International Journal of Applied Engineering Research ISSN 0973-4562 Volume 19, Number 1 (2024) pp. 11-18

Design of Brushless DC Motor Control System for Downhole Tubing Cutting Based on DSP

Jun Jing[1], Yiman Qin[1], Bin Tan[2] and Chao He[2]

1 School of Mechatronic Engineering, Southwest Petroleum University
Chengdu, Sichuan 610500, China
2 China National Petroleum Corporation (CNPC) Chuanqing Drilling Engineering Company Limited
Guanghan 618399, China

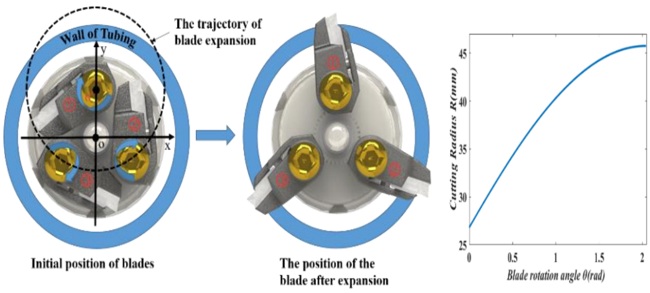
ABSTRACT

The underground electric cutting tool is an important equipment for cutting and unblocking the production column of oil and gas wells that cannot be removed due to obstruction. The precise control of a small brushless DC motor for the push rod electric cylinder is the key to ensuring the accurate feed amount of the tool and then completing the safe and efficient cutting of the column. Due to the small radial size and compact structure of the cutting tool, a brushless DC motor control system based on a digital signal processor (DSP) is designed, which can simplify the hardware circuit and reduce the structural size of the motor drive board while meeting the motor control requirements. Based on the control principle and requirements of the brushless DC motor, this paper proposes the overall control scheme of the system, gate driver module, and the software scheme of motor control program and human-machine interaction interface. The results of the system test experiment show that the control system meets the expected design requirements and has the characteristics of high motor control accuracy and fast response speed.

Keywords: DSP; brushless DC motor; Downhole information acquisition; Control program

INTRODUCTION

Oil and gas well overhaul is an important means of increasing production in the middle and later stages of oilfield production. However, during the well repair process, accidents such as production tubing stuck due to oil pipe anchors, sealing devices unable to be unsealed, and completion pipe columns buried and stuck often occur, which bring many difficulties to later well repair and reconstruction. Downhole electric cutting tools use electrically driven cutting blades to quickly cut through stuck pipe columns, and have become an important means of quickly solving production tubing stuck accidents. For a certain type of three-blade wing-out electric cutting tool, due to the eccentricity between the swing center of the tool and the axis of the tool, the radial feed amount formed by the swing of the tool is nonlinear with the rotation speed of the tool's swing drive motor, as shown in Figure 1.



(a) (b)

Figure 1. The process of blade expansion. (a)Schematic diagram of the blade expansion. (b) Function diagram of the relation between blade rotation angle and cutting radius [1].

To ensure that the equivalent radial feed of the cutting tool remains constant during the cutting process and to avoid cutting vibrations caused by excessive feed, which can lead to damage to the tool, the precision of the speed control of the motor that drives the tool must be very high. In addition, electric cutting tools need to work in high temperature and high-pressure underground environments for a long time, and real-time detection and processing of the underground environment is required to ensure the normal operation of the tool. However, in traditional motor control systems, there are problems such as large structural size, high heat generation, and low control precision, which cannot be applied to electric cutting tools with small radial dimensions.

Compared with traditional DC motors, brushless DC motors use a permanent magnet rotor instead of an excitation winding, and electronic commutation replaces commutation pieces and brushes, making brushless DC motors small in size, light in weight, and low in noise [2],[3]. Therefore, choosing a small brushless DC motor as the push rod electric cylinder motor for electric cutting tools, and designing a high-precision and small-sized brushless DC motor hardware circuit and control program, is the key to achieving precise tool feeding.

This article designs a control system for a brushless DC motor based on DSP to meet the requirements of small structural space dimensions and high precision of motor speed control for underground electric cutting tools. After logical processing of the Hall signal with position information, the DSP generates a control signal, which is sent to the integrated gate driver to control the conduction sequence and time of the MOS tube in the inverter circuit, realizing closed-loop control of motor speed and detection of motor voltage and current. A PI controller is added to the speed control program to achieve more accurate control of motor speed. In addition, a human-machine interaction interface is designed to graphically display the motor speed and current through a communication interface, achieving more intuitive and accurate control of the control system. In the speed test experiment, the motor is subjected to acceleration and deceleration tests, and the motor speed and current are recorded and analyzed. The experimental results show that the control system can meet the control requirements.

METHOD

System overall scheme design

The overall scheme of the control system is shown in Figure 2. The hardware circuit mainly includes power supply circuit, gate driver circuit, inverter circuit, voltage detection circuit, current detection circuit, position detection circuit and analog signal acquisition circuit. The power supply circuit supplies power to the microcontroller and peripheral circuits by reducing the input voltage through the voltage reduction module [4]; the gate driver circuit provides isolation between the microcontroller and the inverter circuit, and controls the motor speed and direction by driving the conduction sequence and time of MOS tubes in the inverter circuit [5]; the bus voltage and phase voltage are obtained by the voltage divider circuit as a reference for observing the motor load; the current is detected by the shunt amplifier integrated in the gate driver; the position is detected by the Hall signal, and the speed is detected and the motor commutation is performed by the speed calculation program; in the analog signal acquisition circuit, the temperature signal is used to determine the motor heat generation and can be used as motor protection; the pressure signal is used to detect the underground environment.

The motor control system can achieve control over the direction, speed, start/stop, etc. of the motor. The control scheme for the motor is: based on the control signal given by the upper computer, combined with the feedback signal of the Hall sensor, after comprehensive logical processing by the main control chip, six PWM (pulse width modulation) signals are generated and input to the gate driver to control the conduction sequence of the six MOS tubes in the inverter circuit, commutate the three-phase current input to the stator winding, and control the motor direction; the duty cycle of PWM is used to control the motor speed, the larger the duty cycle of PWM, the higher the output voltage and the faster the motor speed, and vice versa; when the motor overload or heat generation is detected, the motor stops rotating.

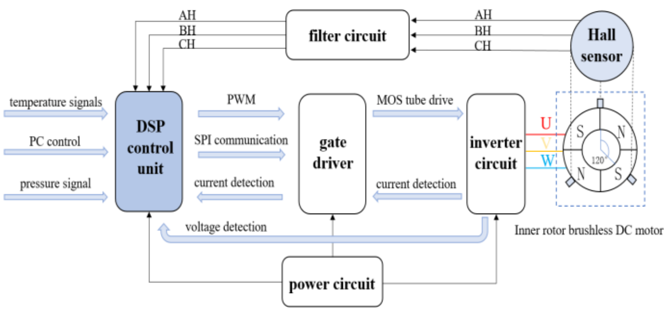


Figure 2. Brushless DC motor control chart

System hardware design

TMS320F28035 is the core of the control system, whose main function is to drive brushless DC motors and collect pressure and temperature information underground. As shown in Figure 3, TMS320F28035 communicates with the upper computer through external extended CAN communication interface and RS485 serial communication interface. In addition, the controller itself has SPI interface to communicate with motor gate driver DRV8353 and AD conversion chip ADS1220, respectively for motor driving and pressure signal acquisition. In terms of motor driving, the main controller receives the motor control signal from the upper computer and the rotor position signal fed back by the Hall sensor, performs logical synthesis operation to generate PWM signal, and controls the on-off sequence of six MOS tubes in the inverter circuit through the gate driver to make the motor run normally. In terms of underground information collection, the main controller collects temperature signal through ADC channel, and processes the pressure digital signal after AD conversion chip before passing it to the upper computer.

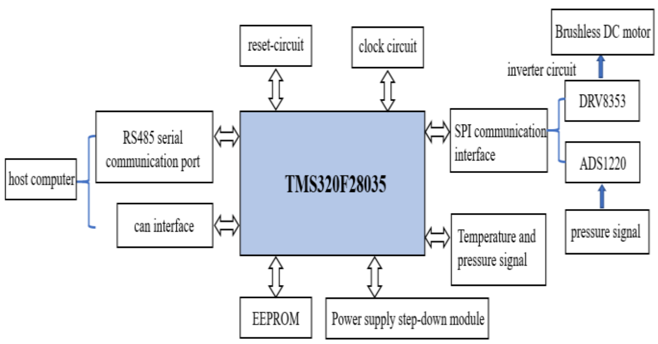


Figure 3. System hardware structure diagram

Motor Drive Circuit

Three-phase gate driver DRV8353 is used to drive the three-phase brushless DC motor. The integrated gate driver has a compact package and integrates analog signal chain components (sensors), digital signal control (PWM), and power management (battery and motor), reducing the number of external components used for circuit protection and optimizing the dead time to prevent breakdown problems [6]. As shown in Figure 4, DRV8353 receives six PWM wave signals generated by the STM32 chip, where three drive the upper bridge arm and three drive the lower bridge arm. Its output terminal is connected to the MOS tube on the high side and low side of the inverter circuit. SPA, SPB, SPC, SNA, SNB, and SNC are connected to both sides of the shunt resistor to detect the circuit current.

The inverter circuit can convert DC voltage into adjustable frequency AC voltage for motor power supply through PWM control, and change the motor speed by changing the motor input voltage [7]. The inverter circuit consists of six MOS tubes, only two of which are conductive and form a loop with the motor winding. Therefore, the on and off of the MOS tubes can be controlled by six PWM control signals to power different windings and complete the six-step motor commutation requirement [8]. At any time, the upper and lower MOS tubes cannot be conductive at the same time, that is, Q1 and Q4 cannot be conductive at the same time, but the switching time of the MOS power tube is different, and the phenomenon of direct conduction may occur, which may burn out the power device. Therefore, it is necessary to compile a dead zone module in the hardware circuit program, that is, when the output switches from the high-frequency MOS tube to the low-frequency MOS tube, sufficient closing time should be left for the high-frequency MOS tube [9].When meeting the power requirements of the controller, MOS tube CSD19536KT with high switching frequency and small conduction loss is used as the switching element [10]. As shown in Figure 5, the A-phase voltage of the motor is divided by voltage divider resistors R37 and R42. At the same time, R37 and C57 form an RC filtering circuit to filter out spikes in the signal and adjust the V1 voltage signal to the range that the main control chip pin can receive. The processed V1 is sent to the analog acquisition interface of the main control chip to monitor the A-phase voltage. The BC-phase voltage circuit is connected in the same way, and the B-phase and C-phase voltages are monitored through V2 and V3.

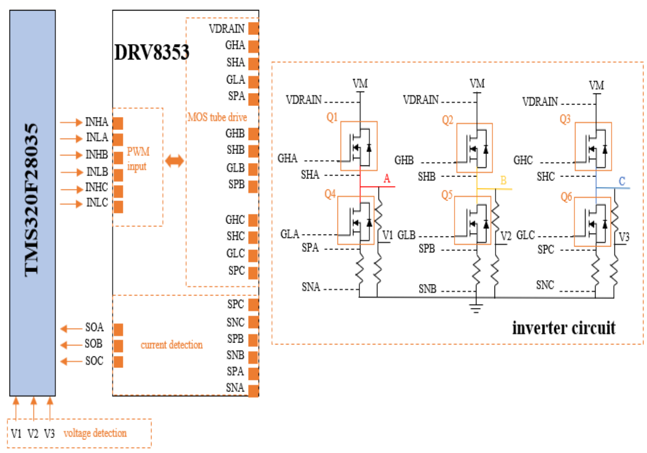


Figure 4. Function diagram of drive circuit

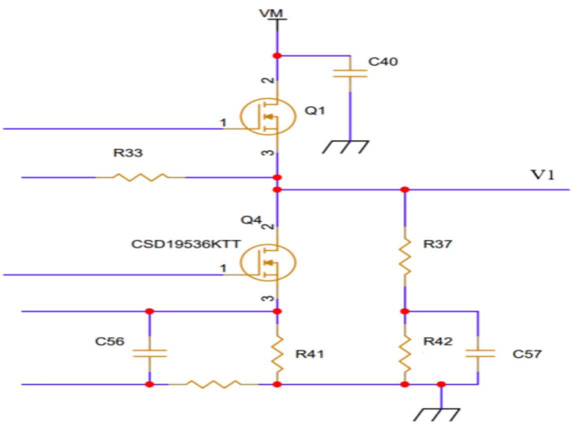


Figure 5. Q1 and Q4 wiring diagram

In order to prevent the MOS tube from being burned due to excessive current, the current shunt amplifier of the DRV8353 chip is used to monitor the motor current, as shown in Figure 6. SOA, SOB, and SOC are used as shunt amplifier outputs. The filtered signal is sent to the analog acquisition interface of the DSP main control chip for current monitoring through a filtering circuit composed of resistors and capacitors [11].

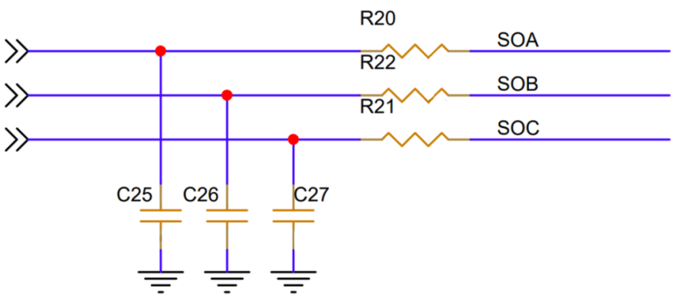


Figure 6. Filter circuit

Hall position detection circuit

The Hall element is a magnetic induction sensor that can convert magnetic field changes into output voltage changes, providing rotor position information. Due to its simple structure and low cost advantages, it is widely used in the driver of high-speed brushless DC motors [12],[13]. The Hall signal with position information is transmitted to the main control chip, and the main control chip calculates the motor speed, performs PWM duty cycle correction, controls the commutation of the stator winding, and realizes closed-loop control of the speed of the DC brushless motor. As shown in Figure 7, the brushless DC motor has three Hall sensors. The Hall signal changes according to the rotor position. When the rotor rotates one circle, a single Hall sensor outputs a high-level digital signal of 180 electrical degrees of rotation and a low-level signal of 180 electrical degrees. The three sensors are offset from each other by 120 electrical degrees, forming six different 3-digit position codes below, corresponding to six-step trapezoidal commutation [14],[15].HALLA~C is the connection interface between the main controller and the Hall sensor, and is connected to a pull-up resistor and capacitor for filtering to reduce signal interference.

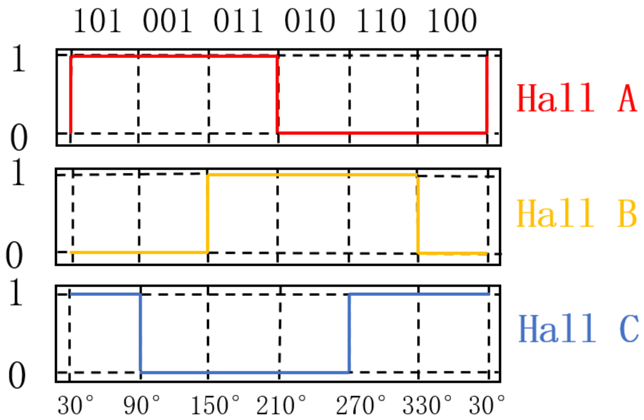


Figure 7. Hall position signal

System Software Design

The software design for the motor control system includes the design of the DSP motor control program and the human-machine interface. The software on the drive side is CCS, an integrated development environment for developing TMS320 series DSP software, developed by TI and written in C language. It is used to detect the motor's motion state and complete the motor drive. The human-machine interface software design is based on the embedded graphical user interface of Qt and Linux device drivers, used to observe the motor's motion state and set the motor's start-stop and speed.

Motor Control Software Design

The motor drive program mainly includes the main program, position detection program, speed detection program, speed PI control program, CAN communication, SPI communication program, SCI communication program, analog-to-digital conversion program, etc.

In the main program, the system clock, peripheral devices, and interrupts are initialized, and then interrupts are enabled to enter the motor control subroutine to achieve closed-loop control of the motor speed. In the position detection program, three Hall sensors detect the motor position, and the three Hall detection signals form six different 3-bit position codes, dividing the motor position into six sectors. The motor direction and speed are determined based on the motor position detection.

The period of the Hall signal is T when the motor rotates one cycle, and the time interval when the Hall signal changes is Δt.

$$T = \triangle t \tag{1}$$

frequency

$$f = \frac{1}{T} \tag{2}$$

In the speed detection program, the motor speed is calculated by the Hall signal

$$n = \frac{60f}{p} \tag{3}$$

That is, the motor speed is

$$n = \frac{10}{\Delta tp} \tag{4}$$

In the formula, n represents the motor speed in revolutions per minute (rpm); f represents the Hall signal frequency in hertz (Hz); p represents the number of motor poles.

When the motor speed suddenly increases, the new speed value is calculated using the formula $n_{k+1}=0.2n_k+0.8n_{k-1}$ to replace the original value for circuit protection, and the maximum speed is limited in the program. The PI control program is called every 1ms to compare the calculated speed of the brushless DC motor with the set speed, and reduce the speed error using proportional gain and integral gain.

The motor position is read through CAN communication, and the SCI module realizes RS485 communication function. The data exchange between the main control chip and the motor driver is established through SPI configuration.

Human-Computer Interaction Interface Software Design

The human-machine interaction interface program developed based on Qt is developed and debugged on a PC. After developing the program on Qt, the serial port of the motor drive board is connected to the serial port of the PC, and the "communication connection" of the human-machine interaction interface is opened to receive real-time motion data of the motor. After analyzing and processing the data, the software draws image information of the current, speed and other states of the motor during the motion process. The software processes various events and data streams through associated signals and slots, connects the click events of buttons with functions that control the motor speed through signals and slots, and then compiles to achieve the setting of the motor speed [16],[17].

To display the collected data graphically, the two files "qcustomplot.h" and "qcustomplot.cpp" need to be added to the project, along with QGridLayout and QTimer functions. X and Y axes need to be created and their ranges, steps, and starting points set. The QGridLayout function divides the plane formed by the X and Y axes into rows and columns and places each widget it manages in the correct cell. The QTimer function is called to update the changes in the monitored motor speed and current in real-time at fixed time intervals. Whenever the time elapsed exceeds the given time, the function xx in timeout.connect(xx) is called, and the timer is stopped after use by calling stop(). The X-axis is defined as time, and the current minutes and seconds are refreshed.

```
QSharedPointer<QCPAxisTickerTime> timeTicker(new QCPAxisTickerTime);
    timeTicker->setTimeFormat("%m:%s");
    plotWidget->xAxis->setTicker(timeTicker);
```

The data is transmitted to the upper computer through the serial port, and the steStyleSheet function is called to draw data curves related to time. The final monitoring system is shown in Figure 8.

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 19, Number 1 (2024) pp. 11-18

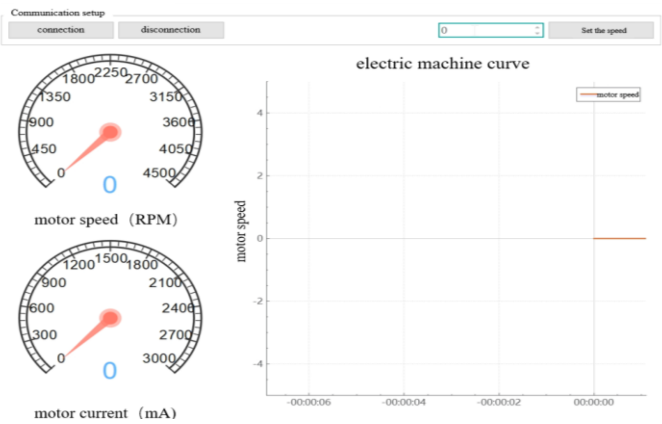


Figure 8. Monitoring interface

RESULTS AND DISCUSSION

In practical applications, the motor drive board and downhole telemetry module use CAN communication, and the downhole telemetry module transmits downhole information to the surface system. The test platform omits other circuits of the electric cutting tool and only tests the performance of the pushrod electric cylinder motor, so a CAN bus protocol analyzer is used to analyze the CAN signal. A system test platform is built using a computer, a CAN bus protocol analyzer, a DC stabilized power supply, and a motor drive circuit board to control the speed of the brushless DC motor and monitor the current. The test platform is shown in Figure 9.

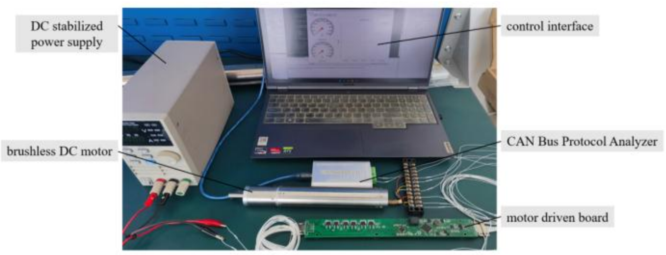


Figure 9. System test platform diagram

When entering the test, connect the communication settings, set the motor speed in the upper right corner, and sequentially set the speed to 1000r/min, 1500r/min, and 2000r/min during the test. After accelerating and then decelerating, check whether the motor meets the driving requirements and the stability of the acceleration and deceleration operation. The test results are shown in Figure 10 and Table I. When the motor is in motion, its target speed is changed, and the speed curve of the motor during acceleration and deceleration is smooth, with small overshoot and can reach stable operation in a short time. The maximum error rate between the actual speed and the target speed is 1.1%, which basically meets the requirements for motor driving.

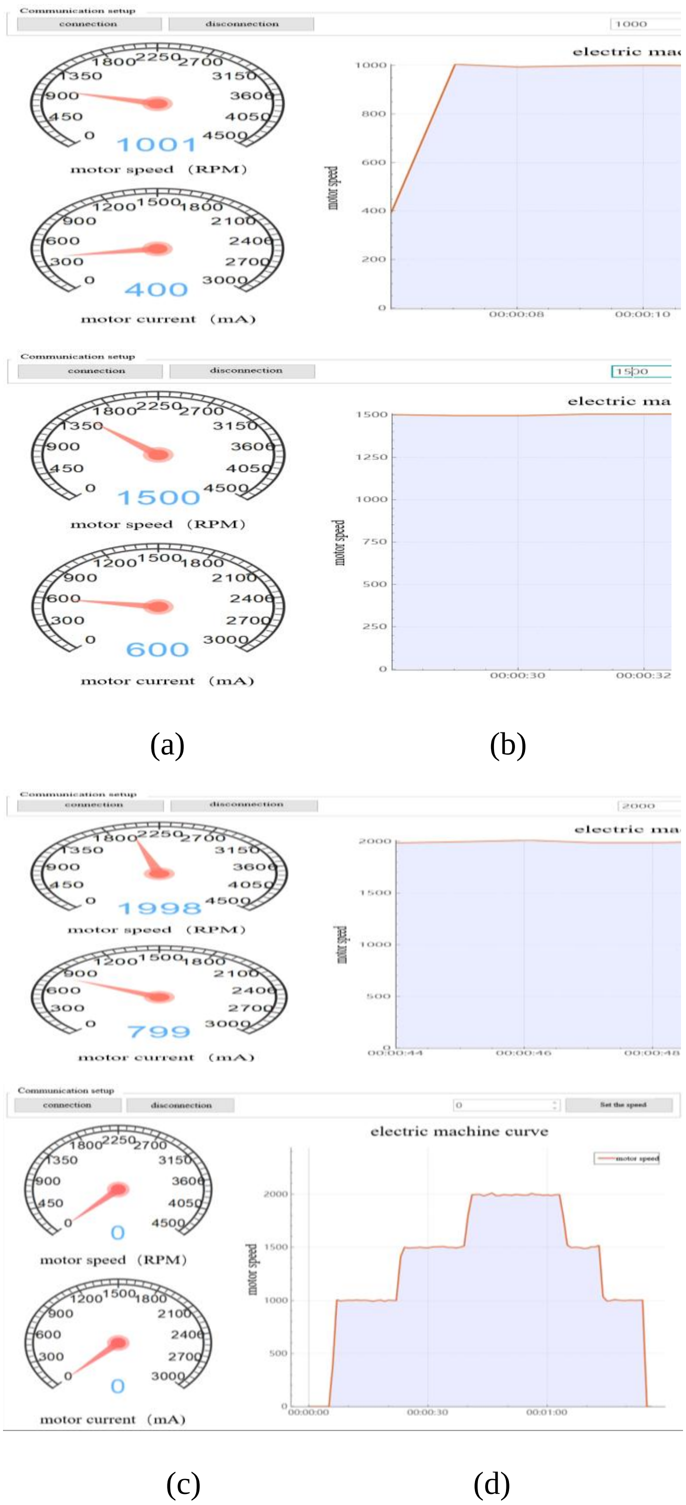


Figure 10. Motor function test diagram. (a)speed 1000r/min. (b)speed 1500r/min. (c)speed 2000r/min. (d) Acceleration and deceleration process diagram

Table 1.Motor experimental results

target speed /(r*min-1)	**Minimum speed /(r*min-1)**	**Maximum speed /(r*min-1)**	**Maximum error rate /%**	**stable current /mA**	**running time /s**
1000	991	1005	0.9	400	16
1500	1492	1507	0.53	600	14
2000	1984	2011	0.8	800	22
1500	1489	1517	1.1	600	17
1000	994	1008	0.8	400	11

CONCLUSION

This article presents a brushless DC motor control system with a DSP as the control core. The system fully utilizes the TMS320F28035 microcontroller with high-efficiency data processing capabilities and the highly integrated DRV8353 gate driver, reducing the number of peripheral components and simplifying the hardware structure of traditional control systems. In the software design, a speed loop PI controller and Hall signal processing are added to make the brushless DC motor control system have the characteristics of small overshoot and fast response. The terminal human-machine interaction interface is easy to configure and modify, which can fully exert the functions of the hardware system and realize online monitoring. Experimental results show that the system can complete the drive according to the control requirements and has the advantages of low cost, stable control, and strong scalability.

ACKNOWLEDGMENT

The authors express deep gratitude to the support from Youth Program of National Natural Science Foundation of China (52004230), and the Natural Science Foundation of Sichuan Province (23NSFSC2101).

REFERENCES

[1] Zhu, X. Zhong, J. Jing, J. Ye, Zhou, B. & Shan, H. ,2023, " Fuzzy proportional–integral–derivative control system of electric drive downhole cutting tool based on genetic algorithm," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*.

[2] Wang, H. ,2012, " Design and Implementation of Brushless DC Motor Drive and Control System,"*Procedia Engineering*, 29, pp.2219-2224.

[3] Ye, J. & Huang, Z,2018, "Design and Realization of Control System of Brushless DC Motor Based on ARM," *Journal of Physics: Conference Series*, 1087, 042070 (8pp).

[4] Sun, L. Yu, J. ,2018, "Design of Vector Control System for Brushless DC motor Based on Hall Sensor," *In 2018 International Symposium on Communication Engineering & Computer Science (CECS 2018)*.

[5] Mohammad, A., M. A. Abedin & M. Z. R. Khan.,2016, " Implementation of a three phase inverter for BLDC motor drive," *In 2016 9th International Conference on Electrical and Computer Engineering (ICECE)*.

[6] Tripathi, P. R. ,2022, " Hardware Engineer's Guide to a Brushless-DC Motor Controller: Design and challenges," *IEEE power electronics magazine*, 9(1), pp.40-45.

[7] Rakhmawati, R., F. D. Murdianto & M. W. Alim. ,2018, "Soft Starting & Performance Evaluation of PI Speed Controller for Brushless DC Motor Using Three Phase Six Step Inverter," *In 2018 International Seminar on Application for Technology of Information and Communication (iSemantic)*.

[8] Dong, Q. & Z. Chu. ,2021, "Brushless DC Motor Driver based on SA306A Integrated Switching Amplifier," *In International Conference on Automation, Control and Robotics Engineering*.

[9] Li, F.,2014, " Study on FPGA-based controller for brushless DC motor," *Manufacturing automation*, 36(17), pp.111-113, 117.

[10] Shen, C. Shang, J. Hu, C. & Xie, Z. ,2019, " Research and design of electric vehicle controller based on brushless DC motor," *Electric Machines & Control Application*, 46(7),pp.76-81.

[11] Zhang, X. Zhai, Y. Zhao, J.,2018, " The Design and

Experimental Study of BLDCM Controller Based on STM32," *Chinese Journal of Electron Device*, 41(1), pp.141-144.

[12] Wang, L., Z. Q. Zhu, H. Bin & L. M. Gong.,2021, "A Commutation Optimization Strategy for High Speed Brushless DC Drives with Inaccurate Rotor Position Signals," *In 2021 Sixteenth International Conference on Ecological Vehicles and Renewable Energies (EVER).*

[13] Lee, C. C., G. J. Chiou, J. Y. Chen, Y. C. Tung & F. S. Juang. ,2017, " Implementation of a novel brushless DC motor controller," *In 2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA).*

[14] Mousmi, A., A. Abbou & Y. E. Houm. ,2020, "Binary Diagnosis of Hall Effect Sensors in Brushless DC Motor Drives,"*IEEE Transactions on Power Electronics*, 35, 3859-3868.

[15] Xie, J., Zhang, S., Yao, Z.,2023, " Modeling and Simulation of Control Systems for Brushless DC Motor Based on Hall Sensor," *International Conference on Guidance, Navigation and Control*.

[16] Zhu, Y. & Shen, X, 2014, " Stepping motor drive control system design based on embedded QT," *Electronic Design Engineering*, 22(21), pp.149-152.

[17] Zhang, C. Q., Shao, J. Y., Chen, K., & Ren, C. Z. ,2012, " A Robotic Manipulator Control and Simulation System with Qt and VTK,"*In Advanced Materials Research*, 462, pp.712–719.

BIOGRAPHIES OF AUTHORS

Jun Jing , He is an associate professor of Mechanical and Electrical Engineering at Southwest Petroleum University. He holds a Ph.D. in Mechatronic Engineering and his research interests include drilling acceleration tools, intelligent downhole equipment based on mechanical-electric-control integration, well integrity and risk assessment. He can be contacted at email:201999010045@swpu.edu.cn.