INVESTIGATION OF FACTORS AFFECTING EFFICIENCY OF LOW POWER BRUSHLESS MOTORS

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ABSTRACT

Today, there are many products suitable for working conditions in the electric motor market. According to the internationally accepted TS EN 60034-30-1 standard, electric motors are listed as IE1, IE2, IE3, IE4 from standard efficiency to super premium efficiency, respectively. The electric motors classified here have a spindle power of 0.12 – 1000kW. By modeling the rotor of the brushless motor using high-performance permanent magnets, high efficiency, power factor and power density can offer efficiency above IE3 standards. In the TS EN 60034-30-2 electric motor standards, there are motors with variable speed motor driver. In order to calculate the losses on the motor driver, the voltage of the system, the current drawn by the motor phases, the temperature of the system and the information on the motor control must be known correctly. Motor driver losses directly affect the efficiency class of the system. In this study, the components and power losses in the brushless motor driver are given. The total loss is calculated by considering the switching frequency, dead time losses and charge losses in the power layer, as well as the energies consumed by the components.

Keywords: Brushless motor, Motor driver losses, Motor efficiency classes

INTRODUCTION

Recently, increasing requirements and trends towards higher efficiency systems have had a significant impact on electric motor design. Many systems in industry and industry move with electric motors. The efficiency of the energy used by electric motors is important. One of the factors that directly affect the efficiency of the electric motor is the controllers. It is necessary to provide motor control at minimum energy and maximum performance (Er et al., 2022). In general, motors used in any field are expected to exhibit the best performance with the least energy. Especially in the industrial sector such as automotive, it is desired that the speed change can be adjusted precisely in addition to these features in motors (Dursun et al., 2015). The most advantageous motors that can be preferred in these directions are Brushless motors. Brushed DC motors; It has a high starting torque and a linear torque-speed character. In other words, it provides some advantages of brushless motors. However, the motor maintenance should be done frequently due to friction formation due to the brush and collector assemblies in the structure of brushed DC motors. This reduces efficiency and increases costs. Brushless motors are used in aerospace systems, automotive industry, defense industry, robotic systems, medical electronics, computer systems, household appliances, that is, in many industrial areas today (Ulu, 2011). If we list the advantages of brushless motors; Their efficiency is very high, their structure is robust, their reliability is high, no arc or spark occurs due to the absence of brushes in their structure, no carbon dust emission, high torque and speed can be obtained, easily cooled, speed control is possible, has high current-torque relationship, high power despite its small dimensions They can produce torque and torque, there is no need for triggering current as in brushed motors and they work quieter than brushed motors. Due to these advantages, brushless motors; It is widely used in computers, spacecraft, military equipment, automotive, industry and household appliances (Shao, 2003). In addition to their advantages, they also have certain disadvantages. These disadvantages are; These are the reasons such as high costs, the necessity of using position sensors in general, and having a complex control circuit and control algorithm (Karakulak and Yaz, 2012). Different semiconductors are preferred in driver circuits at different voltages, operating conditions, considering cost and life. Motor drivers have an important place in electronic systems, especially in areas where brushless motors are used.

MATERIALS AND METHODS

Brushless motors have high power density, high reliability, high efficiency, low noise and simple structure. Thanks to these features of brushless motors; It is used in many areas such as industrial control systems, automotive industry, medical equipment, white goods industry. In brushless motors, torque is provided by the driver (Çabuk., 2019). The direction of the current flowing through the stator with the driver is realized by sensing the position of the poles of the permanent magnets placed in the body (Yedamale, 2003).

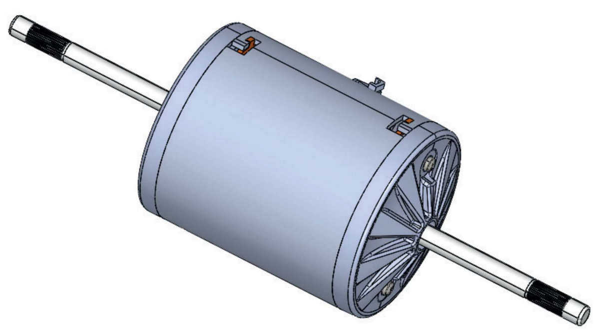


Figure 1. Brushless motor

The brushless motor is produced by mounting permanent magnets on the body and being a part of the circle (Tanç, 2014). The drawing of the brushless motor is given in Figure 1. Due to the increase in the usage areas of brushless motors, studies on the control of the motor continue rapidly (Alaca and Selbaş., 2022). Motor control is of great importance in applications that require precise speed and position. When there is any load on the motor, the microcontroller must respond to this situation in a timely manner. For this reason, motor drivers for brushless motors should respond quickly to load changes and be unaffected by external factors, high efficiency, that is, a long-lasting system should be designed. The efficiency of these motor drivers designed as desired is also high (Yıldız, 2009). In this section, information about the designs of brushless motor and brushless motor driver is given. The studies carried out are explained. Data were obtained by examining different design models.

BRUSHLESS MOTORS

In applications where brushless motors are used, it has a significant impact on the overall performance of the system. Reliable control and operation of the overall systems depends primarily on the motor type and control trigger selected. Motor driver selection varies according to application requirements. Brushless motors can be thought of as a new DC motor with electronic commutation. It continues to be widely used in industrial applications since the 1970s. Brushless motors are preferred in many applications due to their high efficiency and precise controllability (Lee and Ehsani, 2001). The model and control structure of the brushless motor is given in Figure 2. Here R is motor resistance, L is motor inductance, E is back emf. S are MOSFETs with switching elements.

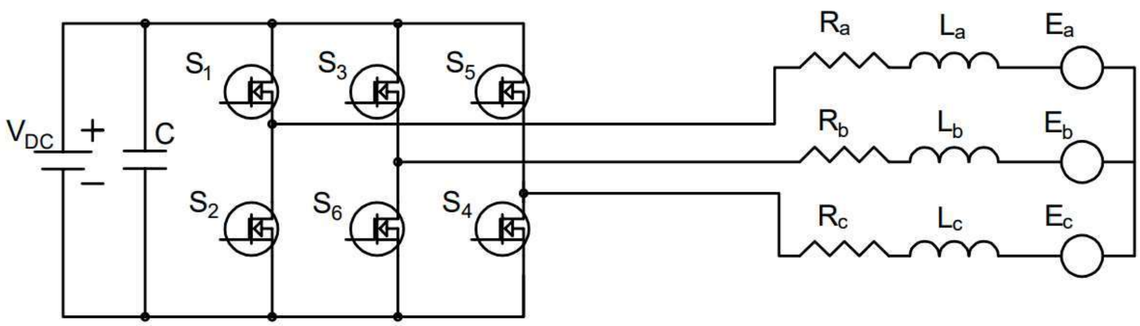


Figure 2. Brushless motor internal structure demonstration

POWER MOSFET

MOSFET, a metal oxide field effect semiconductor transistor, is a very fast switching transistor. It has high performance in high frequency and power applications. Other trade names for this circuit element, circuit and symbol of MOSFET are shown in Figure 3 (Sen, 1996).

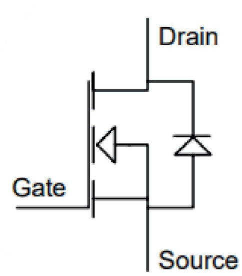


Figure 3. MOSFET symbol

Unlike Current controlled transistors like Bipolar junction transistor (BJT), MOSFET is voltage controlled. By applying a positive voltage to the gate, the transistor conducts from the drain to the source. Gate circuit input impedance is high because it is insulated with silicon oxide layer. This feature allows the MOSFET to be driven directly by CMOS or TTL logic (Barkhordarian, 1996). The DMOS Gate driver current is therefore quite low (Harrison, 2022). The switching characteristic of the MOSFET is similar to the bipolar junction transistor. MOSFET can switch under high current and voltage conditions. MOSFETs can switch very fast. Switching losses can be neglected depending on the load. However, transmission losses are high because the voltage drop at the time of transmission is high (Baliga, 2010).

DMOS material has improved the process steps used in MOSFET construction, allowing a larger Source surface area to be left. In this way, it is planned to provide less resistance and more current. The MOSFET used in this study is in DMOS structure. According to the classical FET, instead of following a horizontal path, the current follows a vertical path in this structure. The trigger voltage between Gate Source may decrease further with this development (Harrison, 2022).

BRUSHLESS MOTOR DRIVE POWER LAYER

Half bridge structure is given in Figure 4. PWM signal is applied to MOSFETs in half bridge structure. The bootstrap method is used for MOSFET control. This PWM control technique is particularly useful for low power brushless DC motor drivers using an inverter with bootstrap driver circuit (Christen and Biela, 2018)

Deadtime; In half-bridge motor drivers, it is the time period when the PWM signals are temporarily held in a position that will turn the switches off, starting just before the high or low switches switch from turn-on or turn-on. This feature is activated during the opening and closing of the MOSFET, preventing the MOSFET from burning. Deadtime is used to wait for the response of the MOSFET during the transition from high to low or from low to high(Mora et al., 2016)

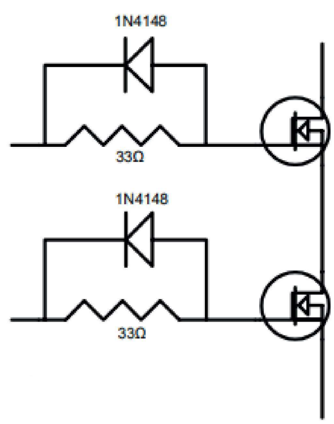


Figure 4. Half bridge MOSFET connection demonstration

For PDD6976, this value is 3.3 mΩ. After that, even if the voltage Vgs increases, this value does not change. Vgs voltage is at most 20 V and after this voltage MOSFET starts to deteriorate (Potens, 2022).

BRUSHLESS DC MOTOR CONTROL AND LOSSES

The maximum voltage to be applied to the Drain end of the MOSFET varies depending on the working areas. The maximum voltage value of the MOSFET preferred here is 65V (Potens, 2022). It will be obtained from 15 volt input voltage with the help of regulator. The internal structure of the STSPIN32G4 IC with adjustable gate voltage for the MOSFET driver is given in Figure 5 (STMicroelectronics, 2022).

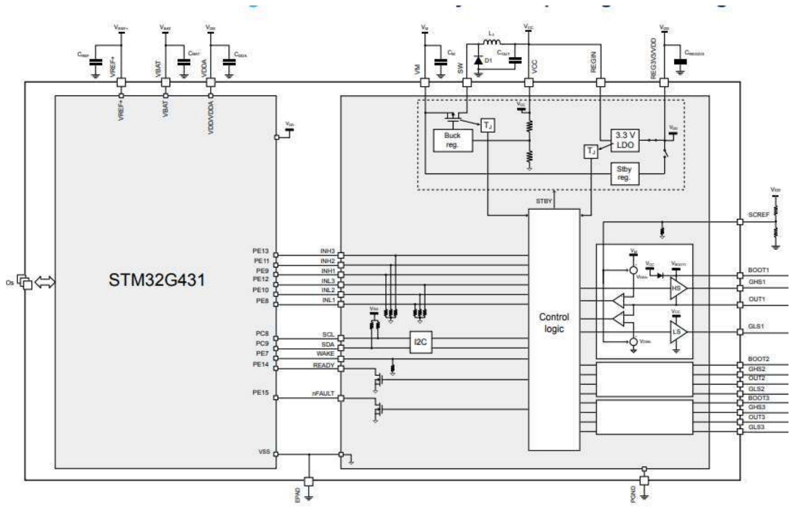
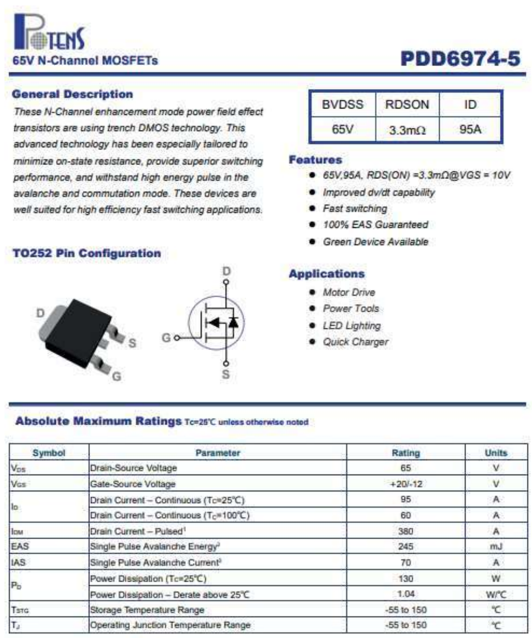


Figure 5. STSPIN32G4 internal structure

Half-bridge circuit is installed to drive the brushless motor. MOSFET drivers in STSPIN32G4 structure are used to drive PDD6976 MOSFETs with DMOS structure(Potens, 2022). To drive the MOSFET, after bringing the Rds(on) resistance value specified in the datasheet closer to 0, the MOSFET turns on. Figure 6 shows the motor driver MOSFET solid schematic (Potens, 2022).



POTENS

65V N-Channel MOSFETs

PDD6974-5

General Description

These N-Channel enhancement mode power field effect transistors are using trench DMOS technology. This advanced technology has been especially tailored to minimize on-state resistance, provide superior switching performance, and withstand high energy pulse in the avalanche and commutation mode. These devices are well suited for high efficiency fast switching applications.

BVDSS	RDSON	ID
65V	3.3mΩ	95A

Features

- *65V,95A, RDS(ON) =3.3mΩ@VGS = 10V*
- *Improved dv/dt capability*
- *Fast switching*
- *100% EAS Guaranteed*
- *Green Device Available*

TO252 Pin Configuration

D G S

Applications

- *Motor Drive*
- *Power Tools*
- *LED Lighting*
- *Quick Charger*

Absolute Maximum Ratings T_C=25℃ unless otherwise noted

Symbol	Parameter	Rating	Units
V_{DS}	Drain-Source Voltage	65	V
V_{GS}	Gate-Source Voltage	+20/-12	V
I_D	Drain Current – Continuous (T_C=25℃)	95	A
	Drain Current – Continuous (T_C=100℃)	60	A
I_{DM}	Drain Current – Pulsed[1]	380	A
EAS	Single Pulse Avalanche Energy[2]	245	mJ
IAS	Single Pulse Avalanche Current[3]	70	A
P_D	Power Dissipation (T_C=25℃)	130	W
	Power Dissipation – Derate above 25℃	1.04	W/℃
T_{STG}	Storage Temperature Range	-55 to 150	℃
T_J	Operating Junction Temperature Range	-55 to 150	℃

Figure 6. Data of MOSFET

Considering the semiconductors and active components used within the scope of the study, the consumed power and losses have been calculated in detail. The calculations here are given as conduction losses, switching losses, MOSFET gate charging losses and dead-time power losses. 20kHz switching frequency is taken as reference in motor driver frequency calculations. As MOSFET, PDD6976 MOSFET with DMOS structure was chosen and internal resistance, rise and fall times, gate load and gate charge voltage were used (Harrison, 2022).

$P_C = R_{DS} \times I_{OUT}{}^2 \times D$ (1)

- $P_C =$ Transmission losses
- $I_{OUT} =$ Output current (7A)
- $R_{DS} =$ MOSFET is the channel resistance (between 3.7 and 4.5 mohm)
- D = Duty cycle (considered as 80% Duty cycle)

The conduction losses depend on the switching element internal resistance, the occupancy rate, and the current drawn from the circuit, as shown in Equation 1 (Texas Instruments, 2020). The square of the current and the loss over the internal resistance are found. It is multiplied by the occupancy rate to get the transmission loss. The loss here was found to be 0.16 W.

$P_{SW} = {}^1/_2 \times V_{IN} \times I_{OUT} \times (t_r + t_f) \times F_{SW}$ (2)

- $P_{SW} =$ Switching losses
- $F_{SW} =$ Switching frequency (20kHz)
- $V_{IN} =$ İnput voltage (26v)
- t_r = MOSFET rise time (33ns)
- t_f = MOSFET drop time (150ns)

Switching losses depend on switching frequency, input voltage and MOSFET times (Texas Instruments, 2020). Although the switching frequency varies, as mentioned, 20kHz is taken as a reference. Starting from Equation 2, the switching losses were found to be 0.32 W.

$P_G = Q_G \times V_{GS} \times F_{SW}$ (3)

- $P_G =$ Gate is a loss of charge
- $Q_G =$ Equivalent total gate load (108nC)
- $V_{GS} =$ Gate charging voltage (2.5V)

As given in Equation 3, the loss can be calculated depending on the frequency, threshold voltage and load used in the switching element Gate charge (Texas Instruments, 2020). The loss here was found to be 0.5 mW.

$P_{dt} = V_f \times I_d \times 2 \times t_{dt} \times f_{sw}$ (4)

- $P_{dt} =$ Dead time power loss
- $V_f =$ Forward voltage (26V)
- $I_d =$ Discharge current (7A)
- $f_{sw} =$ Switching frequency (20kHz)
- $t_{dt} =$ tdt dead time (600ns)

Dead time occupies an important place in half bridge applications. It directly affects motor efficiency and performance. Starting from Equation 4, losses due to dead time can be calculated depending on switching frequency, duration of dead time, voltage and current (Dyer et al., 2017). The loss here was found to be 4.1 W.

Table 1. Brushless motor drive losses

	Power Consumed (T_c=100°C)
Stspin32G4	2 W
Dead-time power loss	4.1 W
Gate is a loss of charge	0.5 mW
Switching losses	0.32 W
Transmission Losses	0.16 W

Table 1 is formed when the expenditures of the active components used in the calculations here are included. The power consumed in the table is expressed in W. Based on the chart, a total power loss of 6.5W has been calculated at 7A load.

In this study, the control system of a brushless motor with a driver is designed. The relevant circuit board is given in figure 7. In this controller design, the driver system design, the creation of control algorithms and software, the printed circuit board design of the driver system and the experimental setup, and the results of a brushless motor running with the designed driver were observed. The oscilloscope images taken during the test are given in figure 8.

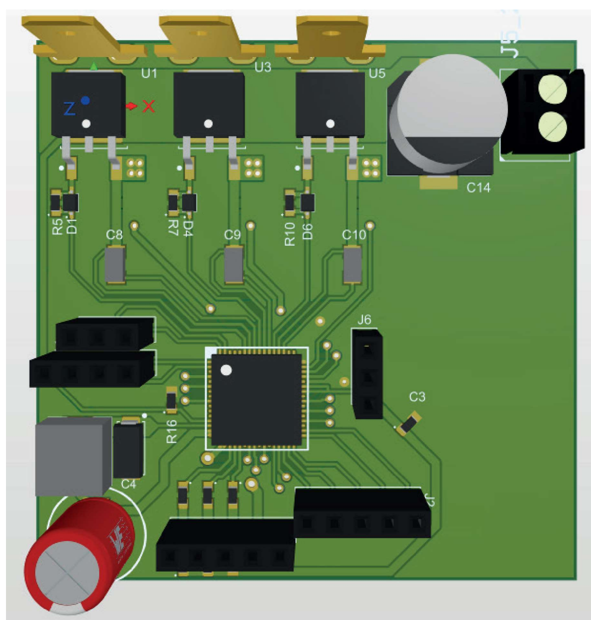


Figure 7. Three dimensional PCB view

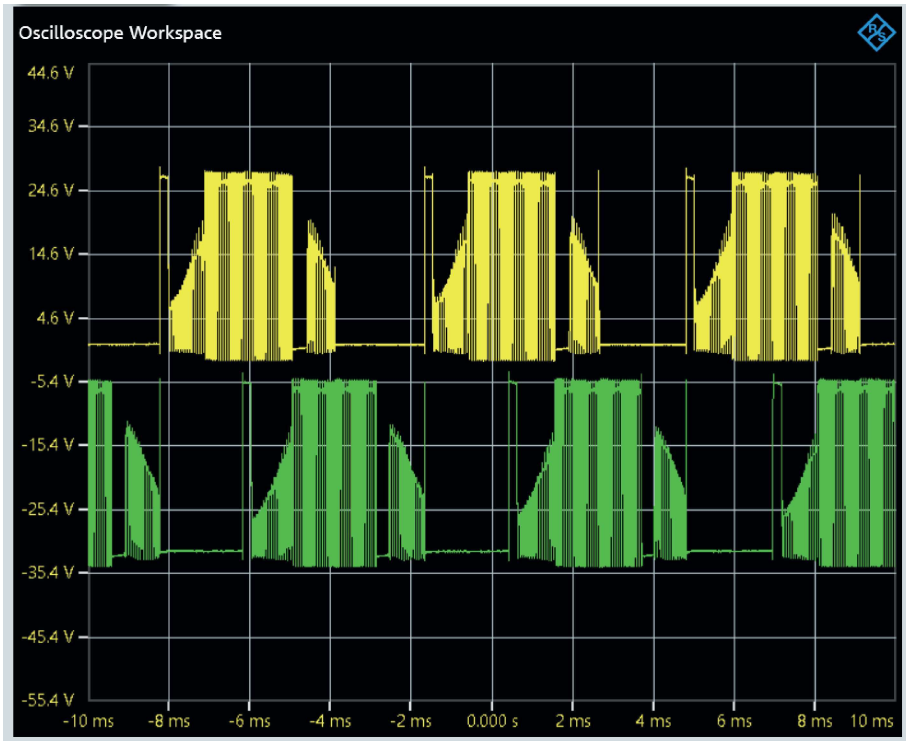


Figure 8. Brushless motor phase chart

RESULTS

In this study, the brushless motor driver power layer designed using Altium Designer was examined and the losses were examined in detail. Power losses were calculated with various formulas by sharing the relevant schematics and necessary component information. MOSFET drivers included in the microprocessor structure are used. On the other hand, MOSFET with DMOS structure has been selected and DMOS structure has been included in the thesis. Simultaneously, details such as bootstrap calculations and deadtime calculations were included in the study. The maximum driver losses were calculated by performing the tests of the driver on the motor under load. In this study, it has been studied on the most efficient design of Brushless motor drives and their presentation to the user with the same efficiency. Initially, the advantages and disadvantages of brushless motors were mentioned. The differences of brushless motors compared to other motor types, the way they work and the motor driver structure are mentioned. It has been noted that the driver circuits of brushless motors are different from other motors and their structure consists of 3 phases. It is known to provide feedback to the driver circuit to determine phase positions while the motor is rotating. PWM signal must be applied to open the motor phases and this signal must be applied for the motor driver to energize the motor efficiently, creating a deadtime during the position change. In this study, it is focused on the design of a low power brushless motor with components that will create minimum power loss. In this direction, power losses in a 150W system have been reduced to 6W.

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