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Performance Evaluation of Brushless Direct Current Motor Control Methods through Low-Cost Microcontroller-Based Real-Time Experiments

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Deneysel Uygulama

Graphical/Tabular Abstract (Grafik Özet)

In this study; 120°, 180°, 150° commutation methods, and direct digital synthesis (DDS) based sinusoidal pulse width modulation (SPWM) are applied to the brushless direct current (BLDC) motor and the performance comparison of BLDC commutation methods is evaluated by means of obtained waveforms, operable speed interval, current draw, and thrust. / Bu çalışmada; 120°, 180°, 150° komütasyon yöntemleri ve doğrudan sayısal sentezleme (DSS) tabanlı sinüzoidal darbe genişlik modülasyonu (SDGM), fırçasız doğru akım motoruna (FDAM) uygulanmış ve yöntemlerin performans karşılaştırması elde edilen dalga biçimleri, çalışma hız aralığı, çekilen akım ve itme kuvvetine göre gerçekleştirilmiştir.

***Figure A**: Schematic illustration of the study / **Şekil A:** Çalışmanın şematik gösterimi*

Highlights (Önemli noktalar)

- *Application of 120°, 180°, 150° commutation and DDS for BLDC/ 120°, 180°, 150° komütasyon ve DSS'nin FDAM için uygulaması*
- *Detailed explanation of applied methods/ Uygulanan yöntemlerin detaylı açıklaması*
- *Performance comparion of case results/ Durum sonuçlarının performans karşılaştırması*

***Aim (Amaç):** The aim of this study is to examine the performance comparison of 120°, 180°, and 150° commutation methods, and DDS based SPWM by using low-cost experimental setup for BLDC motor. / Bu çalışmada 120°, 180° ve 150° komütasyon yöntemleri ile DSS tabanlı SDGM'nin düşük maliyetli bir deneysel düzenek kullanarak FDAM için performans karşılaştırması amaçlanmıştır.*

***Originality (Özgünlük):** To the best of the authors' knowledge, the performance comparison of 120°, 180°, and 150° commutation methods, and DDS based SPWM is realized for the first time. In this context, it is also the first time that the performance of DDS algorithm is compared with mostly used commutation methods. / Yazarların bildiği kadarıyla, 120°, 180°, 150° komütasyon yöntemleri ile DSS tabanlı SDGM'nin performans karşılaştırması ilk kez gerçekleştirilmiştir. Bu kapsamda ayrıca DSS algoritmasının performansı ilk kez başlıca kullanılan komütasyon yöntemleriyle karşılaştırılmıştır.*

***Results (Bulgular):** The case studies have shown that DDS based sinusoidal commutation is convenient to be used in BLDC motor applications due to its lower power consumption and wider operable speed range. / Durum çalışmaları, daha düşük güç tüketimi ve daha geniş çalışma hızı aralığı nedeniyle DSS tabanlı sinüzoidal komütasyonun FDAM uygulamalarında kullanılmaya uygun olduğunu göstermiştir.*

***Conclusion (Sonuç):** In this study, the performance comparison of 120°, 180°, 150° modes, and DDS based SPWM was realized through case studies by observing waveforms, operable speed interval, current draw, and thrust. The study had shown that the DDS based SPWM had more best results than the other methods. / Bu çalışmada 120°, 180°, 150° modlarının ve DSS tabanlı SDGM'nin performans karşılaştırması, dalga biçimleri, çalışma hız aralığı, çekilen akım ve itme kuvveti gözlemlenerek durum çalışmaları yoluyla gerçekleştirilmiştir. Çalışma, DSS tabanlı SDGM'nin diğer yöntemlere göre en iyi sonuçlara sahip olduğunu göstermiştir.*

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Performance Evaluation of Brushless Direct Current Motor Control Methods through Low-Cost Microcontroller-Based Real-Time Experiments

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Abstract

Brushless direct current (BLDC) motors are high efficiency synchronous motors that are employed in a variety of applications due to prominent features such as long operational life, low maintenance requirements, and great dynamic response. BLDC motors are driven by energizing the stator windings with an inverter circuit. To commutate the inverter switches, the trapezoidal (120°) method is generally used by considering the back electromagnetic force induced on unenergized phase of BLDC. Furthermore, depending on the application requirements, alternative commutation modes (CM) such as 180°, 150°, and sinusoidal-based approaches are utilized. In the literature, the performance comparison of some CMs was studied for two-phase on operation and three-phase on operation mode by considering the switching patterns. However, only a few research assessed the performance of two or three commutation modes simultaneously. In this study, the performance comparison of pulse width modulation (PWM) based commutation modes are examined by considering 120°, 180°, 150° modes, and sinusoidal PWM. In this scope, it is the first time that direct digital synthesis (DDS) is addressed as a BLDC control algorithm in a performance comparison study. In experimental studies, a simple and a low-cost drive circuit is designed to acquire the case results. According to the results, the proposed DDS-based sine commutation method is more efficient than other commutation methods and it has lower power consumption at both low and high speeds also a wider operable speed range than other applied methods.

Fırçasız Doğru Akım Motor Kontrol Yöntemlerinin Düşük Maliyetli Mikrodenetleyici Tabanlı Gerçek Zamanlı Deneylerle Performans Değerlendirmesi

Makale Bilgisi

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Öz

Fırçasız doğru akım motorları (FDAM), uzun çalışma ömrü, düşük bakım gereksinimleri ve çok iyi dinamik yanıt gibi öne çıkan özellikleri nedeniyle çeşitli uygulamalarda kullanılan yüksek verimli senkron motorlardır. FDAM bir inverter devresi ile stator sargılarına enerji verilerek sürülür. Evireç anahtarlarının komütasyonu için genellikle FDAM enerjisiz fazında indüklenen zıt elektromanyetik kuvvetine dayanan trapez (120°) yöntemi kullanılır. Ayrıca, uygulama gereksinimlerine bağlı olarak 180°, 150° gibi alternatif komütasyon modları (KM) ve sinüzoidal tabanlı yaklaşımlar kullanılır. Literatürde, bazı KM'lerin performans karşılaştırması, iki fazlı çalışma ve üç fazlı çalışma modu için anahtarlama düzenleri dikkate alınarak incelenmiştir. Ancak, sadece birkaç araştırma aynı anda iki veya üç komütasyon modunun performansını değerlendirdi. Bu çalışmada, darbe genişlik modülasyonu (DGM) tabanlı komütasyon modlarının performans karşılaştırması 120°, 180°, 150° modları ve sinüzoidal DGM kullanılarak gerçekleştirilmiştir. Bu kapsamda, doğrudan sayısal sentez (DSS) ilk kez bir performans karşılaştırma çalışmasında bir BLDC kontrol algoritması olarak ele alınmaktadır. Deneysel çalışmalarda, basit ve düşük maliyetli bir sürücü devresi durum sonuçlarını elde etmek için tasarlanmıştır. Elde edilen sonuçlara göre, önerilen DSS tabanlı sinüs komütasyon yönteminin diğer komütasyon yöntemlerine göre daha verimli, hem düşük hem de yüksek hızlarda daha düşük güç tüketimine ve uygulanan diğer yöntemlere göre daha geniş çalışma hızı aralığına sahip olduğu görülmüştür.

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1. INTRODUCTION (GİRİŞ)

Brushless direct current (BLDC) motors and permanent magnet synchronous motors are used in various application areas, such as drones, household appliances, aerospace, office automation, automotive applications, etc. They are preferred in many industries due to their high torque-to-weight ratio, efficiency, and lower maintenance requirements when compared to traditional direct current (DC) motors [1], [2]. Generally, there are two structurally distinct BLDC motors are employed [3]. The inrunner type BLDC motor is similar to the induction motor in that the rotor shaft is placed inside the stator windings while the rotor is placed outside of the stator windings at the outrunner types.

The rotor of BLDC motor is controlled by generating the rotational magnetic field at their stator, which is similar in principle to the three-phase induction motors. However, the field is produced by energizing the phase windings of the stator with a semi-conductor-based three-phase inverter circuit in the BLDC motor drive as shown in Figure 1. In the figure, R, L, and M represent phase stator resistance, self-inductance, and mutual inductance, respectively. Further, the induced back electromagnetic forces (back-EMF) on the stator windings are denoted by e_a, e_b, and e_c. Generally, MOSFETs, IGBTs, and power transistors are used as switching elements. Each switching element in the inverter circuit conducts current and changes its conduction state according to the commutation table. The ideal current conduction for the BLDC motor is given in Figure 2.

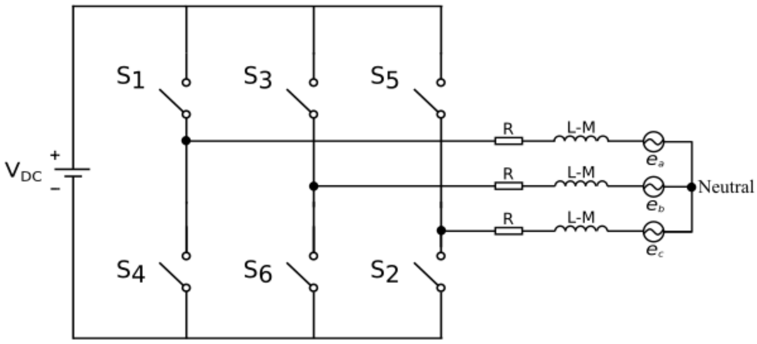


Figure 1. The power circuit of BLDC motor driver (FDAM sürücüsünün güç devresi)

There are widely used two methods for detecting the rotor position of BLDC motors which are known as sensored and sensorless-based methods. Sensored-based methods are usually established with hall sensors embedded into the stator [4]. These sensors provide the rotor position (even at a standstill) and it is evaluated to perform the commutation action on the motor phases. However, their negative aspects such as reliability, sensitivity to temperature, and increasing power consumption of motors have led researchers to study sensorless-based methods [5].

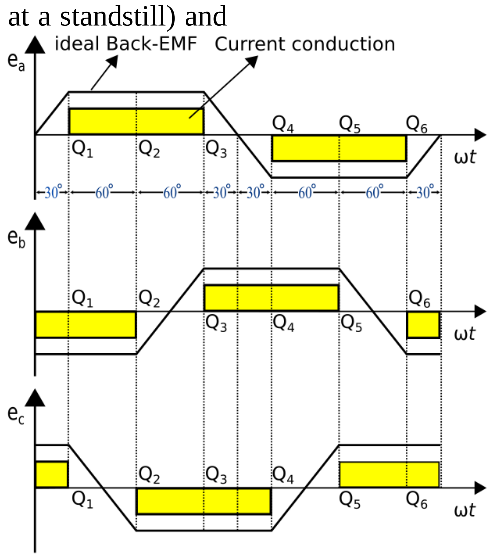


Figure 2. Back-EMF and commutation relation (Zıt elektromanyetik kuvvet ve komütasyon ilişkisi)

It is to be noted that sensorless-based methods often benefit from the back-EMF phenomena created in stator windings. This phenomenon generates a time-changing voltage on the unenergized phase. Back-EMF is proportional to motor speed and serves as an indication of rotor position. To identify the commutation states for a BLDC motor, rotor position information is required thus the back-EMF signal is used to determine the commutation states. In the literature, there are numerous back-EMF-based rotor position detection methods for BLDC motors. One of them relies on terminal voltage sensing. The terminal voltages are utilized to detect the back-EMF zero-crossing points on the unenergized phases, and then a 30° phase shift is performed to acquire the commutation states [6].

Another back-EMF method is based on the integration of back-EMF to find the commutation states. In this method, the commutation point is calculated by taking the integral of the unenergized phase from zero crossing to the predefined threshold value [7]. Apart from these techniques, the third harmonic of the back-EMF-based methods has been developed to find the commutation states. This method acquires the rotor position by using the voltage between the neutral point and the virtual neutral point. However, in many BLDC applications, the neutral point is not provided by the manufacturer so the voltage between the virtual neutral point and the midpoint of the dc-link is used to obtain the rotor position in the virtual third harmonic back-EMF method [8]. Also, the position observers are used to find the rotor position by estimating the back-EMF [9]. After detecting the rotor position selected commutation procedure is applied to the motor phases.

In literature, 120°, 180°, 150° commutation modes, and space vector modulation (SVM) are the commonly used methods for driving BLDC motors. These commutation modes have some pros and cons according to each other. To mention a few, the detection of zero-crossing points of back-EMF can be easily achieved and extracted from the unenergized phase in 120° commutation mode, while it is not possible in 180° commutation mode since there is no unenergized phase [10]. If the application needs more torque, 180° commutation mode can be preferred because all of the three-phases contribute to torque at each commutation state [11]. If the low harmonic content is needed in the current and voltage waveforms, 150° commutation mode can be used in the applications [12]. Furthermore, if higher torque and speed control is required, the field-oriented control (FOC) is typically utilized in conjunction with sinusoidal pulse width modulation (SPWM) or SVM. FOC establishes high efficiency and decoupled control of flux and torque [13]. However, its implementation is more complex than the other methods.

The performance comparison of some CMs is studied for two-phase on operation and three-phase on operation mode by considering the switching patterns [14]. In this study, the performance comparison of 120°, 180°, 150° and direct digital synthesis (DDS) based SPWM is realized with the experimental results of the operable speed interval, the current draw, the generated thrust, and the waveforms of line-to-line and phase-to-ground.

The commutation strategies are crucial in the selection of an open-loop starting method, especially in battery-powered applications such as drones. Also, the efficient use of energy sources is an important issue addressed by researchers [15], [16]. With this motivation in mind, the power consumption of frequently used commutation methods such as 120°, 180°, 150°, and DDS-based SPWM, which are detailed in the following sections, are experimentally tested in a real-time environment. The main contributions of the present research can be summarized as follows. To the best of the authors' knowledge the performance comparison of the aforementioned four methods has not been addressed yet in the literature. Also, it is the first time that comparison of DDS algorithm based SPWM method with widely used driving methods for BLDC motor control is realized. According to the comparison results, the proposed DDS-based sine commutation method is more efficient than other commutation methods and has lower power consumption at both low and high speeds also a wider operable speed range. In addition, it is also found that the generated thrust is greater than the other compared methods.

The remainder of the study is organized as follows. The most commonly used commutation modes are explained in section 2. The driver circuit design of the BLDC motor, experimental setup, and implementation details are discussed in section 3. The data gathered from the experiments for each commutation mode are given in section 4. The comparison of commutation modes is realized via a constructed comparison table, and the study is ended with the inferences from the experimental studies in section 5.

2. INVERTER COMMUTATION MODES
(EVİREÇ KOMÜTASYON MODLARI)

A classical three-phase voltage source inverter (VSI) is used to drive BLDC motors according to the selected commutation method. The typical power circuit of VSI is given in Figure 1. Several commutation modes are utilized in the control algorithm of VSI. The selection of these modes is depended on the application requirements (such as smooth operation, torque control, low noise, etc.). In this section, 120°, 180°, 150°, and the DDS-based sine commutation are examined, respectively.

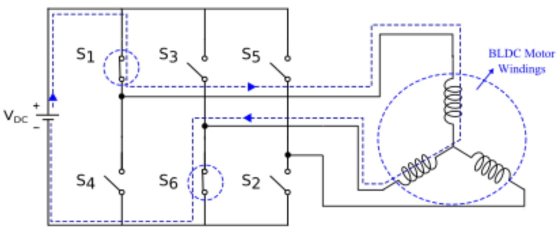
2.1. 120° Commutation Mode (120° Komütasyon Modu)

120° commutation mode is a widely used method to drive a BLDC motor. It is also known as the six-step or trapezoidal commutation mode. Generally, BLDC motor has three-phase stator windings in its structure. In this mode, the two stator phase windings are always energized and one phase is left unenergized. Energization of phase windings is achieved by switching on one high-side and one low-side switch.

There are six commutation steps given in Figure 3(a). The duration of each commutation step as given in Figure 4 is 60°. In the table, the current conducting and non-conducting switches are denoted by 1 and 0, respectively. In this mode, each switch must be controlled individually. For instance, in the first step of Figure 3(a), S_1 and S_6 are connected to the positive and negative side of the source respectively and they are closed while the other four switches are kept open. This is shown in Figure 3(b). The speed of the motor is adjusted by changing the duration of each commutation step. This commutation mode has an easy implementation and also can be integrated into both the open-loop and closed-loop control algorithms.

Step	S1	S4	S3	S6	S5	S2
1	1	0	0	1	0	0
2	1	0	0	0	0	1
3	0	0	1	0	0	1
4	0	1	1	0	0	0
5	0	1	0	0	1	0
6	0	0	0	1	1	0

(a)



(b)

Figure 3. a) Switch states of 120° commutation mode, b) Illustration of first commutation step of the table (a) 120° komütasyon modunun anahtarlama düzenleri, b) Tablodaki ilk komütasyon adımının gösterimi)

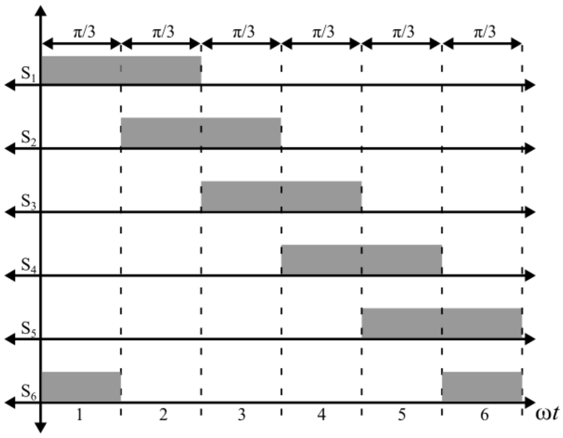


Figure 4. Switch states of 120° commutation mode [12] (120° komütasyon modunun anahtarlama düzenleri [12])

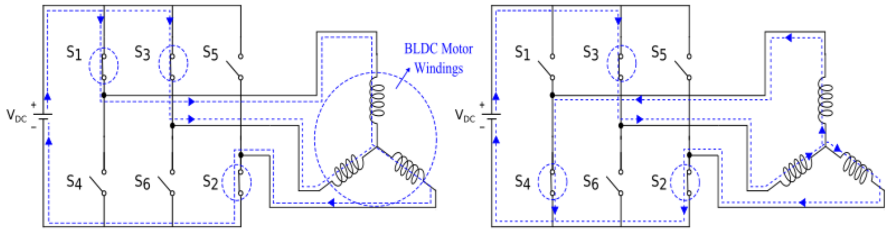
2.2. 180° Commutation Mode (180° Komütasyon Modu)

180° commutation mode is generally used to control the induction electrical machines and also is used to drive BLDC motor. In this mode, the three stator phase windings are always energized therefore there is no available gap to measure back-EMF directly [17]. There are six commutation steps given in Figure 5(a). In the table, the current conducting and non-conducting switches are denoted by 1 and 0, respectively. The duration of each commutation step as given in Figure 6 is 60°. The energization of stator windings is achieved by closing the two high-sides and one low-side switches in the first step and one high-side and two low-sides switches in the second step. In other words, three-switches are always activated.

The operation principle of 180° commutation mode can be explained according to first two commutation step described in Figure 5(a). In the first step, S_1 and S_3 high-side switches and S_2 low-side switch are closed. In the second step, the S_1 high-side switch is opened and the S_4 low-side switch is closed. This is shown in Figure 5(b). The speed of motor is adjusted by changing the duration of each commutation step.

Step	S1	S4	S3	S6	S5	S2
1	1	0	1	0	0	1
2	0	1	1	0	0	1
3	0	1	1	0	1	0
4	0	1	0	1	1	0
5	1	0	0	1	1	0
6	1	0	0	1	0	1

(a)



(b)

Figure 5. a) Switch states of 180° commutation mode, b) Illustration of first two commutation steps of the table (a) 180° komütasyon modunun anahtarlama düzenleri, b) Tablodaki ilk iki komütasyon adımının gösterimi)

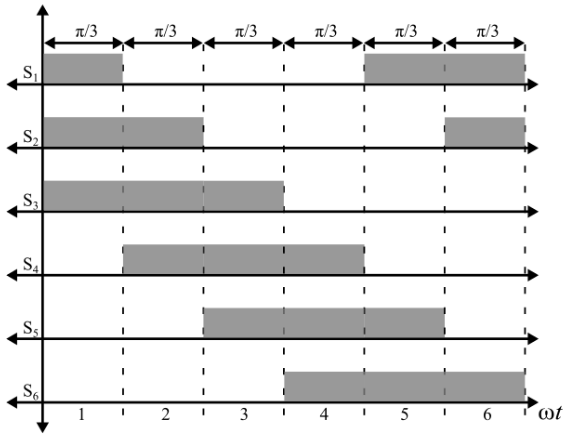


Figure 6. Switch states of 180° commutation mode [12] (180° komütasyon modunun anahtarlama düzenleri [12])

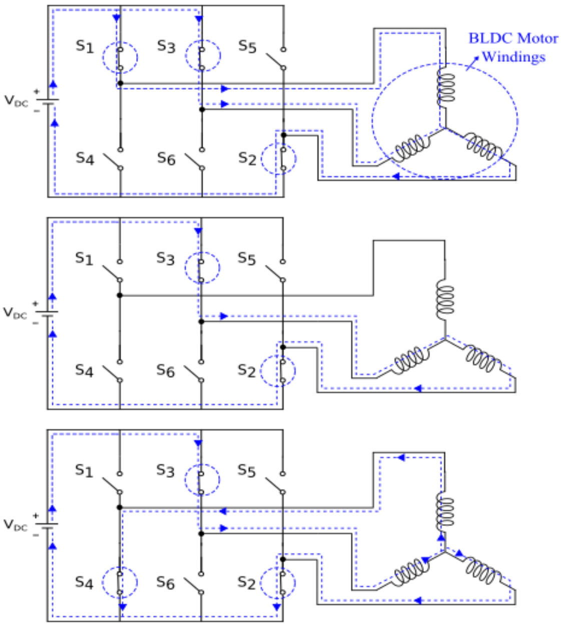
2.3. 150° Commutation Mode (150° Komütasyon Modu)

150° commutation mode is generally used in the algorithms of inverters and uninterruptable power supplies. It is also used to drive BLDC motor since it reduces torque ripple and has low harmonic content than 120° commutation mode [18]. It can be said that its step sequence is the combination of 120° and 180° commutation modes. It is actualized by inserting each 120° commutation step between consecutive steps of 180° mode. Figure 7(a) depicts the twelve commutation steps in this mode. At the first step, all stator windings are energized whereas just two stator windings are energized at the second step. The energization of phase windings can be explained in three steps. In the first step, two high-side switches and one low-side switch are activated. In the second step, one high-side and one low-side switch are activated and in the third step one high-side and two low-side switches are activated.

In the table, the current conducting and non-conducting switches are denoted by 1 and 0, respectively. The first three-step is explained as follows. In the first step, S1 and S3 high-side and S2 low-side switches are in a closed condition. In the second step, the S_1 high-side switch is opened and the others have remained unchanged. In the third step, S_4 low-side switch is closed and the others have remained unchanged. This commutation scheme is given in Figure 7(b). The duration of each commutation step as given in Figure 8 is 30°. The speed of the motor is adjusted by changing the duration of each commutation step. The advantages of this method relative to 120° and 180° commutation modes are the increasing of RMS output voltage and the creation of a 30° safety margin period to avoid short circuits on the DC supply [12]. This method can also be integrated into the open and closed-loop control algorithms.

Step	S1	S4	S3	S6	S5	S2
1	1	0	1	0	0	1
2	0	0	1	0	0	1
3	0	1	1	0	0	1
4	0	1	1	0	0	0
5	0	1	1	0	1	0
6	0	1	0	0	1	0
7	0	1	0	1	1	0
8	0	0	0	1	1	0
9	1	0	0	1	1	0
10	1	0	0	1	0	0
11	1	0	0	1	0	1
12	1	0	0	0	0	1

(a)



(b)

Figure 7. a) Switch states of 150° commutation mode, b) Illustration of first three commutation steps of the table (a) 150° komütasyon modunun anahtarlama düzenleri, b) Tablodaki ilk üç komütasyon adımının gösterimi)

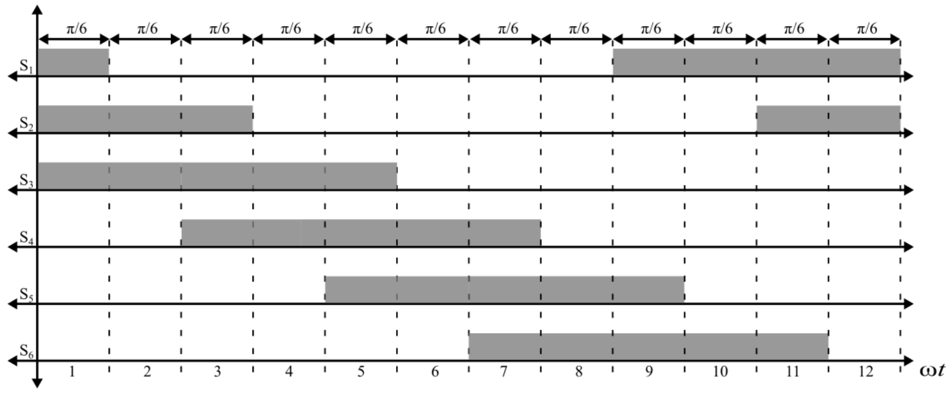


Figure 8. Switch states of 150° commutation mode [12] (150° komütasyon modunun anahtarlama düzenleri [12])

2.4. Sinusoidal Pulse Width Modulation

(Sinüzoidal Darbe Genişlik Modülasyonu)

Pulse width modulation (PWM) is the process to generate high-frequency and variable-length pulse trains that is proportional to the applied control signal [19]. Different PWM techniques have been used in various applications such as variable speed drives (VSD), static frequency changers (SFC) and uninterruptible power supplies (UPS), etc. In the PWM process, variable-length pulses are obtained by comparing the three-phase reference signals with a triangular carrier. The magnitude and frequencies of the output sinusoidal signal can be controlled by changing the magnitude and frequency of the reference signal [20]. Besides the analog method, digital methods such as the direct digital synthesis (DDS) method can be used to generate high-frequency sinusoidal signals.

The DDS method is a way to generate waveforms usually a sine wave by storing waveform properties on a look-up table that is an array in a microcontroller’s memory that holds amplitude information of the waveform being generated. The block diagram of the DDS method is given in Figure 9. The waveform information is stored in Amplitude/Sine Conv. block. It is usually a look-up table of a sine. The phase accumulator computes a phase (angle) address for the look-up table. The look-up table outputs the amplitude value of the phase which is then converted to analog waveform by a digital-to-analog converter (DAC) unit. The frequency of the output waveform can be changed by either modifying the tuning word or reference clock [21].

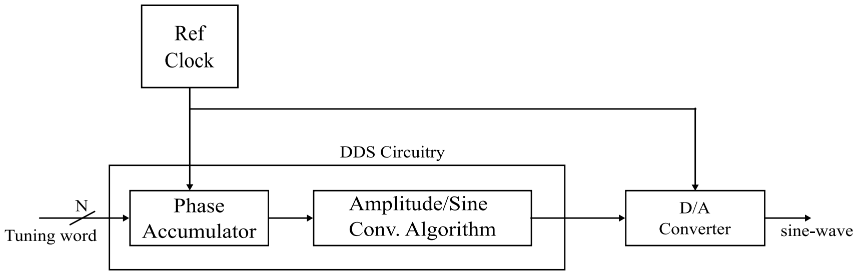


Figure 9. DDS method building blocks (DSS yönteminin temel blokları)

3. MATERIAL AND METHODS (MATERYAL VE METOD)

A driver circuit that includes the microcontroller (Arduino Nano) is designed in order to control the BLDC motor. The specification of the microcontroller, the circuit schematic, the printed circuit board (PCB) of the driver, and the hardware itself are given in Table 1, Figure 10, Figure 11, and Figure 12 respectively. At the PCB circuit, red and yellow lines represent traces and jumpers, respectively. The driver circuit includes two L298N integrated circuits, a potentiometer, a voltage regulator, diodes, and resistors. L298Ns has four half bridges. Hence, it has the capability of driving four-phase electrical motors. A potentiometer is connected to the microcontroller's analog input for adjusting the speed of the motor. Also, a back-EMF detection circuit composed of nine resistors is included for future studies. Flywheel diodes are used to protect switching elements from voltage spikes. During the experimental studies, the control algorithm of each method was examined as an open-loop. During the implementation of 120° and 150° commutation modes, the couple switches (such as S_1 and S_4) can be operated individually (S_1 is closed whereas S_4 is opened) or as a group (S_1 and S_4 are opened or closed at the same time). In 180° commutation mode and the DDS-based SPWM method, switches are operated individually. All methods supply a three-phase sine-wave signal to the stator windings of BLDC.

The experimental setup of this study was given in Figure 13. This setup consisted of a tachometer, precision scale, and sample BLDC motor. BLDC motor is rated at 880rpm/voltage (KV) with an internal resistance of 107mΩ and inductance of 0.005mH. This motor is fixed on the precision scale to measure its thrust. A 10x4.5inch (1045r) propeller was attached to the rotor of the BLDC motor. The tachometer was used to measure the rpm of the motor. All experimental results of each method were taken from this configuration.

Table 1. Arduino nano technical details [22] (Arduino nano teknik detayları [22])

Microcontroller	Atmega328p
Crystal Oscillator	16MHz
Input Voltage	6V-12V
Maximum Current Rating	40mA
D0-D13	Digital Input / Output pins
A0-A7	Analog Input / Output pins
Pin # 3, 5,6, 9, 10, 11	Pulse Width Modulation (PWM) pins
D2 & D3	External Interrupt pins

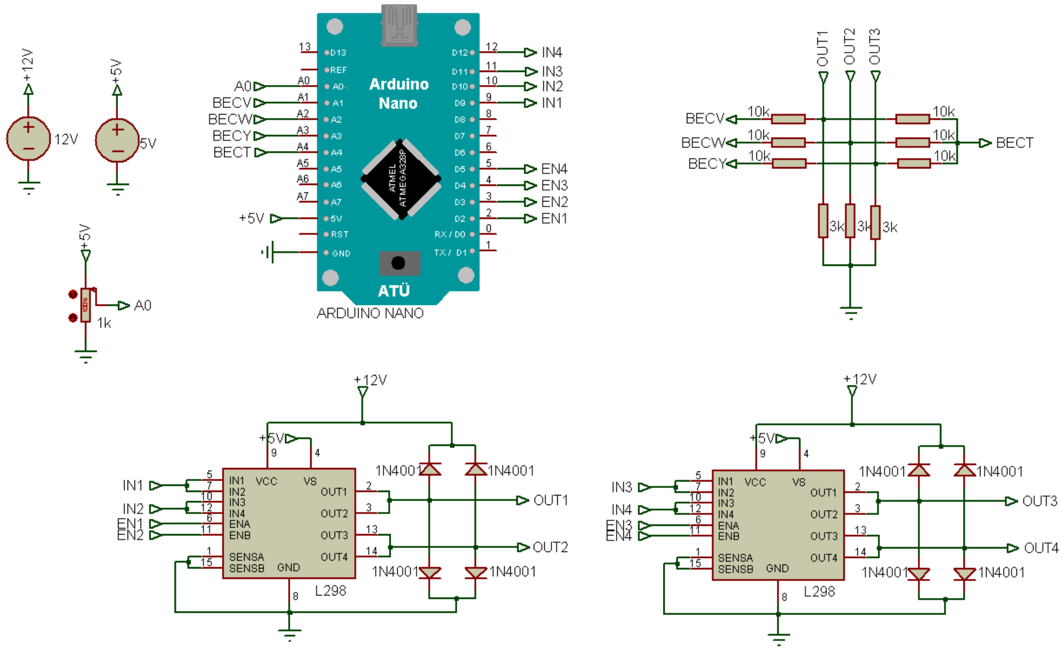


Figure 10. The circuit schematic of inverter circuit (Evireç devresinin devre şeması)

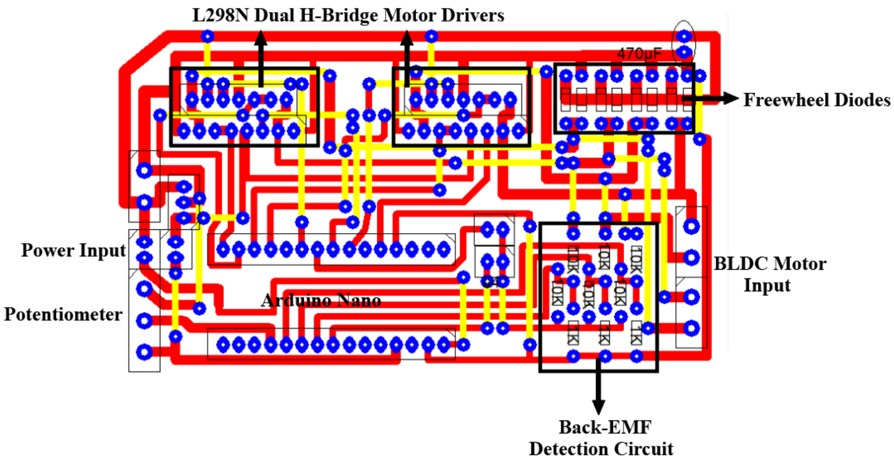


Figure 11. PCB of inverter circuit (Evireç devresinin baskı devresi)

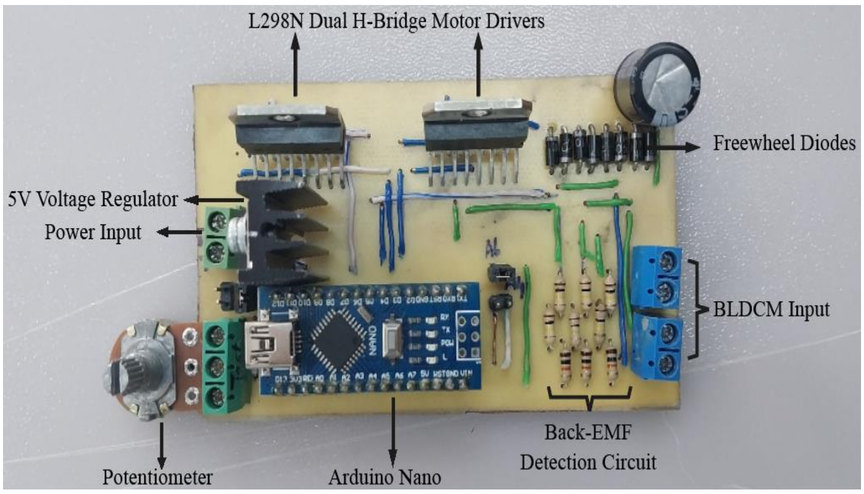


Figure 12. BLDC motor drive circuit (FDAM sürücü devresi)

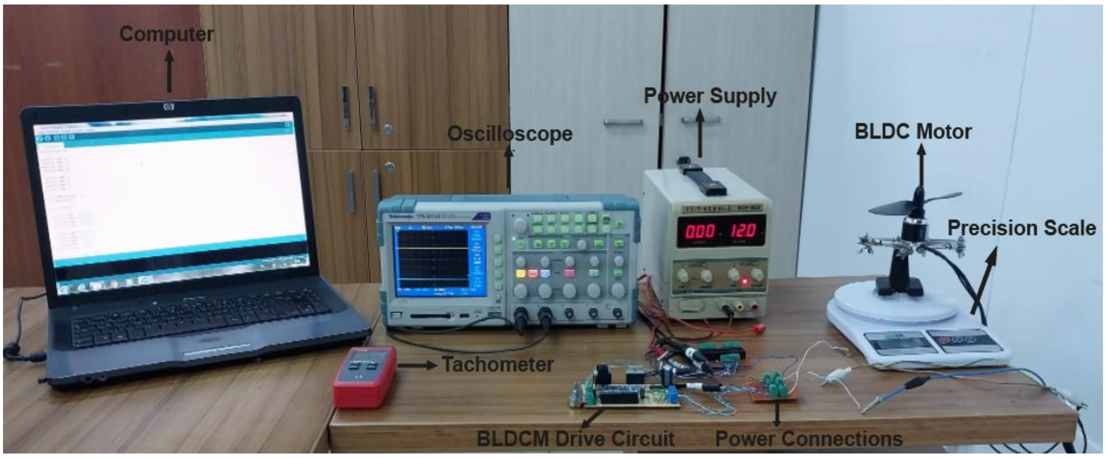


Figure 13. Experimental setup (Deney düzeneği)

4. CASE STUDIES (DURUM ÇALIŞMALARI)

In the experimental cases, each method given above was evaluated by considering the current drawn from the source, thrust, and rpm values for minimum speed and maximum speed. Then, the voltage waveform on the oscilloscope was captured for each method when the BLDC motor was at the highest rpm value. 12VDC is used to energize the driver circuit given in Figure 13. Arduino integrated development environment (IDE) interface was used to upload codes of each method to the microcontroller. The experimental data of each method was gathered and given in the tables with output waveforms. In the table, there are three rows related to current, thrust, and rpm values, respectively. These three parameters are compared for the minimum and maximum speeds which are given in two columns.

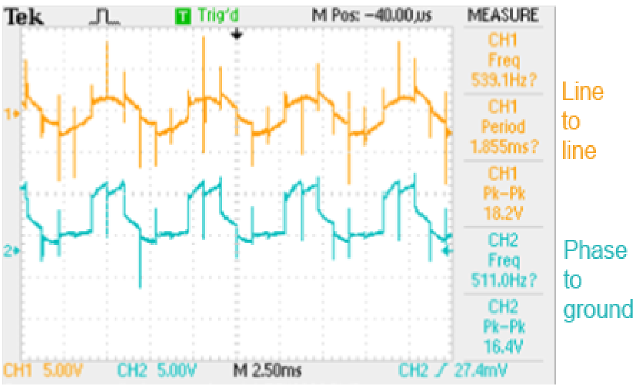
4.1. Case 1: 120° Commutation Mode (Durum 1: 120° Komütasyon Modu)

In this mode, the commutation steps given in Figure 3(a) were applied to the BLDC motor via driver circuit. Minimum and maximum attainable speed was observed. At the minimum speed of 186rpm, the thrust was measured as 0 gram-force (gf) and the current was drawn as 2.45A. At the maximum speed of 1526rpm, the thrust was measured as 33gf and the current was drawn as 2.60A. According to these results, it can be said that the increase of current value was calculated as 6.1%.

The results of minimum/maximum operable speeds and thrust were given in Figure 14(a). The waveforms of the applied voltage to BLDC motor stator windings were given in Figure 14(b). It was taken at the maximum speed with a frequency of 193Hz.

	Minimum Speed Results	Maximum Speed Results
Current (A)	2.45	2.60
Speed (rpm)	186	1526
Thrust (gf)	0	33

(a)



(b)

Figure 14. a) 120° commutation mode results, b) 120° commutation mode waveform at maximum speed (a) 120° komütasyon modu sonuçları, b) En yüksek hızda 120° komütasyon modu dalga formu)

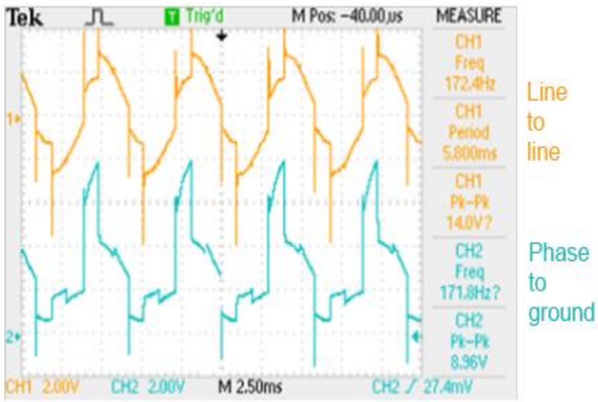
4.2. Case 2: 180° Commutation Mode (Durum 2: 180° Komütasyon Modu)

In this mode, the commutation steps given in Figure 5(a) were applied to the BLDC motor via the driver circuit. Minimum and maximum attainable speed is observed. At the minimum speed of 178rpm, the thrust was measured as 0gf and the current was drawn as 3.01A. At the maximum speed of 1480rpm, the thrust was measured as 30gf and the current was drawn as 3.08A. According to these results, a higher current draw was seen than 120° and 150° commutation modes as expected. Since the three-phases are always active. Also, it can be said that the increase of current value was calculated as 2.32%.

The results of minimum/maximum operable speeds and thrust were given in Figure 15(a). The waveforms of the applied voltage to BLDC motor stator windings were given in Figure 15(b). It was taken at the maximum speed with a frequency of 167Hz.

	Minimum Speed Results	Maximum Speed Results
Current (A)	3.01	3.08
Speed (rpm)	178	1480
Thrust (gf)	0	30

(a)



(b)

Figure 15. a) 180° commutation mode results, b) 180° commutation mode waveform at maximum speed
(a) 180° komütasyon modu sonuçları, b) En yüksek hızda 180° komütasyon modu dalga formu)

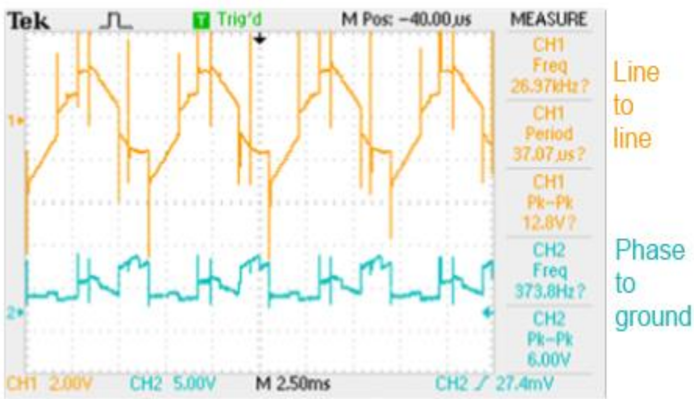
4.3. Case 3: 150° Commutation Mode (Durum 3: 150° Komütasyon Modu)

In this mode, the commutation steps given in Figure 7(a) were applied to the BLDC motor via the driver circuit. Minimum and maximum attainable speed is observed. At the minimum speed of 178rpm, the thrust was measured as 0gf and the current was drawn as 2.73A. At the maximum speed of 1327rpm, the thrust was measured as 25gf and the current was drawn as 2.90A. According to these results, it can be said that the increase of current value was calculated as 6.2%.

The results of minimum/maximum operable speeds and thrust were given in Figure 16(a). The waveforms of the applied voltage to BLDC motor stator windings were given in Figure 16(b). It was taken at the maximum speed with a frequency of 153Hz.

	Minimum Speed Results	Maximum Speed Results
Current (A)	2.73	2.90
Speed (rpm)	178	1327
Thrust (gf)	0	25

(a)



(b)

Figure 16. a) 150° commutation mode results, b) 150° commutation mode waveform at maximum speed
(a) 150° komütasyon modu sonuçları, b) En yüksek hızda 150° komütasyon modu dalga formu)

4.4. Case 4: Direct Digital Synthesis Based SPWM Method (Doğrudan Sayısal Sentez Tabanlı Sinüzoidal DGM Yöntemi)

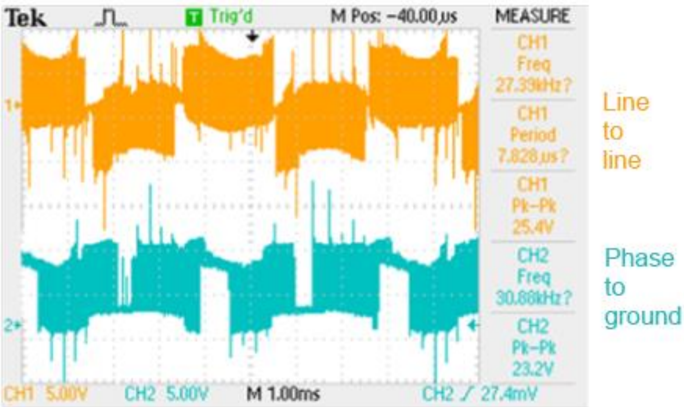
In this case study, the DDS algorithm was applied to the SPWM method and then, it was used to control the BLDC motor [23]. The switching sequences of DDS-based SPWM are the same with 180° commutation mode. At the experimental setup, the reference clock was taken as 1024Hz and the timer1 interrupt of Arduino was adjusted to generate a 30.88kHz waveform given in Figure 17(b). Then, the duty cycle of PWM was changed by using the lookup table of the sine function. In this lookup table, the value of the sinusoidal waveform ranged from 0 to 255. The potentiometer was used to adjust the tuning word. Hence, the frequency of the output signal was changed.

In this mode, the commutation steps given in Figure 5(a) were applied to the BLDC motor via the driver circuit. Minimum and maximum attainable speed was observed. At the minimum speed of 143.8rpm, the thrust was measured as 0gf and the current was drawn as 2.38A. At the maximum speed of 2116rpm, the thrust was measured as 70gf and the current was drawn as 1.98A. According to these results, it can be said that the decrease in current value was calculated as 16.8%.

The results of minimum/maximum operable speeds and thrust were given in Figure 17(a). The waveforms of the applied voltage to BLDC motor stator windings were given in Figure 17(b). It was taken at maximum speed with a frequency of 250Hz.

	Minimum Speed Results	Maximum Speed Results
Current (A)	2.38	1.98
Speed (rpm)	143.8	2116
Thrust (gf)	0	70

(a)



(b)

Figure 17. a) DDS method results, b) DDS method waveform at maximum speed (a) DSS yöntemi sonuçları, b) En yüksek hızda DSS yöntemi dalga formu)

5. CONCLUSION (SONUÇLAR)

Nowadays, BLDC motors have been replacing other three-phase electrical motors in many fields such as drones, household appliances, aerospace, office automation, automotive applications, etc. due to their high efficiency, low maintenance requirement, and high torque-to-weight ratio. They are controlled by six-pulse inverter-based drivers. To commute the inverter switches, the 120° method is generally preferred by considering back-EMF induced on the unenergized phase of the BLDC. Also, 180° mode, 150° mode, and the sinusoidal-based methods are used according to the application requirements.

In this study, the performance comparison of 120°, 180°, 150° modes, and DDS-based SPWM was examined. It is the first time to observe the performance comparison of the previously described four methods in the literature. In this context, it is the first time that a comparison of the DDS algorithm based SPWM method with widely used driving methods for BLDC motor control was realized. For the case studies, a simple and low-cost drive circuit was designed. According to the results, ripples on voltage waveforms when changing to a new commutation state were observed. Also, a performance comparison of case studies was given in Table 2. It is clearly revealed that the DDS method has performed better in terms of lower power consumption, higher thrust, lower operable speed, and wider speed range than the other methods. It can be concluded that the DDS method is more efficient than other commutation methods. Therefore, it is a suitable control method to utilize in appliances. In addition, 180° mode has drawn more current as expected because three windings are energized at all times.

Table 2. Performance comparison of case studies (Durum çalışmalarının performans karşılaştırması)

Method	Current at Minimum Speed (A)	Current at Maximum Speed (A)	Minimum Speed (rpm)	Maximum Speed (rpm)	Thrust at Maximum Speed (gf)
120°	2.45	2.60	186	1526	33
150°	2.73	2.90	178	1327	25
180°	3.01	3.08	178	1480	30
DDS-based SPWM	2.38	1.98	143.8	2116	70

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Emre YORAT*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

***Necdet Sinan ÖZBEK*:** He contributed the writing process and analyzed the results.

Sonuçların analizi ve makale yazım aşamasında katkıda bulunmuştur.

***Lütfü SARIBULUT*:** He contributed in the algorithm design and the writing process.

Algoritma tasarımı ve makale yazım aşamasında katkıda bulunmuştur.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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