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# Driving a symmetric permanent magnet synchronous six-phase machine with consecutive three phases

## *Simetrik sürekli mıknatıslı senkron altı fazlı bir makinenin ardışık üç fazının kullanılarak sürülmesi*

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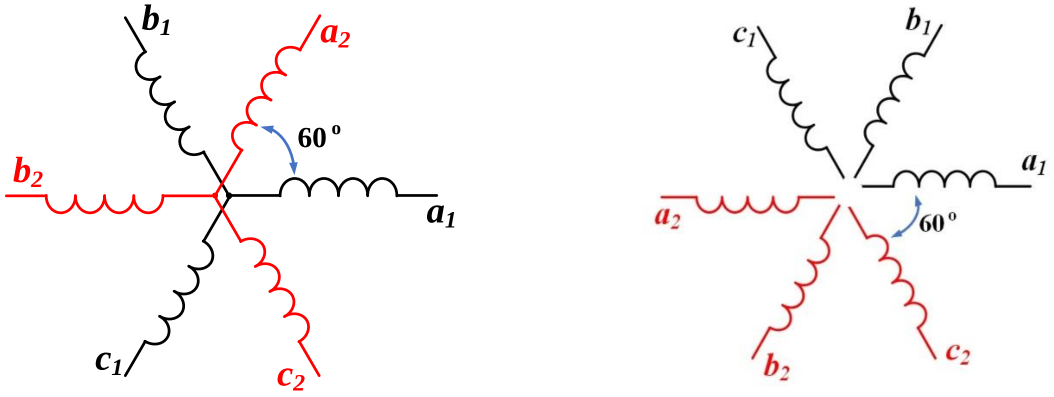
# Driving a Symmetric Permanent Magnet Synchronous Six-Phase Machine with Consecutive Three Phases

### *Highlights*

- *Dividing the six-phase machine into two parts using its consecutive phases*
- *Driving the six-phase machine with three-phase supply*
- *Driving a six-phase machine only using three set of phases*

### *Graphical Abstract*

*This paper investigates a new driving method for a Permanent Magnet (PM) Synchronous six-phase machine by using its consecutive three phases.*




a) Existing Tecnique

b) Presented Technique

**Figure.** Dividing a six-phase machine into two three-phase machine
a) existing technique b) Presented technique

### *Aim*

*The aim of this study is to separate the six-phase machine into two separate three-phase machines with a new method. This method also gives the machine designer a new flexibility in machine designs such as 6, 9, 12 phases, which consist of multiple 3-phase machines.*

### *Design & Methodology*

*The instantaneous power is the product of phase current and its back-EMF. The proposed technique has been developed using this power equations.*

### *Originality*

*In driving six-phase machines, six-phase balanced current feeding the phases or separate feeding of two separate three-phase machines is used. This study presents the separation and driving of a six-phase machine into two different three-phase machines from a new perspective.*

### *Findings*

*A simetric six-phase machine has been succesfully driven by using its consecutive three phases.*

### *Conclusion*

*The analytical results obtained in this study has been verified on a six-phase machine which has been designed in an FEA ( Simens MagNet) software. As a result, the machine has been driven without ripple in torque with the proposed method.*

### *Declaration of Ethical Standards*

*The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.*

# Driving a Symmetric Permanent Magnet Synchronous Six-Phase Machine with Consecutive Three Phases

***Research Article / Araştırma Makalesi***

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**ÖZ**

This paper investigates a driving method for a Permanent Magnet (PM) Synchronous six-phase machine by using its consecutive three phases. The torque of PM synchronous machine is the division of instantaneous power (I-power) of the machine to the rotor speed. The I-power of a machine gives information about the torque. The torque output of a PM synchronous machine can be predicted by looking at the I-power. This study investigates the torque of a PM synchronous six-phase machine by exciting its phase coils for the combination of conventional three-phase, double conventional three-phase, consecutive three phases of six-phase machine and double consecutive three phases of six-phase machine. This paper also investigates the way of driving a six-phase machine using the balanced three-phase supply. Firstly, analytical studies have been done for these exciting combinations. These analytical results indicate that symmetric six-phase machine can be driven using these combinations. Secondly, a PM synchronous six-phase machine has been designed in a finite element analysis (FEA) software. Lastly, that designed six-phase machine excited with these combinations to observe the torque wave form of the machine. As a result of this study, a symmetric six-phase machine can be run by its consecutive three phases without torque ripple.

**Keywords: Double three-phase machine, multi-phase machine, permanent magnet machine, symmetric six-phase machine, synchronous machine.**

# Simetrik Sürekli Mıknatıslı Senkron Altı Fazlı Makinenin Ardışık Üç Fazının Kullanılarak Sürülmesi

**ABSTRACT**

Bu makale, sürekli mıknatıslı (PM) senkron altı fazlı bir makinenin ardışık üç fazının kullanılarak sürülmesini araştırmaktadır. PM senkron makinenin torku, makinenin anlık gücünün (I-power) rotor hızına bölünmesidir. Bir makinede I-power tork hakkında bilgi verir. PM senkron makinenin tork çıkışı I-power dalga formuna bakılarak tahmin edilebilir. Bu çalışma, PM senkron altı fazlı bir makinenin, iki üç fazlı makinenin enerjilendirilmesi, altı faz dengeli kaynak ile enerjilendirilmesi ve bunlara ek olarak ardışık üç fazdan oluşan makinelerin enerjilendirilmesinin torka etkisini araştırmaktadır.Bu makale aynı zamanda dengeli üç fazlı beslemeyi kullanarak altı fazlı bir makinenin çalıştırılmasını da sunmaktadır. Bu enerjilendirme durumları için öncelikle matematiksel analizler yapılmıştır. Elde edilen analitik sonuçlar, simetrik altı fazlı makinenin yukarıda belirtilen kombinasyonlar kullanılarak sürülebileceğini göstermektedir. İkinci olarak, sonlu elemanlar analizi (FEA) yazılımında PM senkron altı fazlı bir makine tasarlanmıştır. Son olarak tasarlanan altı fazlı makine bu kombinasyonlarla enerjilendirilerek makinenin tork dalga formu gözlemlenmiştir. Sonuç olarak, simetrik altı fazlı bir makinenin ardışık üç fazı ile torkta dalgalanma olmadan sürülebileceği görülmüştür.

**Anahtar Kelimeler: Çift üç fazlı makine, çok fazlı makine, kalıcı (sürekli) mıknatıslı makine, simetrik altı fazlı makine, senkron makine.**

## 1. INTRODUCTION

In recent years, multi-phase machines have attracted academics' attention [1-9]. The reason for this may be the advantages of these machines. For example, the torque of the machine can be enhanced by injecting the higher current harmonics (3rd, 5th, etc.)[10-14]. Torque of a multi-phase machine can be increased by injecting the third harmonic current component in a five-phase machine. To increase the torque, this five-phase machine need to have the third harmonic back-EMF component in its back-EMF waveform[15]. When this machine is purely sinusoidal machine, there will be no torque enhancement by injecting the third harmonic. It is valid also for other multi-phase machines, to increase the torque by injecting the higher current harmonics, back-EMF of the machine or winding function of the machine should include these related higher harmonics. It is possible increasing the torque by injecting the third harmonic current in a six-phase machine as well[16]. However, six-phase machine should be an asymmetric machine for the torque enhancement. The fault-tolerant capability of a multi-phase machine when one or more phases are open-circuited or short-circuited is another important feature [1], [17-19]. Under the faulty conditions, these machines can still produce smooth torque. These are a few advantages of multi-phase machines over their three-phase counterparts.

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It can be said that multi-three-phase machines are a special case of the multi-phase machines. Double three-phase (six-phase), triple three-phase (nine-phase), twelve-phase machines and so on can be given as examples of multi-three-phase machines. The most studied multi-three-phase is the six-phase machine. Six-phase machines are generally divided into two three-phase machines. If there is 60o electrical degree between two three-phase machines, it is called a symmetric six-phase machine. If the angle between two machines is 30o, it is called an asymmetric six-phase machine. Both of them have advantages and disadvantages when compared to each other. For instance, a symmetric six-phase machine can be driven by three-phase balanced currents so that this machine can be driven by a three-phase balanced supply[20]. Additional to this, two series connected machines (six-phase and three-phase) can be run using only one six-phase inverter thanks to that symmetric configuration[21]. The advantage of asymmetric configuration is the torque improvement when the third harmonic component of currents is injected into coils[22]. Similar things can be said for the other multi-three-phase machines. If the angle between three-phase machines for a multi-three-phase machine changes, then it may have a different feature.

In this paper, a symmetric six-phase machine is run by using its consecutive three phases. The conventional approach to run a six-phase symmetric machine is generally dividing it into double three-phase machine. Analytical results show that, a symmetric six-phase machine can also be run by using its consecutive three phases. The sum of I-power of these three phases has no term to cause ripple in the torque in the analytical solution. That means that, torque of the machine will be smooth. Analytical analysis also has been done for the existing techniques to compare to presented technique in this study. Existing driving techniques are driving it as double three-phase machines and feeding the coils with six-phase balanced currents. This study also investigates the driving method of a symmetric six-phase machine with three-phase balanced currents. In [23], control of symmetric double three-phase machine was implemented for the existing winding configuration. The driving technique using three-phase balanced currents has also introduced for the presented dividing method of a six-phase machine. Lastly, to validate these theoretical studies a symmetric six-phase machine has been designed to use star of slots method in FEA. This machine has been tested for six-phase balanced currents, conventional double three-phase currents and presented consecutive three phase currents.

## 2. ELECTROMAGNETIC TORQUE OF SINUSOIDAL SIX-PHASE MACHINE

The I-power of a phase is the product of a current flowing inside the coil and back-EMF of it. Assuming that the designed symmetric six-phase permanent magnet machine has purely sinusoidal back-EMF to avoid pulsating power. As mentioned in [24] other harmonics apart from fundamental in back-EMF may cause ripple in the torque.Back-EMF waveforms of a symmetric six-phase machine can be written as follow in (1).

$$\begin{aligned}
e_a(\theta) &= E \cdot sin(\theta) \\
e_b(\theta) &= E \cdot sin(\theta - {}^{2\pi}/_{6}) \\
e_c(\theta) &= E \cdot sin(\theta - {}^{4\pi}/_{6}) \\
e_d(\theta) &= E \cdot sin(\theta - {}^{6\pi}/_{6}) \\
e_e(\theta) &= E \cdot sin(\theta - {}^{8\pi}/_{6}) \\
e_f(\theta) &= E \cdot sin(\theta - {}^{10\pi}/_{6})
\end{aligned} \tag{1}$$

Where E is the amplitude of back-EMF, and θ is the electrical angle. To drive a symmetric six-phase machine currents in (2) are required to produce a smooth power output.

$$\begin{aligned}
i_a(\theta) &= I_m \cdot sin(\theta) \\
i_b(\theta) &= I_m \cdot sin(\theta - {}^{2\pi}/_{6}) \\
i_c(\theta) &= I_m \cdot sin(\theta - {}^{4\pi}/_{6}) \\
i_d(\theta) &= I_m \cdot sin(\theta - {}^{6\pi}/_{6}) \\
i_e(\theta) &= I_m \cdot sin(\theta - {}^{8\pi}/_{6}) \\
i_f(\theta) &= I_m \cdot sin(\theta - {}^{10\pi}/_{6})
\end{aligned} \tag{2}$$

Where I_m is the amplitude of phase currents. Phase currents and back-EMF should be in phase for maximum torque. Therefore, both have the same electrical angle. The instantaneous power of each phase can be written as following in (3).

$$\begin{aligned}
P_a(\theta) &= E \cdot I_m \cdot sin(\theta) \cdot sin(\theta) \\
P_b(\theta) &= E \cdot I_m \cdot sin(\theta - {}^{2\pi}/_{6}) \cdot sin(\theta - {}^{2\pi}/_{6}) \\
P_c(\theta) &= E \cdot I_m \cdot sin(\theta - {}^{4\pi}/_{6}) \cdot sin(\theta - {}^{4\pi}/_{6}) \\
P_d(\theta) &= E \cdot I_m \cdot sin(\theta - {}^{6\pi}/_{6}) \cdot sin(\theta - {}^{6\pi}/_{6}) \\
P_e(\theta) &= E \cdot I_m \cdot sin(\theta - {}^{8\pi}/_{6}) \cdot sin(\theta - {}^{8\pi}/_{6}) \\
P_f(\theta) &= E \cdot I_m \cdot sin(\theta - {}^{10\pi}/_{6}) \cdot sin(\theta - {}^{10\pi}/_{6})
\end{aligned} \tag{3}$$

The sum of the instantaneous powers can be expressed as follow in (4)

$$\begin{aligned}
P(\theta) &= P_a(\theta) + P_b(\theta) + P_c(\theta) + P_d(\theta) \\
&\quad + P_e(\theta) + P_f(\theta) \\
P(\theta) &= 3 \cdot I_m \cdot E
\end{aligned} \tag{4}$$

The torque of a sinusoidal back-EMF symmetric six-phase machine is as below in (5).

$$T(\theta) = \frac{P(\theta)}{w_r} = \frac{3}{w_r} \cdot I_m \cdot E \tag{5}$$

## 3. CONVENTIONAL DRIVING APPROACH FOR A SIX-PHASE MACHINE

In the literature, some academics drive a six-phase machine as expressed in the previous section (2). An illustration of the winding layout of a six-phase machine can be seen in Figure 1.

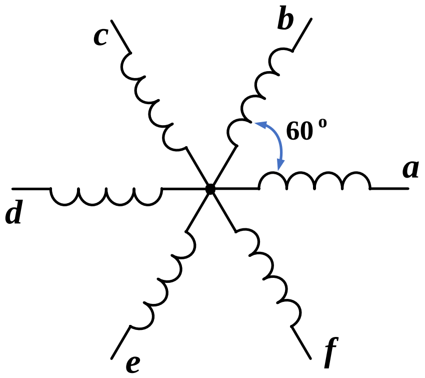



**Figure 1**. Stator winding configuration of a six-phase machine

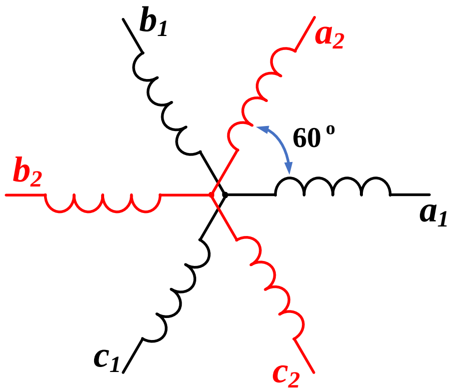



**Figure 2**. Stator winding configuration of a symmetric dual three-phase machine

However, the most common driving method among academics is separating the six-phase machine into two parts as a dual three-phase winding configuration. It is called a symmetric six-phase machine if there is 60º electrical angle between two independent three-phase machines. A symmetric double three-phase machine can be illustrated in Figure 2.

The instantaneous power of this configuration can be divided into two parts. One comes from the first three-phase machine, and the other one is due from the second three-phase machine. Phase currents for the first three-phase machine can be written as follow in (6), and the phase currents for the second three-phase machine are as in (7).

$$i_{a1}(\theta) = I_m \cdot sin(\theta) \tag{6}$$

$$i_{b1}(\theta) = I_m \cdot sin\left(\theta - {}^{2\pi}/_{3}\right)$$
$$i_{c1}(\theta) = I_m \cdot sin\left(\theta - {}^{4\pi}/_{3}\right)$$

$$\begin{aligned} i_{a2}(\theta) &= I_m \cdot sin\left(\theta - {}^{2\pi}/_{6}\right) \\ i_{b2}(\theta) &= I_m \cdot sin(\theta - \pi) \\ i_{c2}(\theta) &= I_m \cdot sin\left(\theta - {}^{10\pi}/_{6}\right) \end{aligned} \tag{7}$$

The displacement of the back-EMF waveform for a symmetric dual six-phase machine is the same as that of non-separated six-phase machines. Therefore, the instantaneous power of each phase belonging to two sinusoidal three-phase machines can be written as follow in (8) and (9).

$$\begin{aligned} P_{a1}(\theta) &= i_{a1}(\theta) \cdot e_a(\theta) \\ P_{b1}(\theta) &= i_{b1}(\theta) \cdot e_c(\theta) \\ P_{c1}(\theta) &= i_{c1}(\theta) \cdot e_e(\theta) \end{aligned} \tag{8}$$

$$\begin{aligned} P_{a2}(\theta) &= i_{a2}(\theta) \cdot e_b(\theta) \\ P_{b2}(\theta) &= i_{b2}(\theta) \cdot e_d(\theta) \\ P_{c2}(\theta) &= i_{c2}(\theta) \cdot e_f(\theta) \end{aligned} \tag{9}$$

The resultant instantaneous power for each sinusoidal three-phase machine can be expressed in (10) and (11). These expressed powers do not include pulsating parts for each machine. That means these machines can be driven independently.

$$\begin{aligned} P_1(\theta) &= P_{a1}(\theta) + P_{b1}(\theta) + P_{c1}(\theta) \\ &= \frac{3}{2w_r} \cdot I_m \cdot E \end{aligned} \tag{10}$$

$$\begin{aligned} P_2(\theta) &= P_{a2}(\theta) + P_{b2}(\theta) + P_{c2}(\theta) \\ &= \frac{3}{2w_r} \cdot I_m \cdot E \end{aligned} \tag{11}$$

The total instantaneous power of a symmetric dual three-phase machine is as follows in (12).

$$P(\theta) = P_1(\theta) + P_2(\theta) = \frac{3}{w_r} \cdot I_m \cdot E \tag{12}$$

If these two three-phase machines are displaced by 30º in space, this machine is called an asymmetric six-phase machine. A demonstration of an asymmetric dual three-phase machine is in Figure 3.

If these two three-phase machines are displaced by 30º in space, this machine is called an asymmetric six-phase machine. A demonstration of an asymmetric dual three-phase machine is in Figure 3.

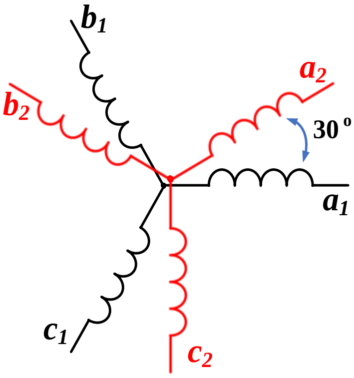



**Figure 3.** Stator winding configuration of an asymmetric dual three-phase machine

As in the previous configuration, the instantaneous power of an asymmetric three-phase machine can also be thought of as two independent machines. Therefore, phase currents for these two machines can be written as (13) and (14).

$$\begin{aligned} i_{a1}(\theta) &= I_m \cdot sin(\theta) \\ i_{b1}(\theta) &= I_m \cdot sin(\theta - {}^{2\pi}/_{3}) \\ i_{c1}(\theta) &= I_m \cdot sin(\theta - {}^{4\pi}/_{3}) \end{aligned} \tag{13}$$

$$\begin{aligned} i_{a2}(\theta) &= I_m \cdot sin(\theta - {}^{\pi}/_{6}) \\ i_{b2}(\theta) &= I_m \cdot sin(\theta - {}^{5\pi}/_{6}) \\ i_{c2}(\theta) &= I_m \cdot sin(\theta - {}^{9\pi}/_{6}) \end{aligned} \tag{14}$$

The back-EMF waveform for an asymmetric dual three-phase machine can be expressed as below in (15) and (16).

$$\begin{aligned} e_{a1}(\theta) &= E \cdot sin(\theta) \\ e_{b1}(\theta) &= E \cdot sin(\theta - {}^{2\pi}/_{3}) \\ e_{c1}(\theta) &= E \cdot sin(\theta - {}^{4\pi}/_{3}) \end{aligned} \tag{15}$$

$$\begin{aligned} e_{a2}(\theta) &= E \cdot sin(\theta - {}^{\pi}/_{6}) \\ e_{b2}(\theta) &= E \cdot sin(\theta - {}^{5\pi}/_{6}) \\ e_{c2}(\theta) &= E \cdot sin(\theta - {}^{9\pi}/_{6}) \end{aligned} \tag{16}$$

The instantaneous power of each phase belongs to these two sinusoidal three-phase machines can be written as follow (17) and (18).

$$\begin{aligned} P_{a1}(\theta) &= i_{a1}(\theta) \cdot e_{a1}(\theta) \\ P_{b1}(\theta) &= i_{b1}(\theta) \cdot e_{b1}(\theta) \\ P_{c1}(\theta) &= i_{c1}(\theta) \cdot e_{c1}(\theta) \end{aligned} \tag{17}$$

$$\begin{aligned} P_{a2}(\theta) &= i_{a2}(\theta) \cdot e_{a2}(\theta) \\ P_{b2}(\theta) &= i_{b2}(\theta) \cdot e_{b2}(\theta) \\ P_{c2}(\theta) &= i_{c2}(\theta) \cdot e_{c2}(\theta) \end{aligned} \tag{18}$$

The resultant instantaneous power for each sinusoidal three-phase machine can be written as in (19) and (20). There are no pulsating terms in the resultant power for each independent three-phase machine as in the symmetric machine.

$$\begin{aligned} P_1(\theta) &= P_{a1}(\theta) + P_{b1}(\theta) + P_{c1}(\theta) \\ &= \frac{3}{2w_r} \cdot I_m \cdot E \end{aligned} \tag{19}$$

$$\begin{aligned} P_2(\theta) &= P_{a2}(\theta) + P_{b2}(\theta) + P_{c2}(\theta) \\ &= \frac{3}{2w_r} \cdot I_m \cdot E \end{aligned} \tag{20}$$

The total instantaneous power of an asymmetric dual three-phase machine is as follow in (21).

$$P(\theta) = P_1(\theta) + P_2(\theta) = \frac{3}{w_r} \cdot I_m \cdot E \tag{21}$$

Above equation (21) belongs to the fundamental current component. If the back-EMF of an asymmetric dual three-phase machine includes the third harmonic component, it is possible to increase torque by injecting the third harmonic component[25]. However, injecting the third harmonic current for a symmetric six-phase machine will produce pulsating parts in the resultant power. This will cause ripple in the torque.

## 4. A NOVEL DRIVING APPROACH FOR A SIX-PHASE MACHINE

This section introduces a novel driving method for a sinusoidal six-phase machine. This machine can be split with a new perspective as seen Figure 4. The first machine will be the first consecutive three phases of a sinusoidal six-phase machine, and the second machine will be the second consecutive three phases.Current waveforms for each three-phase machine can be expressed in (22) and (23).

$$\begin{aligned} i_{a1}(\theta) &= I_m \cdot sin(\theta) \\ i_{b1}(\theta) &= I_m \cdot sin(\theta - {}^{2\pi}/_{6}) \\ i_{c1}(\theta) &= I_m \cdot sin(\theta - {}^{4\pi}/_{6}) \end{aligned} \tag{22}$$

$$i_{a2}(\theta) = I_m \cdot sin(\theta - {}^{6\pi}/_{6}) \tag{23}$$

$$i_{b2}(\theta) = I_m \cdot sin(\theta - {}^{8\pi}/_6)$$
$$i_{c2}(\theta) = I_m \cdot sin(\theta - {}^{10\pi}/_6)$$

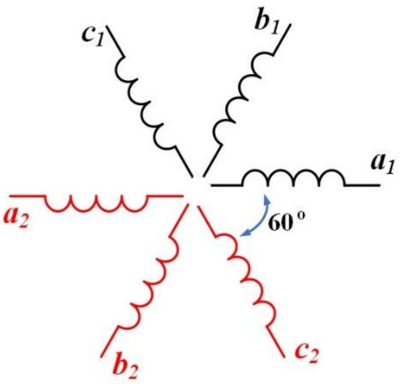



**Figure 4.** Stator winding configuration of a symmetric dual three-phase machine with new perspective

Their back-EMF waveforms will be the same as a symmetric machine's waveforms. Therefore, the instantaneous power of each machine will be as below in (24) and (25).

$$\begin{aligned} e_{a1}(\theta) &= E \cdot sin(\theta) \\ e_{b1}(\theta) &= E \cdot sin(\theta - {}^{2\pi}/_6) \\ e_{c1}(\theta) &= E \cdot sin\left(\theta - {}^{4\pi}/_6\right) \end{aligned} \tag{24}$$

$$\begin{aligned} e_{a2}(\theta) &= E \cdot sin(\theta - {}^{6\pi}/_6) \\ e_{b2}(\theta) &= E \cdot sin(\theta - {}^{8\pi}/_6) \\ e_{c2}(\theta) &= E \cdot sin(\theta - {}^{10\pi}/_6) \end{aligned} \tag{25}$$

The instantaneous power of each phase belonging to separated parts of the machine can be written as follow in (26) and (27).

$$\begin{aligned} P_{a1}(\theta) &= i_{a1}(\theta) \cdot e_{a1}(\theta) \\ P_{b1}(\theta) &= i_{b1}(\theta) \cdot e_{b1}(\theta) \\ P_{c1}(\theta) &= i_{c1}(\theta) \cdot e_{c1}(\theta) \end{aligned} \tag{26}$$

$$\begin{aligned} P_{a2}(\theta) &= i_{a2}(\theta) \cdot e_{a2}(\theta) \\ P_{b2}(\theta) &= i_{b2}(\theta) \cdot e_{b2}(\theta) \\ P_{c2}(\theta) &= i_{c2}(\theta) \cdot e_{c2}(\theta) \end{aligned} \tag{27}$$

The resultant instantaneous power for each separated part of the machine is below in (28) and (29). These results also do not include pulsating parts.

$$\begin{aligned} P_1(\theta) &= P_{a1}(\theta) + P_{b1}(\theta) + P_{c1}(\theta) \\ &= \frac{3}{2w_r} \cdot I_m \cdot E \end{aligned} \tag{28}$$

$$\begin{aligned} P_2(\theta) &= P_{a2}(\theta) + P_{b2}(\theta) + P_{c2}(\theta) \\ &= \frac{3}{2w_r} \cdot I_m \cdot E \end{aligned} \tag{29}$$

The total instantaneous power can be seen as follow in (30).

$$P(\theta) = P_1(\theta) + P_2(\theta) = \frac{3}{w_r} \cdot I_m \cdot E \tag{30}$$

As mentioned in previous sections, the resultant instantaneous power for each three-phase machine is constant for a dual three-phase machine. The sum of the instantaneous power of consecutive three phases is also constant. As a result, the machine can be split into two parts using these successive three phases.

## 5. DRIVING A SINUSOIDAL SYMMETRIC SIX-PHASE MACHINE BY THREE-PHASE BALANCED CURRENTS

So far, a symmetric six-phase machine has been discussed using six-phase balanced currents. However, this machine can be run using three-phase balanced currents [20], [26]. The neutral point of the second three-phase machine for a dual three-phase machine can be changed as seen in Figure 5.

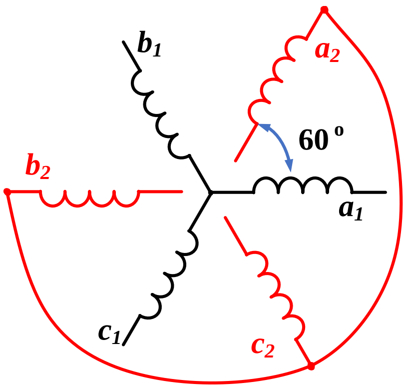



**Figure 1.** New neutral point for a symmetric dual three-phase machine

Current waveforms to run the dual three-phase machine by three-phase balanced currents should be as below in (31). Changing the neutral point as in Figure 5 allows us to reverse the current direction.

$$\begin{aligned} i_{a1}(\theta) &= -i_{b2}(\theta) = I_m \cdot sin(\theta) \\ i_{b1}(\theta) &= -i_{c2}(\theta) = I_m \cdot sin(\theta - {}^{2\pi}/_3) \\ i_{c1}(\theta) &= -i_{a2}(\theta) = I_m \cdot sin\left(\theta - {}^{4\pi}/_3\right) \end{aligned} \tag{31}$$

The resultant instantaneous power is constant, so torque production will be constant for the above arrangement. Three-phase balanced currents also can be applied to the proposed driving technique in Section 4. The new neutral connection should be arranged as seen below in Figure 6.

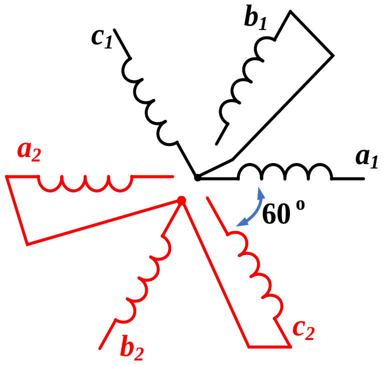



**Figure 6.** New neutral point for proposed symmetric dual three-phase machine

Thanks to the above arrangement, the proposed machine configuration can also be driven by three-phase balanced currents, and these currents can be written as below in (32).

$$\begin{gathered} i_{a1}(\theta) = -i_{a2}(\theta) = I_m \cdot sin(\theta) \\ -i_{b1}(\theta) = i_{b2}(\theta) = I_m \cdot sin(\theta - {}^{4\pi}/_{3}) \\ i_{c1}(\theta) = -i_{c2}(\theta) = I_m \cdot sin\left(\theta - {}^{2\pi}/_{3}\right) \end{gathered} \tag{32}$$

## 6. FEA SIMULATION RESULTS

### *A) Designing the Six-phase Machine Using Star of Slots Method to Simulate in an FEA Software*

In this section of this study is going to be examined the design of 12 slots 10 poles a symmetric six-phase fractional slot machine. The star of slots method is a great method to design a fractional slot machine. The star of slots of a machine consists of its phasors. The number of phasors corresponds to the number of slots, and each phasor is assigned a number corresponding to the respective slot number. For instance, phasor number 1 aligns with slot number 1, and so forth. A specific winding arrangement for an m-phase machine is considered viable when a particular condition is met in (33).

$$\frac{Q}{mt} = integer\ number \tag{33}$$

$Q$ is the slot number of the machine, and $t$ is the greatest common divisior (GCD) between pole pairs ($p$) and slot numbers ($Q$):

$$t = GCD(Q, p) \tag{34}$$

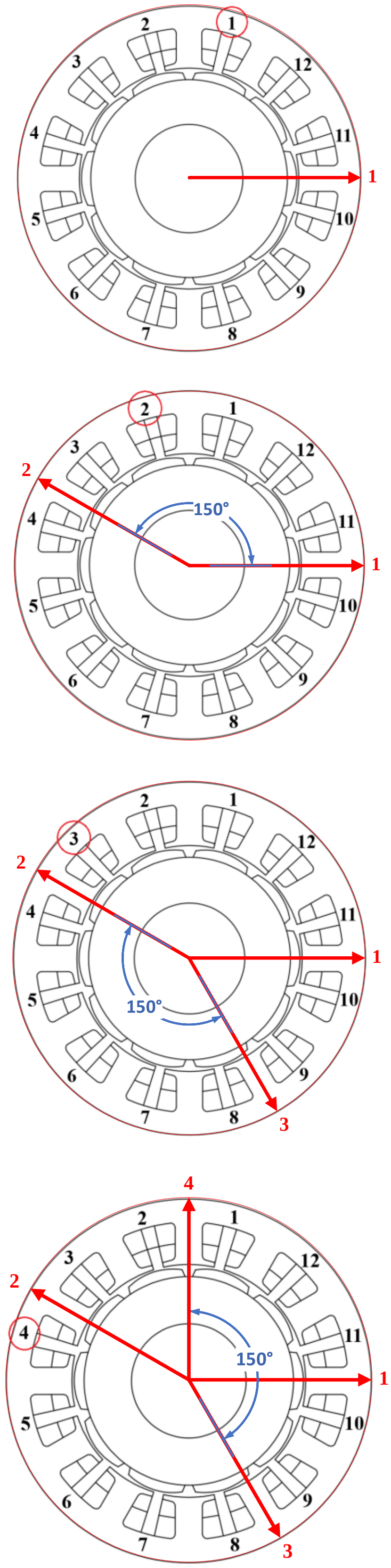



**Figure 2.** Arranging the star of slots for the 12 slots/10 poles six-phase machine

**Table 1:** Winding distribution of 12 slots / 10 poles symmetric six-phase machine.

| Phase A | | Phase B | | Phase C | | Phase D | | Phase E | | Phase E | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *in* | *out* | *in* | *out* | *in* | *out* | *in* | *out* | *in* | *out* | *in* | *out* |
| 1 | 2 | 11 | 12 | 9 | 10 | 7 | 8 | 5 | 6 | 3 | 4 |
| 6 | 7 | 4 | 5 | 2 | 3 | 12 | 1 | 10 | 11 | 8 | 9 |
| 6 | 7 | 4 | 5 | 2 | 3 | 12 | 1 | 10 | 11 | 8 | 9 |
| 11 | 12 | 9 | 10 | 7 | 8 | 5 | 6 | 3 | 4 | 1 | 2 |

The arrangement of slots forms a star with $Q/t$ spokes, and each spoke accommodates $t$ phasors. The electrical angle separating the phasors of two consecutive slots is denoted as $\alpha_s^e = p\alpha_{ph}$, where $\alpha_{ph}$ represents the slot angle in mechanical radians, specifically $\alpha_{ph} = 360/Q$. The angular separation between two spokes yields:

$$\alpha_{ph} = \frac{360}{(Q/t)} = \frac{\alpha_s^e}{p} t \tag{35}$$

The star of first slot is assumed as a reference slot. The second star due to second slot placed $\alpha_s^e = p\alpha_{ph} = 5 \cdot 30 = 150°$ as seen Figure 3, the third star that is coming from slot number 3 placed 150° forward of the second star, and fourth star is replaced by 150° according to the third star as seen in Figure 3. The completed phasors can be seen in Figure 3.

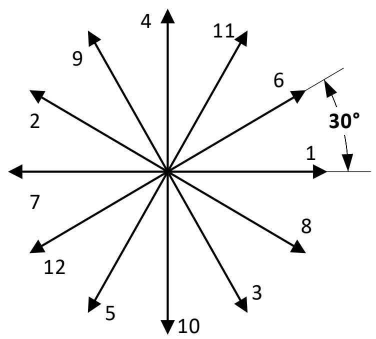



**Figure 3.** Star of slots for the 12 slots/10 poles six-phase machine.

According to star of slots in Figure 3, these stars separated in to six equal sectors as seen in Figure 4. Each sector corresponds to a phase winding distribution. For instance, the first coil of phase A goes in slot number 1 and goes out slot number 2, the second coil of phase A goes in slot number 6 and goes out slot number 7 in the pink sector. This is a two-layer winding layout. To obtain purely sinusoidal back-emf waveform, the number of coils can be increased. Rotating the coloured phasor circle 30° direction of counterclockwise gives additional coils for each phase. For example, the first additional coil goes in 6 and goes out slot number 7, the second additional coil goes in number 11 and goes out slot number 12 for the phase A. The winding layout of the machine is given in Table 1. Determining the winding layout, a six-phase machine has been designed in an FEA software as seen below in Figure 5.

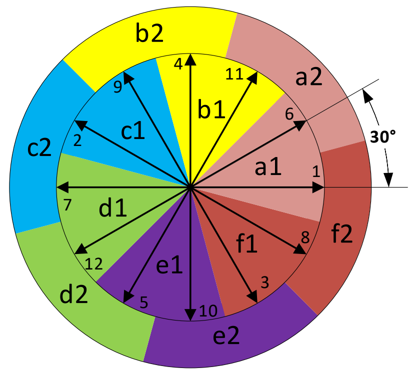



**Figure 4.** Multi-layer winding layout of symmetric six-phase machine

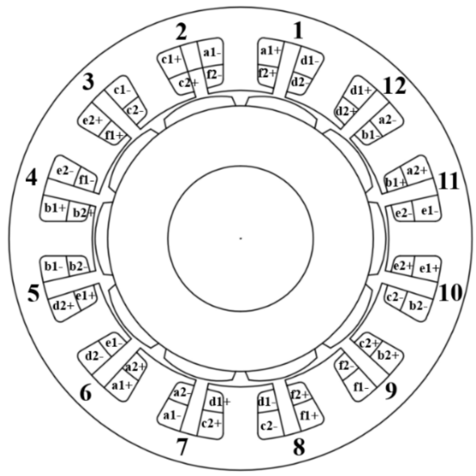



**Figure 5.** Multi-layer winding layout of symmetric six-phase machine in an FEA software

***B) Simulation in an FEA Software***

FEA software tools are mostly used tools in the literature [27 - 29] for validation of theories. In this study, MagNet FEA software tool , which is product of Siemens, has been used to validate the proposed theories that have been discussed so far. A six-phase machine has been designed as in Figure 10 using the multi-layer star of slots method [30] to undertake FEA experiments. Parameters of the machine can be seen below Table 2. Additional to multi-layer winding method, magnets of the machine have been shaped to obtain a smooth sinusoidal back-EMF, as seen in Figure 10.

**Table 2.** Design parameters of the six-phase machine

| **Specifications of designed machine** | | | |
|---|---|---|---|
| Rated Torque (Nm) | 132 Nm | Core Material | M400-50 |
| Rated Speed (rpm) | 1200 | Magnet Material | NdFeB:28/23 |
| Supply Voltage (V) | 300 | Outer diameter | 200 mm |
| Rated Current (A) | 12 | Depth | 150 mm |
| Winding Method | Multi-layer Concentrated | Inner diameter | 110 mm |
| Number of phases | 6 | Turns per phase | 75 turns |
| Poles/slots | 10/12 | Magnet Thickness | 5 mm |

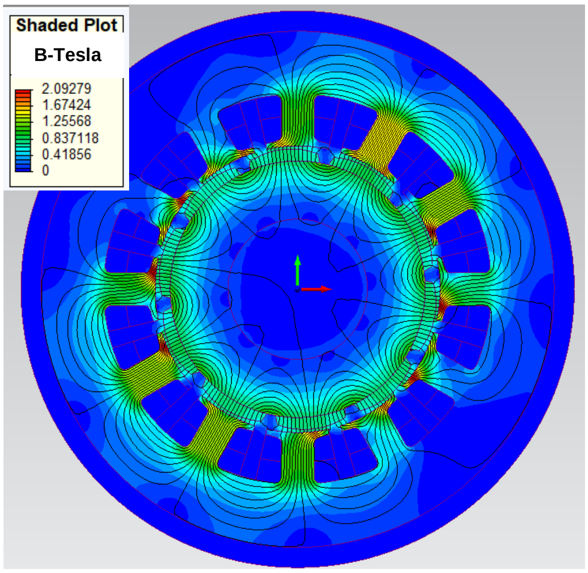



**Figure 6.** Flux distribution of designed machine in MagNet

The back-EMF waveform of the designed machine is shown in Figure 12. It has a sinusoidal waveform as it should be. However, back-EMF of the machine still including harmonics. The harmonic components of back-EMF of the machine up to 7th are; 0,69% 2nd, 5.05% 3rd, 0.35% 4th, 0.42% 5th, 0.21% 6th and 0.28% 7th in the back-EMF.

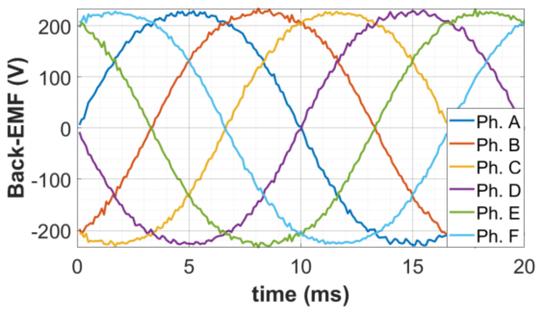



**Figure 7.** Back-EMF FEA waveform result of the designed symmetric six-phase machine

The other important parameter for a permanent magnet machine is cogging torque[29], [31].For the designed machine, the cogging torque can be seen in Figure 13. Magnet angle and slot-pole combination have been chosen to keep the cogging torque low.

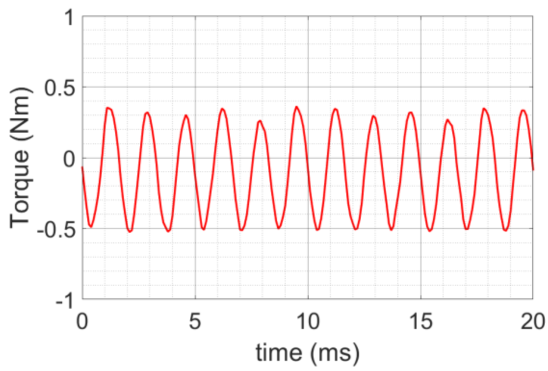
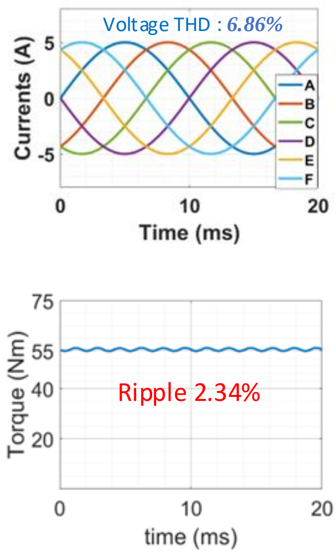
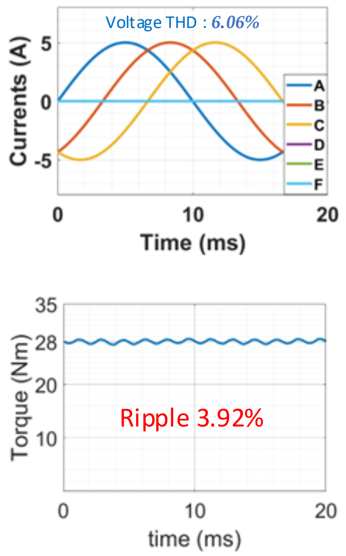



**Figure 13.** The cogging torque of the designed symmetric six-phase machine

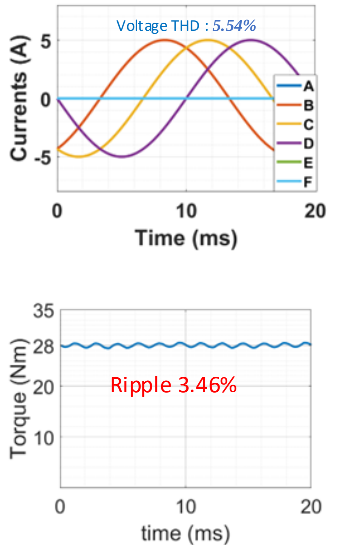
Seven experiments have been done to confirm the theories. The rotor speed has been chosen is 600 rpm for the FEA simulations, so the electrical frequency is 50 Hz. The amplitude of the sine wave currents is 5 Amps for all experiments. The first experiment is to observe the torque of the designed machine when the machine excited with the balanced six-phase currents. This torque result has been used as a reference for other experiments. The balanced six-phase currents and the torque of this experiment can be seen Figure 8 (a). The Figure 8 (b,c, d, e) belongs to when the adjacent three phases of the six-phase machine are excited. These experiments' torque results validate the theory mentioned in previous sections. As seen in these figures, the machine's torque is half of the torque in Figure 8 (a) as expected. Additional to these experiments, two more experiments have been undertaken as well. One of the experiments is to run the six-phase machine with three-phase balanced currents as shown in, its FEA torque result and current waveforms in Figure 8 (f). The last FEA experiment is to observe the torque when the conventional excitation method, mentioned in section 3, is used. Only the torque of one of the double three-phase machines has been observed. The machine's current waveforms and torque result can be seen below in Figure 8 (g). When the torque ripple of the machine compared to obtained results for the all conditions, better result has been observed when all the phases of the six-phase machine excited with the value of 2.34% as expected in Figure 8 (a) and (f). For the three phase excitation conditions torque ripple is around 3.50% except the condition which phases A, B



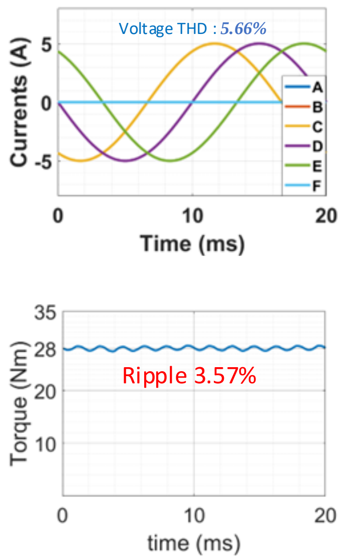

(a) Currents and torque when balanced six-phase are excited.



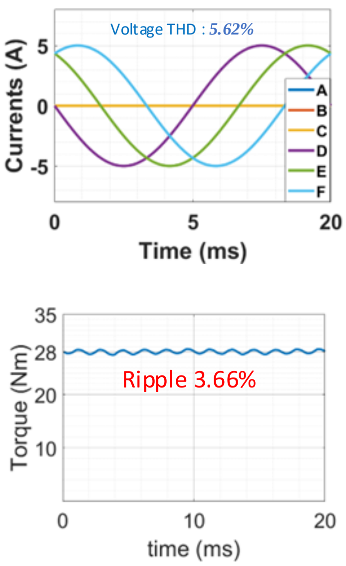

(b) Currents and torque when phases A, B and C are excited (proposed method).



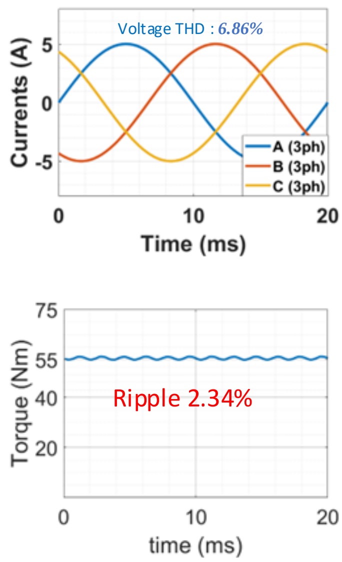

(c) Currents and torque when phases B, C and D are excited (proposed method).



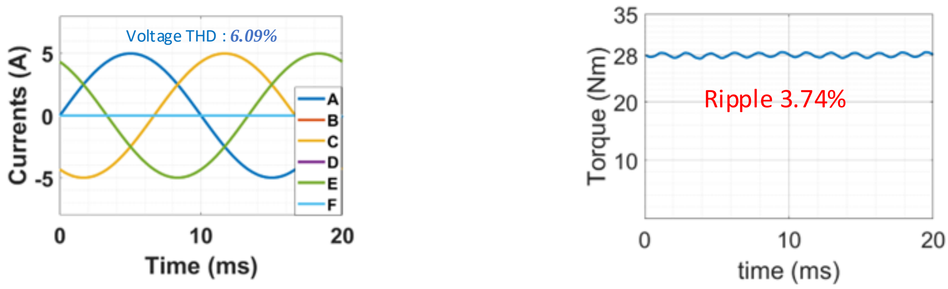

(d) Currents and torque when phases C, D and E are excited (proposed method).




(e) Currents and torque when phases D, E and F are excited (proposed method).




(f) Currents and torque when three-phase balanced currents fed to all-phases for the proposed method as in figure (6).




(g) Currents and torque when phases A, C and E are excited (conventional method).

**Figure 8.** FEA analysis torque results

and C are excited. When the phases A, B and C are fed, the torque ripple of the machine is 3.92%. At this condition, the interaction between the fundamental current and the lower harmonics of the back-EMF is a bit higher compared to the other consecutive three phase connected conditions.

If the THD value of the current and voltages are examined, the THD value of the current is 0% since the simulation has been done with a current source. Current source that is supplied to each phase has pure sinusoidal waveform, so it has no harmonics. However, voltage value of the phases has a THD value, and the THD value of the voltages is given in the Figure 8 and these values have been calculated up to 13th harmonic, including both even and odd harmonics.

## 7. CONCLUSION

A new double three-phase configuration for a symmetric six-phase machine has been introduced. A symmetric 12 slots / 10 poles six-phase machine has been designed in FEA software to validate the study. Winding layout of the machine has been arranged by using star of slots method. To obtain better sinusoidal back-EMF, multi-layer winding technique has been chosen. In the conventional method, coils of the three-phase machine in a symmetric six-phase machine is placed as 120o apart from each other. However, for the proposed double three-phase machine, coils of the three-phase machine are placed as 60o apart from each other. FEA analysis of proposed and existing methods has been done. FEA results validate the introduced theory. This new arrangement has some advantages compared to the conventional double three-phase machine. For example, the conventional method will not allow the user to run the machine without using fault-tolerant techniques in case of open-circuit conditions of adjacent two phases. The torque will have higher ripple if the machine runs without fault-tolerant control methods.

Nevertheless, the proposed configuration will let running the machine without higher torque ripples under these conditions. Torque ripple of a symmetric six-phase machine when all phases are excited is 2.34%. Torque ripple is around 3.50% when consecutive three phase are excited. That means, there will be no higher torque ripple while running the machine under open phase fault-condition. As it is known, torque will be half for a given amplitude of balanced currents compared to the healthy condition, since only the one of the three-phase machines will be active under a fault condition. THD values of voltages varies from 5.54% to 6.86% for the experiments. Additionally, the symmetric six-phase machine has been driven by three-phase balanced currents.

## DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in their studies do not require ethics committee approval and/or legal-specifial permission.

## AUTHORS' CONTRIBUTIONS

**Ali AKAY:** Performed the experiments and analyse the results. Wrote the manuscript.

## CONFLICT OF INTEREST

There is no conflict of interest in this study.

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