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Design of FOC Drive Circuit for Low-Power BLDC

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Abstract

This paper presents the comprehensive design of a drive circuit for low-power brushless DC (BLDC) motors based on the Field-Oriented Control (FOC) algorithm. To meet the demands of applications requiring high efficiency, high precision, and a compact form factor, this design integrates carefully selected components into a robust system. The core of the control system is an STM32F405RGT6 microcontroller, which provides the necessary computational performance for complex FOC algorithms. A DRV8301 integrated gate driver is utilized to drive the three-phase MOSFET inverter bridge, simplifying the power stage and incorporating essential features such as a buck converter and various protection circuits. For accurate feedback, the circuit employs a high-side, three-shunt current sensing architecture with AD8418 amplifiers, enabling precise current measurement. The design also includes stable power management, a CAN bus interface for reliable communication, and sensors for voltage and temperature monitoring. The resulting hardware provides a highly integrated, efficient, and reliable solution for the precise control of low-power BLDC motors in applications like robotic joints, drones, and advanced consumer electronics.

Keywords

Brushless DC Motor (BLDC); Field-Oriented Control (FOC); Low-Power; Drive Circuit; STM32; DRV8301.

1. Introduction

Brushless direct current motors(BLDC) have become critically important in modern power electronics due to their high efficiency, high power density, long lifespan, low noise, and excellent controllability. They are widely used in consumer electronics, home appliances, power tools, drones, robotic joints, medical equipment, and various portable instruments. The advantages of BLDC motors are particularly prominent in low-power applications (typically ranging from tens to hundreds of watts) where strict requirements for size, weight, energy efficiency, and dynamic response are paramount.

Field-Oriented Control (FOC) is a key technology that enables BLDC motors to achieve performance comparable to or even exceeding that of DC motors. The core idea of FOC is to decouple the motor's stator current into independent magnetic flux and torque components, allowing for their precise and separate control. This decoupled control method enables the motor to achieve smooth torque output, rapid dynamic response, excellent low-speed performance, and near-theoretical maximum efficiency across its entire speed range. For low-power applications, the benefits of FOC extend beyond performance enhancement; the resulting energy efficiency is crucial for extending the battery life of portable devices. Therefore, in-depth research and design of FOC-based driver circuits for low-power BLDC motors hold significant practical value and broad application prospects.[1]

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2. BLDC Motors and FOC Control Principles

A BLDC motor consists of a three-phase stator winding and a permanent magnet rotor. It uses electronic commutation instead of the mechanical brushes found in brushed DC motors. Electrical energy is converted into mechanical energy via a rotating magnetic field, resulting in less frictional contact and higher operational efficiency. Furthermore, the absence of brush wear leads to reduced maintenance, longer lifespan, and greater stability.

Due to its mechanical structure, a BLDC motor requires an inverter circuit to convert DC power into a variable magnetic field to drive the rotor. The traditional control method is six-step (trapezoidal) commutation, which drives the motor by switching the states of a three-phase inverter in a fixed sequence. While six-step commutation is low-cost and simple to implement, it suffers from torque ripple and lower efficiency, making it increasingly replaced by FOC in precision control applications.[2]

Field-Oriented Control (FOC), also known as vector control, is a method that controls the magnitude and frequency of the inverter's output voltage. The fundamental concept is to control the motor's excitation and torque currents separately by measuring and controlling the stator current vector according to the principle of field orientation. This transforms the control of a three-phase AC motor into the equivalent of controlling a DC motor. The implementation involves coordinate transformations that convert the three-phase stationary coordinate system into a two-phase rotating coordinate system. This process transforms the coupled three-phase AC stator currents into two orthogonal, independently decoupled components: torque and flux. This allows for direct torque control by manipulating the torque current, similar to a separately excited DC motor. Compared to six-step commutation, FOC provides continuous, ripple-free torque, fast dynamic response, and high efficiency under all operating conditions. It is ideal for low-power applications such as robotic joints, home appliances, and smart home devices, offering both energy savings and quiet operation.[3] The working principle is is shown in the following figure 1.

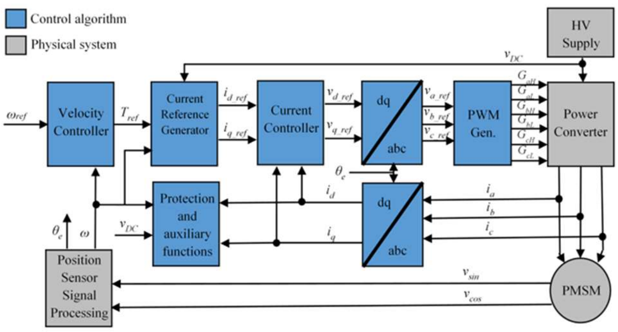

Figure 1. Field Oriented Control (FOC)

3. Overall Design Scheme of FOC Drive Circuit

The overall architecture of the FOC-based low-power BLDC motor driver circuit primarily consists of a control circuit, a power driver circuit, a current sensing circuit, a position sensing circuit, and a power supply circuit.[4]

- **Control Circuit:** As the core of the system, it executes the FOC algorithm, processes signals like current and position, and generates the necessary Pulse Width Modulation (PWM) signals to precisely control the switching of the power devices.
- **Power Driver Circuit:** This stage converts the DC supply into three-phase AC power to drive the motor. Its performance directly impacts the motor's output power and stability.

- **Current Sensing Circuit:** It continuously monitors the motor's phase currents and provides feedback to the control circuit for closed-loop current control, ensuring the motor operates within specified limits.
- **Position Sensing Circuit:** It acquires the rotor's position information, which is essential for the coordinate transformations and current decoupling in the FOC algorithm. Accurate position feedback is crucial for precise motor control.
- **Power Supply Circuit:** It provides stable and appropriate voltages for all parts of the circuit, ensuring the entire system functions correctly.

These components work in concert to achieve high-efficiency, high-precision FOC control of the low-power BLDC motor. A block diagram of the system is shown in the figure 2.

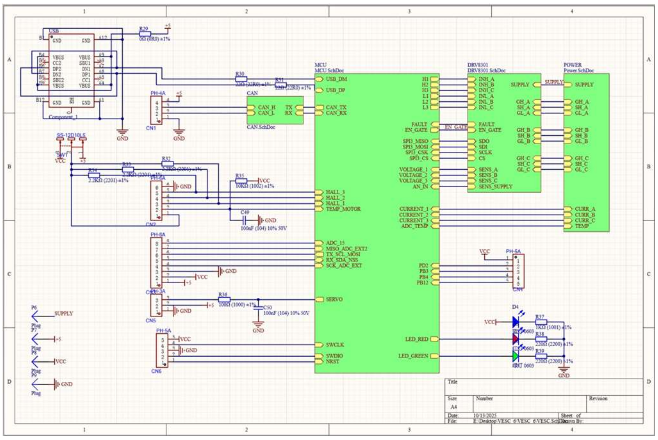

Figure 2. Overall Design Scheme of FOC Drive Circuit

4. Detailed Circuit Design

4.1. Power Supply Circuit Design

The power supply circuit designed in this paper provides three voltage levels: 12-36V, 5V, and 3.3V. The 12-36V bus voltage (labeled as SUPPLY) powers the entire circuit, including the three-phase inverter bridge and the BLDC motor. This voltage range was chosen to ensure circuit safety and accommodate the motor's operating requirements. Most components in the circuit operate at 3.3V, while some require 5V. Therefore, the bus voltage must first be stepped down to 5V, which is then regulated down to 3.3V (labeled as VCC).

A BUCK converter and a Low-Dropout (LDO) linear regulator are common choices for voltage reduction. A BUCK converter is highly efficient and can handle significant power, but it produces higher output ripple and requires more external components. An LDO has low output ripple and a simple circuit design but is less efficient, especially with a large voltage drop, and handles less power.[5]

Considering these characteristics, a hybrid approach was adopted: a BUCK converter is used to step down the bus voltage to 5V, and an LDO is used to convert 5V to 3.3V. Since the DRV8301 gate driver integrates a TPS54160 buck converter, it is used for the bus-to-5V conversion. The output voltage (VO) of the integrated TPS54160 is determined by resistors R1 and R2 according to the formula: $VO = Vref * (R1 / (R1 + R2))$, where Vref is 0.8V. For a 5V output, R1 and R2 can be chosen as 3.3kΩ and 18kΩ, respectively. For the 5V to 3.3V conversion, the commonly used AMS1117-3.3 LDO is employed. The schematics are shown in figure 3 and figure 4.

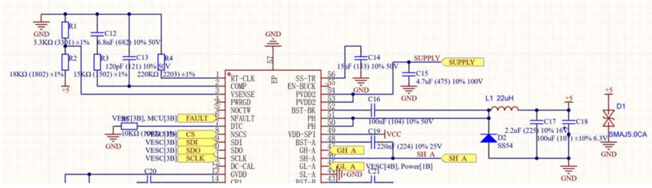

Figure 3. DRV8301 buck circuit

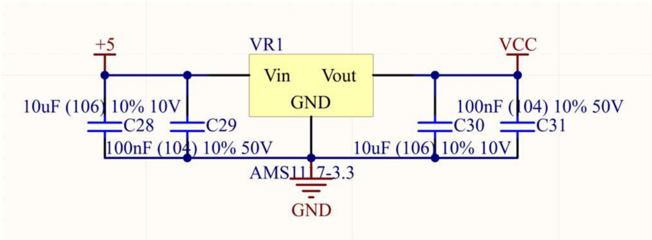

Figure 4. AMS1117 LDO Circuit Design

4.2. Main Control Circuit Design

The implementation of FOC involves a large number of complex calculations, including coordinate transformations and trigonometric functions. To ensure sufficient processing power and speed, an MCU from the STM32F4 series was chosen. This series features a Cortex-M4 core with a clock speed of up to 168 MHz, an integrated single-cycle DSP instruction set, and a Floating Point Unit (FPU), which significantly enhance its computational capabilities for complex control algorithms.[7]

After pin allocation based on functional requirements, the specific model selected was the STM32F405RGT6 in an LQFP-64 package. A minimal system circuit was designed to ensure its proper operation, with other pins assigned as needed. The schematic for the main control circuit is shown in figure 5.

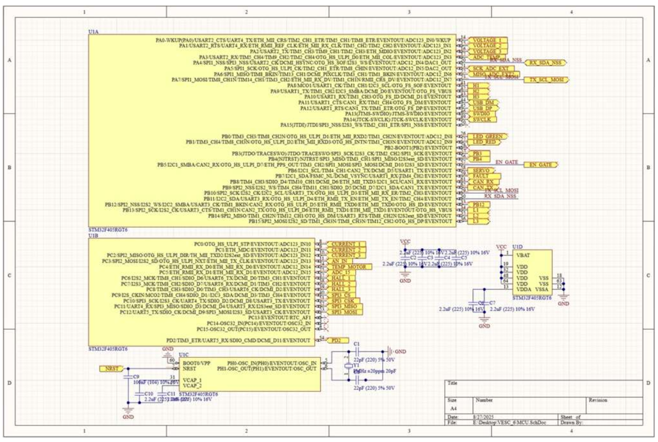

Figure 5. Main Control Circuit Design with STM32F405RGT6

4.3. DRV8301 Driver Circuit Design

The main control chip lacks the capability to directly drive the MOSFETs in the three-phase inverter with sufficient current, which would result in slow switching speeds and negatively impact circuit performance and stability. To address this, the DRV8301 integrated gate driver is used. The DRV8301 supports a voltage range of 6V to 60V, provides a gate drive current of 1.7A (source) and 2.3A (sink), and is compatible with both 3.3V and 5V logic levels. It also integrates a buck converter with adjustable output voltage and switching frequency, capable of supplying up to 1.5A. Additionally, it features adjustable dead-time and overcurrent protection.[7]

In the designed circuit, the DRV8301 contains three half-bridge drivers, each controlling two N-channel MOSFETs. Once the DRV8301 is enabled, the STM32F405RGT6 MCU transmits six PWM signals via the INH_A, INL_A, INH_B, INL_B, INH_C, and INL_C pins. The driver then uses its GH_A, GL_A, GH_B, GL_B, GH_C, and GL_C outputs to drive the gates of the six MOSFETs in the three-phase inverter.

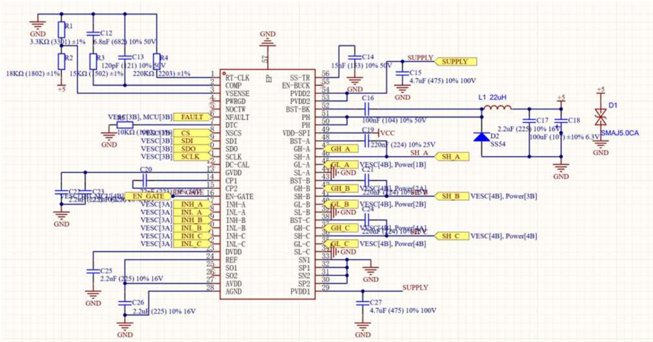

Figure 6. DRV8301 Driver Circuit Design

4.4. Main Power Circuit Design

The core of the main power circuit is the three-phase full-bridge inverter, which converts DC power into three-phase AC power to drive the BLDC motor. This inverter consists of six power MOSFETs arranged in three half-bridges (upper and lower arms).

Using N-channel MOSFETs as an example, the drains of the upper-arm MOSFETs are connected to the positive DC supply, and their sources are connected to the motor's phase windings. The sources of the lower-arm MOSFETs are connected to the negative DC supply (ground), and their drains are also connected to the motor windings. By controlling the on/off state of the upper and lower arm MOSFETs with PWM signals according to a specific timing and duty cycle, an AC current with a 120° phase shift is generated in each winding, creating a rotating magnetic field that drives the rotor.[3]

Several factors must be considered when designing the inverter. First is the selection of MOSFETs, focusing on parameters like on-resistance (RDS(on)), voltage rating, switching speed, and thermal performance. Proper heatsinking is essential to dissipate the power losses generated during switching and ensure the MOSFETs operate within a safe temperature range. Second, to protect the MOSFETs from the back-EMF generated during turn-off, a freewheeling diode must be connected in parallel with each MOSFET (often an internal body diode is sufficient). Finally, filter capacitors should be added at the DC input and three-phase output to smooth the DC voltage and filter out harmonics in the AC output, improving power quality and motor stability.

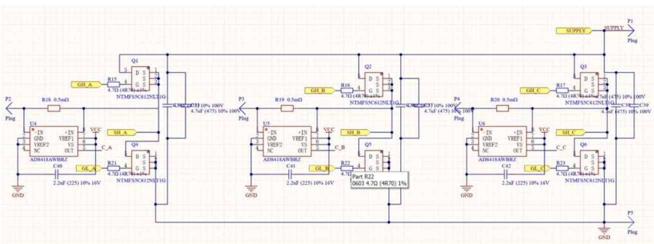

Figure 7. Three-phase Inverter Circuit Design

4.5. Other Circuit Designs

a) CAN Communication Circuit Design

Controller Area Network (CAN) bus technology enables real-time information sharing and solves issues associated with traditional wiring, such as complex harnesses and high costs. CAN bus is widely used due to its many advantages: it uses differential signaling for high noise immunity and long-distance transmission (up to 1 Mbps at 40m, or 10km at lower speeds), features non-destructive bitwise arbitration, and supports a multi-master architecture. Using CAN bus for motor control ensures stable signal transmission and simplifies wiring in multi-motor systems.

The STM32F405RGT6 has a built-in CAN controller but requires an external transceiver for communication. The TJA1051 CAN transceiver was selected for this purpose. One side of the chip connects to the MCU, and the other connects to the bus lines. To enhance signal quality and noise immunity, a termination resistor is placed at the end of the bus. The circuit design is shown in figure 8.

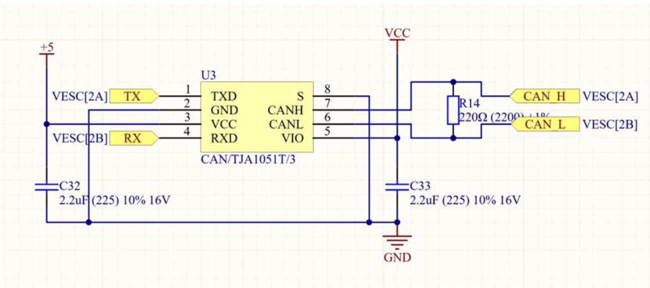

Figure 8. CAN Transceiver Circuit Design

b) Current Sampling Circuit Design

For the low-power application in this paper, a shunt resistor-based current sensing method is a suitable choice due to its simple design, low cost, and minimal power dissipation. Among various resistor-based methods, a high-side three-shunt configuration was chosen. The advantage of this approach is that sampling can be performed at any time, independent of the PWM state.

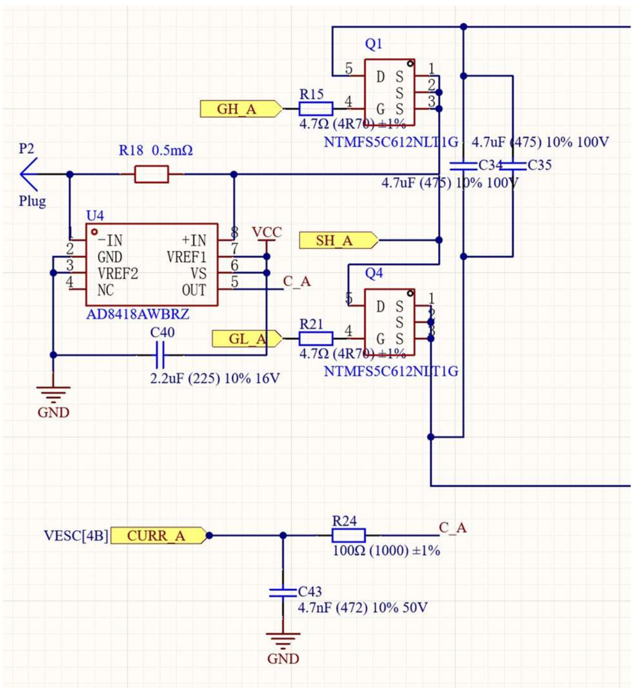

Figure 9. Current Sampling Circuit Design

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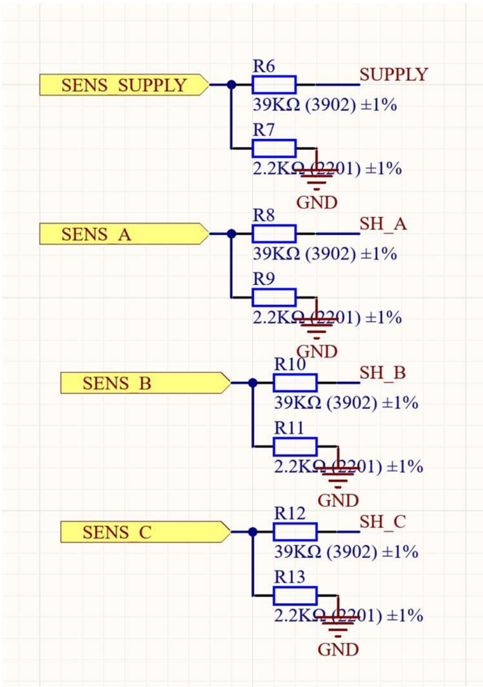
The AD8418 is an ideal choice for the current sense amplifier in this architecture due to its ability to withstand high common-mode voltages, its high precision with zero drift, built-in gain, and bidirectional current sensing capabilities. It simplifies the circuit design and enhances system stability and reliability. Based on the motor's operating power and the ADC's input voltage range, 0.5mΩ shunt resistors in a large package capable of handling sufficient power were selected. The schematic for one phase is shown in figure 9.

c) Voltage Sampling and Temperature Detection Circuit Design

The voltage and temperature sensing circuits are relatively simple. They are based on a voltage divider principle, where the output is connected to an ADC input for measurement. The temperature detection circuit uses a thermistor as one of the resistors in the divider.[8] The resistor values are chosen based on the ADC's input voltage range. The respective circuit diagrams are shown in figure 10 and figure 11.



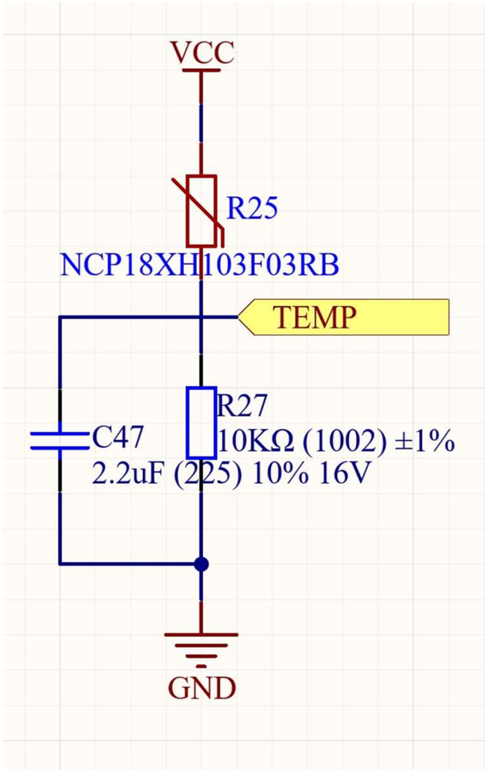


Figure 10. Voltage Sampling Circuit Design **Figure 11.** Temperature Detection Circuit Design

5. Conclusion

This paper has presented the comprehensive design of a driver circuit for low-power brushless DC motors based on the Field-Oriented Control (FOC) algorithm. The system is architected around a high-performance STM32F405RGT6 microcontroller, which possesses the necessary computational power to handle the complex FOC calculations efficiently. An integrated DRV8301 gate driver is employed to effectively drive the three-phase MOSFET inverter bridge, simplifying the power stage and providing essential features like an integrated buck converter and protection mechanisms.

For precise feedback control, a high-side, three-shunt resistor configuration paired with AD8418 amplifiers is implemented, ensuring accurate and robust current measurement. The design is completed with stable power management circuits, a TJA1051-based CAN bus interface for reliable communication in networked systems, and straightforward circuits for voltage and temperature monitoring. This modular and highly integrated approach results in a compact, efficient, and reliable driver solution. The resulting system is well-suited for demanding low-power applications such as robotic joints, drones, and high-performance consumer electronics, where precise motion control and energy efficiency are critical requirements.

References

[1] Al-Faruq H Y, Septanto H. A comparison between six-step and sine-wave commutation methods for brushless direct current motors[J]. International Journal of Power Electronics and Drive Systems, 2022, 13(2): 665.

[2] Mohanraj D, Aruldavid R, Verma R, et al. A review of BLDC motor: state of art,advanced control techniques, and applications[J]. Ieee Access, 2022, 10: 54833-54869.

[3] ROFIQ CAHYO PRAYOGO, ARIS TRIWIYATNO, MUNAWAR AGUS RIYADI. Field Oriented Control Implementation on BLDC Motor Controller with PI and SVPWM using STM32F103C8T6[J]. Journal of Physics:Conference Series,2023,2622(1).

[4] H. Wang, M. Yang, C. Zhu, J. Tong and K. Cai, "Research on Brushless DC Motor Drive Systems Based on Embedded Microcontrollers," 2024 11th International Forum on Electrical Engineering and Automation (IFEEA), Shenzhen, China, 2024, pp. 1041-1045.

[5] D. W. J. Pulle and R. Dhaouadi, "Real-Time Embedded Control of Electrical Drives: A New Approach for Bringing Hands-On Experience Into the Classroom," in IEEE Industrial Electronics Magazine, vol. 17, no. 4, pp. 32-44, Dec. 2023.

[6] WEIQIANG HUANG, KAI LU. Design of Permanent Magnet Synchronous Motor Power-assisted System Based on Field Oriented Control Algorithm[J]. Journal of Physics:Conference Series,2022,2246(1).

[7] Ranjith S, Abeykoon C, Maithripala D. Design of a Sensorless Field Oriented Control Drive for Brushless DC Motors[C]//Proceedings of the 9th International Conference of Control, Dynamic Systems, and Robotics (CDSR'22). 2022: 02-04.

[8] S G SRIVANI, SAHANA R. Smart Cooling: Temperature-Controlled BLDC Motor with Advanced System Health Monitoring[C]//2024 8th International Conference on Computational System and Information Technology for Sustainable Solutions. 2024:1-6.