanent Magnet Synchronous Motor (PMSM) is widely used in industrial control fields such as numerical control machine tools and transfer robots due to its excellent speed regulation performance. As a typical representative of transfer robots, Automated Guided Vehicle (AGV) has attracted extensive attention and research. PMSM control system for AGV is specified on many aspects, such as small size, high power density and low power consumption. In this paper, the control system of PMSM for AGV is studied, including the design of hardware circuit and software control algorithm. STM32's abundant on-chip resources are fully utilized and Intelligent control strategies such as space vector pulse width modulation and fuzzy PID control are adopted to control the system in real time. By experimental test and results analysis, the control system designed in this paper shows good dynamic performance and low power consumption.**

Keywords—PMSM, AGV, high power density, low power consumption, fuzzy PID control

I. Introduction

Automatic Guided Vehicle (AGV) refers to an intelligent transport vehicle equipped with optical or electromagnetic guidance detection devices and capable of traveling along specified routes [1]. AGV is a branch of wheeled mobile robots, which is widely used in various industries, such as manufacturing industy, warehousing industry, etc. The whole frame of AGV is mainly composed of on-board controller, chassis drive device and guide detection device [2]. The chassis drive of AGV requires high control accuracy, small volume and has the characteristics of low voltage and high power density.

With the rapid development of modern science and technology, the technology and properties of rare earth permanent magnets have been significantly improved. At the same time, the development of permanent magnet materials has further promoted the development of permanent magnet motors. Permanent magnet synchronous motor (PMSM) has many advantages such as small size, light weight and simple maintenance [3]. PMSM control system powered by frequency converter can achieve excellent speed regulation performance through double closed-loop of position and current. It has been widely used in aerospace, numerical control machine tools, electric vehicles, robots and other fields which require high control accuracy and good reliability [4]. Therefore, PMSM control system is very suitable for chassis drive of AGV. As the power density and current is quite high, the PMSM control system will generate a lot of heat, which brings the challenge of circuit design. In order to ensure the PMSM control system work well, the heat dissipation and loss of power transistors must be concentrated. In this paper, a PMSM control system for AGV with high performance and reasonable price is designed, and its performance is verified by experiments.

II. General Design Scheme

The overall framework of PMSM control system for AGV is shown in Fig. 1. The maxium input voltage of the system is 48V, and the maxium output power is 400W.

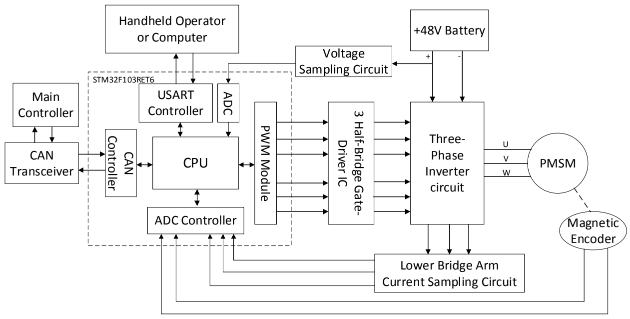

Fig. 1. The overall framework of PMSM control system.

The control system of PMSM for AGV designed in this paper communicates with the main controller of vehicle in real time through CAN bus. The main controller can send speed instructions and emergency braking instructions to the control system, and the control system can also feedback speed, bus voltage, three-phase current and other information to the main controller. The serial port of the system can be connected with the handheld operator or the upper computer to debug and monitor the system. The system generates complementary PWM signals embedded with dead-time through the advanced timer interface of STM32, and then amplifies the signals by half-bridge gate driver chip to drive the MOSFET on and off, so as to generate three-phase alternating current of driving motor. The ADC port of the system is responsible for receiving the three-phase current signal and speed signal from the sensor to realize double closed-loop control of speed and current in the DSP. At the same time, the system detects the DC bus voltage through ADC port to prevent the impact of high bus voltage on the system.

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III. THE DESIGN OF SYSTEM HARDWARE

A. Controller

STM32F103RET6, the STM32 series single chip computer produced by ST company, is used as the core unit. This series of MCU is based on cortex-M3 core, and uses Harvard structure to transmit data and address. The MCU has many advantages, such as rich peripherals, excellent real-time performance, excellent power control [5]. It has excellent computing ability and can be conventionally used to implement vector control algorithm of PMSM. In addition, it is equipped with advanced timers specially for motor control, which can output complementary PWM waveforms embedded in dead-time.

B. Drive Circuit

The main circuit of the inverter consists of six MOSFETs, which are used to convert DC input voltage into three-phase sinusoidal output voltage. The circuit of the three-phase bridge inverter is shown in Fig. 2.

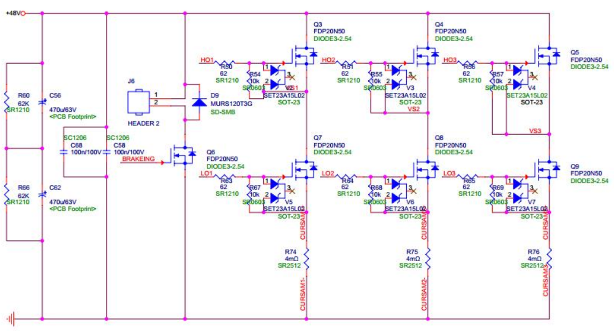

Fig. 2. Three-phase bridge inverter circuit.

The N-channel MOSFET FDMS86183 is selected. It has the following characteristics: the maximum drain to source voltage is 100V; the maximum drain current is 124 A at 25 ºC; and the on-resistance is only 4.2 milliohms. The MOSFET is encapsulated in Power 56, which dissipates heat through bottom copper laying technology, greatly saving the space of Printed Circuit Board. In order to reduce the switching loss and the heat of MOSFET as much as possible, it is very important to select a suitable resistance in series with the gate of MOSFET. The gate resistance will affect the driving ability of the driving circuit for MOSFET. If the gate resistance is too large, it will hinder the conduction of the gate; if the gate resistance is too small, the driving voltage will oscillate [6]. In general, the appropriate gate resistance can be obtained from the recommended values given by the datasheet of components, and verfied by the double-pulse experiment.

FAN7888 half-bridge gate driver chip developed by ON Semiconductor is selected as the driver chip of MOSFET. The chip is compatible with 3.3V and 5V logic input, and its bootstrap working channel floating voltage can reach + 200V. It can convert the 3.3V switching signal output by MCU into the gate driving signal of MOSFET. In addition, the chip has built-in shoot-through prevention circuit for all channels with typically dead time, which can prevent the short-circuit of upper and lower bridge arms during the operation of the circuit. Therefore, the driver chip is suitable for the PMSM control system for AGV designed in this paper.

C. Current Detection Circuit

In order to realize current closed-loop control, three phase currents need to be sampled. According to the characteristics of PMSM control system for AGV, the current sampling scheme of lower bridge arm is adopted in this paper. Each phase current is sampled by connecting a milliohm precision resistance in series with each lower arm of the three-phase bridge. In the real-time control of the motor, the voltage signal on the sampling resistance corresponding to the three-phase current is sampled through the ADC module of the DSP. Then in the DSP, the better two phase currents are selected as the actual sampling current value, and Clark/Park conversion is carried out on them. Finally, the current closed-loop is realized by PI regulator. This sampling scheme has the advantages of low cost, high precision and simple implementation. It is suitable for the PMSM control system for AGV designed in this paper.

The TLV2316 dual-channel operational amplifier is used to enlarge the sampling values, and the appropriate DC voltage bias is set to match the input requirement of ADC port. In order to ensure the accuracy of sampling circuit, clamping circuit is used, as shown in Fig. 3.

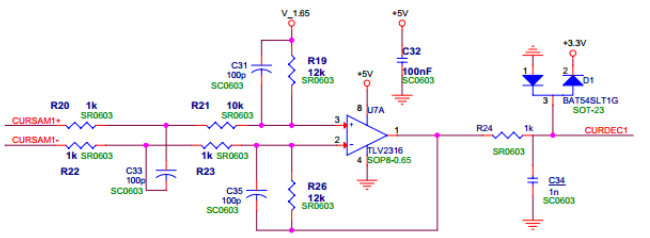

Fig. 3. One-phase current detection circuit.

D. DC Bus Voltage Detection Circuit

DC bus voltage sampling circuit is used to monitor the fluctuation of real-time bus voltage, so that the system can make corresponding protection measures when the bus overvoltage or undervoltage is detected. The resistance voltage dividing method is used to detect the DC bus voltage. The DC bus voltage is converted to a voltage ranging from 0 to 3.3 volts and sent to the ADC port, and then the detected voltage is restored in the DSP.

E. Braking circuit

In order to suppress bus voltage fluctuation, brake resistance and brake switch can be connected in series between buses. The brake switch can adopt a MOSFET of the same type as the main circuit of the inverter, and a push-pull circuit can be designed separately to drive it. The push-pull circuit is shown in Fig. 4.

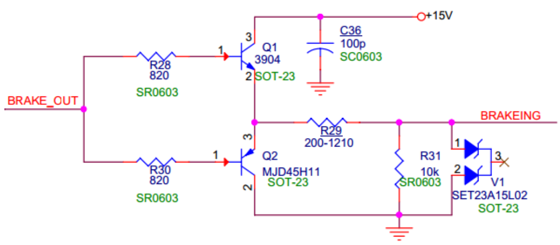

Fig. 4. One-phase current detection tcircuit.

F. Encoder Circuit

A1330 angle sensor chip produced by Allegro company is adopted, which has a maximum resolution of 12 bits. A1330 is a magnetic encoder, which needs to be used in conjunction with a magnet embedded in the motor shaft with a certain magnetic field strength. The analog output of the A1330 angle sensor is sampled by the ADC module of the DSP. The speed loop is realized through PI regulator in the MCU.

G. Power Supply Circuit

The power supply circuit is used to supply power to each component of the PMSM control system for AGV. The power supply requirements for the system are shown in Fig. 5.

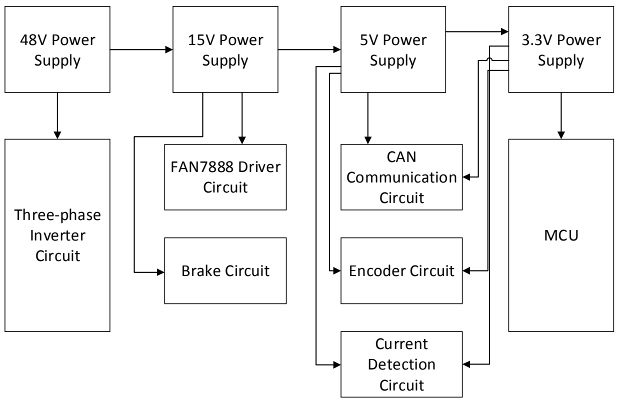

Fig. 5. Power supply requirements.

According to the above power supply requirements, 48V power supply voltage needs to be converted to 15V, 5V and 3.3V. By comprehensively considering both the performance and the power consumption of components, LM5161 Synchronous Step-Down converter, LM7805 3-Terminal Positive Voltage Regulator, LM1117 Low Dropout Positive Voltage Regulator, are adopted. In addition, a number of capacitors should be added to the power supply circuit to eliminate the low-frequency and high-frequency harmonics.

IV. FUZZY-PID CONTROL STRATEG

In order to improve the performance of PMSM control system for AGV, the fuzzy PID control strategy is adopted in this paper. Fuzzy-PID control strategy continuously detects and calculates the deviation E and deviation change rate EC of the current control system, and applies fuzzification, fuzzy reasoning and de-fuzzification to them [7]. Finally, the variation of PID parameters ΔKp, ΔKi and ΔKd are obtained. Then, the system can be controlled by using the PID control strategy. The structure of the fuzzy PID control system is shown in Fig. 6.

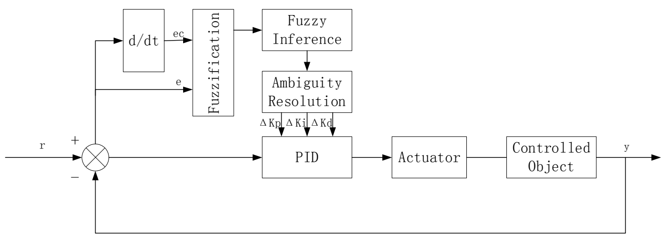

Fig. 6. Fuzzy-PID control system.

Compared with the traditional PID control algorithm, the fuzzy PID control algorithm can modify the PID parameters online according to the different E and EC, thus improving the control performance of the system [8-9]. The formulation of fuzzy rules is very important for the whole fuzzy PID control system. For the PMSM control system for AGV, its rules can be formulated according to the following experience. When the absolute error is large, a larger Kp can be selected to accelerate the system response; when the absolute error is moderate, Kp can be reduced to prevent system overshoot; when the absolute error is small, Ki can be increased appropriately to ensure better steady-state characteristics.

In order to verify the feasibility of the control strategy, a Simulink simulation model of PMSM control system for AGV based on fuzzy PID control is built according to the basic principle of vector control of PMSM and the algorithm of fuzzy PID control. The simulation model is shown in Fig. 7.

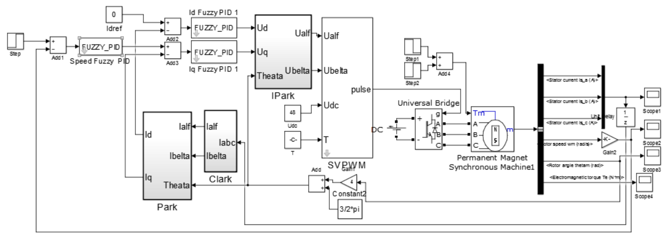

Fig. 7. Simulation model of PMSM control system.

According to the simulation model, the speed response curve of the fuzzy PID controller can be obtained. The comparation of the speed response curve of the traditional PID controller and fuzzy PID controller is shown in Fig. 8.

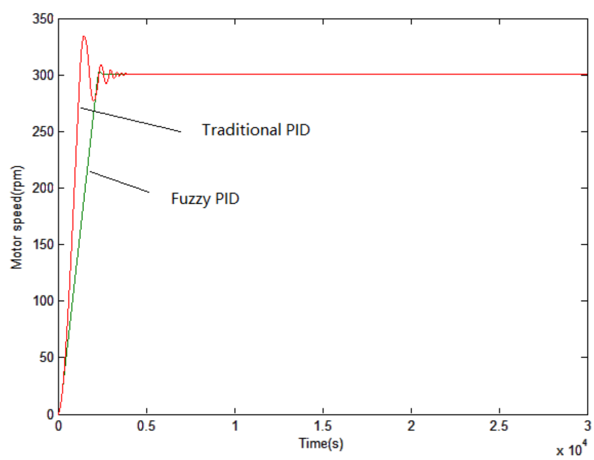

Fig. 8. Comparation of the speed response curve of the traditional PID controller and fuzzy PID controller.

The results show that compared with the traditional PID control system, the oscillation of the fuzzy PID control system is greatly reduced, and the recovery time is also shortened. Therefore, the use of fuzzy PID control strategy can improve the dynamic quality of the system.

V. THE DESIGN OF SYSTEM SOFTWARE

The flow chart of the main program of the system software is shown in Fig. 9.

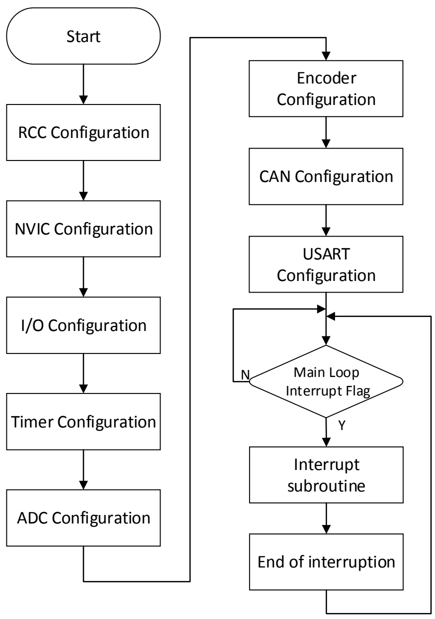

Fig. 9. The flow chart of the main program.

The process includes initialization of each module of the system, main loop program and interrupt service subroutine. The program is executed from main function. Firstly, the initialization of hardware and software modules, including system clock, ADC, timer, I/O port, timer, CAN bus, serial port and so on, is executed. Then the program enters the main loop program and waits for the interrupt. When the interrupt arrives, the interrupt service subroutine is executed, the interrupt flag is cleared after execution, and then the process returns to the main program, waiting for the next interrupt.

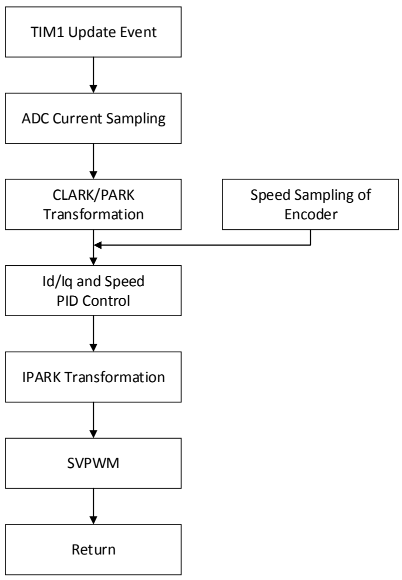

Fig. 10. PWM generation.

The whole control algorithm will be completed in the interrupt service subroutine. Due to the three-phase current sampling scheme, the update event of TIM1 is set as the triggering condition of ADC interruption, and the sampling data is recorded when the lower bridge arm is opened. In order to ensure the sampling accuracy, the two phase currents with small duty cycle are selected as the actual sampling values, and the third phase current value is calculated according to the connection mode of the motor. Then Clark/Park conversion is performed on the current sampled values and sent to the current regulator for operation. At the same time, the sampled speed values are sent to the speed regulator for operation. Finally, the operation results are converted into two phase orthogonal voltage by Park inverse transformation, and then the MOSFET is turned on or off by SVPWM algorithm. The process of PWM generation is shown in Fig. 10.

VI. Experiment Result And Analysis

In the experiment, a three-phase 8 pole PMSM is used as the test motor. The physical connection diagram is shown in Fig. 11.

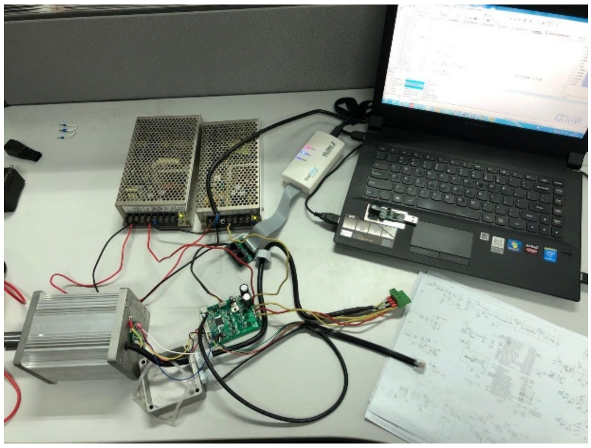

Fig. 11. Physical connection diagram.

Fig. 12 shows the phase current waveform at rated value. From the waveform, it can be seen that the phase current tends to be sinusoidal state, which accords with the actual operation. In addition, through the detection of thermal imager, the temperature of the circuit board is within a reasonable tolerance range, which can be concluded that the design of hardware is reasonable.

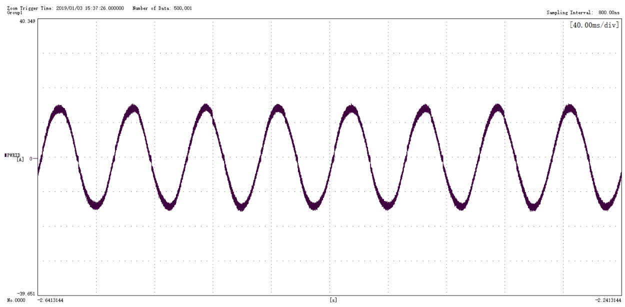

Fig. 12. One phase current waveform.

In order to verify the actual control performance, the speed is set step by step from zero to the rated speed, and the control performance is observed by using virtual oscilloscope. The output waveform of the virtual oscilloscope is shown in Fig. 13.

As can be seen from Figure 14, there is a little jitter in the velocity waveform. According to the spectrum analysis, this is the first harmonic of the mechanical frequency of the motor caused by the different concentricity of the encoder and the motor rotor. It is believed that this problem can be solved with the improvement of experimental conditions.

Generally speaking, the feedback speed follows the set speed well, and the speed control effect is better.

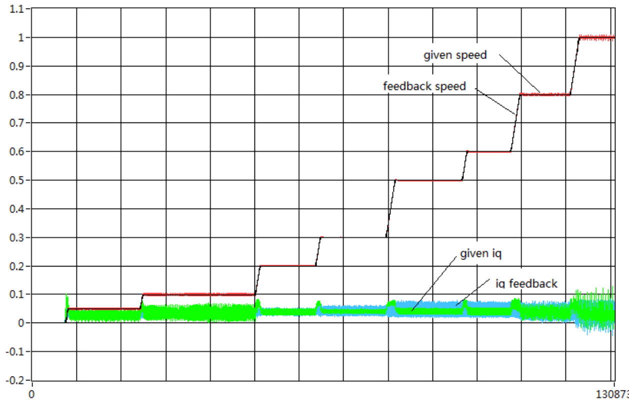

Fig. 13. The output speed waveform of virtual oscilloscope.

In order to further verify the low power requirement of the system, the double pulse test experiment is carried out on the circuit board, and the gate resistance is adjusted appropriately according to the experimental results. The inductor for double pulse test is 84uH and the pulse width is 26.25us. The formulas for calculating turn-on loss and turn-off loss are as follows:

$$P_{turn-on} = \int_{t_1}^{t_2} V_{DS}(t) I_D dt \qquad (1)$$

$$P_{turn-\mathrm{off}} = \int_{t_3}^{t_4} V_{DS}(t) I_D dt \qquad (2)$$

where V_{DS} is the drain to source voltage, I_D is the drain current, $t_2 - t_1$ is the turn-on time of MOSFET and $t_4 - t_3$ is the turn-off time of MOSFET.

After repeated experimental tests, the gate resistance of 7.5 ohms is selected finally. The experimental waveform of double pulse is shown in Fig. 14 and Fig. 15.

According to the measured waveforms of double-pulse experiment, the switching loss of MOSFET is about 1.692 W, which meets the requirement of low power consumption.

VII. Conclusion

In this paper, the overall design scheme of PMSM control system for AGV is formulated, and the design of hardware circuit and software control algorithm are discussed in detail. After testing and analysis, the control system designed in this paper can control the PMSM for AGV very well, and has good dynamic quality and stable performance. In addition, the dual-pulse experiment shows that the switch has low power consumption and is suitable for the control system of PMSM for AGV. The control system has great practical value, and it can also be used for reference in the study of other low voltage, high power density control systems.

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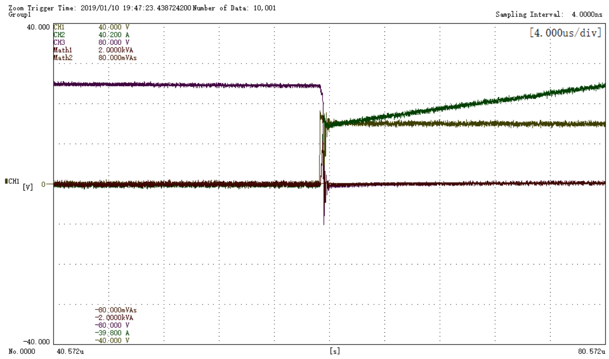

Fig. 14. Turn-off waveform of MOSFET for dual-pulse test.

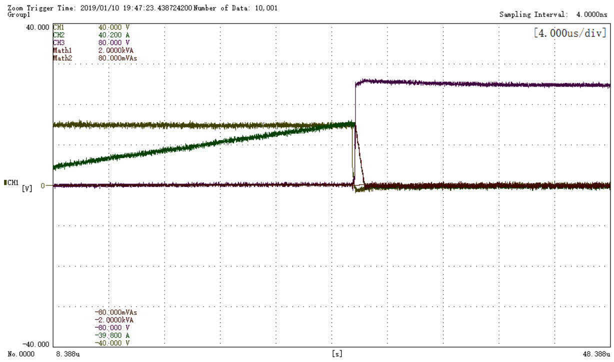

Fig. 15. Turn-on waveform of MOSFET for dual-pulse test.

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