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A novel initial rotor position alignment method for permanent magnet synchronous motor using incremental encoder

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Abstract: This paper presents a new method for the alignment of the rotor of permanent magnet synchronous motors with the phase axis of the stator during start-up. Once the rotor alignment is achieved, the real rotor position angle can be measured by using an incremental encoder and this value can be used in the field oriented control of the motor. Typically, a current is forced into the q-axis. In the proposed method a current is formed in the d-axis instead. Rotor alignment with the phase axis is achieved without any sudden motion by using a PI controller in the current loop. Preventive measures for exceptional situations that may occur during the application of this method are also discussed. Experimental results show that the performance of the proposed method is very satisfactory.

Key words: Permanent magnet synchronous motors, initial rotor position, incremental encoder

1. Introduction

Electric motors are used in many applications today. Although direct current motors and induction motors are the most widely used types of electric motors, the use of permanent magnet synchronous motors (PMSMs) is increasing day by day due to their high energy density [1].

The torque of PMSMs is a result of the interaction force between the rotor flux and the stator flux. Rotor flux is constant because it is created by permanent magnets placed on the rotor. For this reason, the torque developed by the PMSM is controlled by stator flux, which depends on the magnitude and position of the stator current. Depending on the initial rotor position, different situations may arise. If the angle (δ) between the stator flux and the rotor flux is near zero, the generated torque may be very small. In this case, the motor may not rotate. When the angle is negative, the developed torque will be negative, causing rotation in the reverse direction. Therefore, the position of the rotor must be known so that the PMSMs can be controlled.

The easiest way to know the rotor position is to use a position sensor. However, it increases the complexity and cost. Therefore, several techniques have been proposed by researchers to calculate the initial rotor position without using any sensor. Applying a high frequency signal to motor phases [2–6], saturating the stator magnetic core [7–11], and utilizing the inductance variation according to the rotor position are some of the techniques proposed in the literature [12–14]. Although sensorless control methods are advantageous in many respects such as cost, weight, volume, and design complexity [2], the position sensor must still be used to provide high-resolution positional accuracy if the application requires positional control.

Incremental encoders [15], absolute encoders, and resolvers can be used to sense the position of PMSMs.

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Although the initial position of the rotor can be known when absolute encoders or resolvers are used, both the costs and the dimensions of these sensors are high. Therefore, incremental encoders are preferred in many applications. However, when incremental encoders are used the initial position of the rotor cannot be known since they measure only the change in position. They define the initial position as zero and therefore there is a need to determine the initial position of the rotor or to bring it to a known position. There are various methods used for this purpose in practice. The most common methods are the application of voltages to stator windings sequentially for one full-turn rotation of the rotor [16] and application of the voltages only to stator phase-B and phase-A sequentially [17]. These methods are detailed in Section 2.

A new control algorithm to bring the rotor to a known initial position is described in the paper. In this proposed method, movement of the rotor is kept under control and there is no need to use a separate controller structure just for the alignment. It utilizes the speed controller of the field oriented control (FOC) algorithm during the alignment process.

The remainder of this paper is structured as follows: in Section 2, alignment methods already presented in the literature are summarized and the proposed method is explained. In Section 3, experimental results are given. In Section 4, the results are discussed.

2. Alignment methods

FOC can be applied with sensorless control methods if position control is not required. On the other hand, the rotor position must be known to generate the required torque in the FOC method. Incremental encoders are usually preferred in position control applications due to their low cost and simple structure. However, they do not provide the initial rotor position information directly [16]. The position value of the incremental encoder at start-up is explained in Figure 1. In this figure e_a is the phase-A voltage, i_a is the phase-A current, θ_r is the real rotor position, θ_{ie} is the incremental encoder position, and θ_{diff} is the position error, which is the difference between real rotor position and encoder position. The zero position of rotor is aligned with the phase-A winding position of the stator. Incremental encoders assume the initial position as zero and define the rotor position with respect to this starting position. If the starting position is different, the position error will change. Therefore, when an incremental encoder is used, either the position error must be known and added to the value given by the incremental encoder, or the rotor must be brought to zero position (phase-A position of the stator) before starting the incremental encoder.

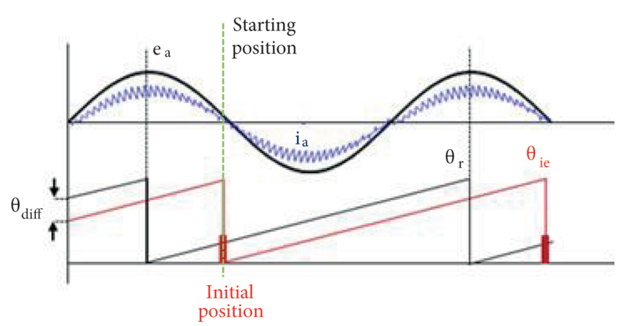

Figure 1. The position information obtained from the incremental encoder [16].

In applications using incremental encoders, there are various methods used to align the rotor with phase-A of the stator. The most common methods are summarized in the following subsection.

2.1. Commonly used alignment methods in applications with incremental angle encoder

There are methods that vary according to the voltage applied to the stator during the alignment with the rotor phase. Stator flux must be in the same direction as that of the magnetic axis of phase-A to align the rotor with the stator phase-A. This can be achieved if the $V_1 = \{1, 0, 0\}$ voltage vector shown in Figure 2 is applied to the stator windings.

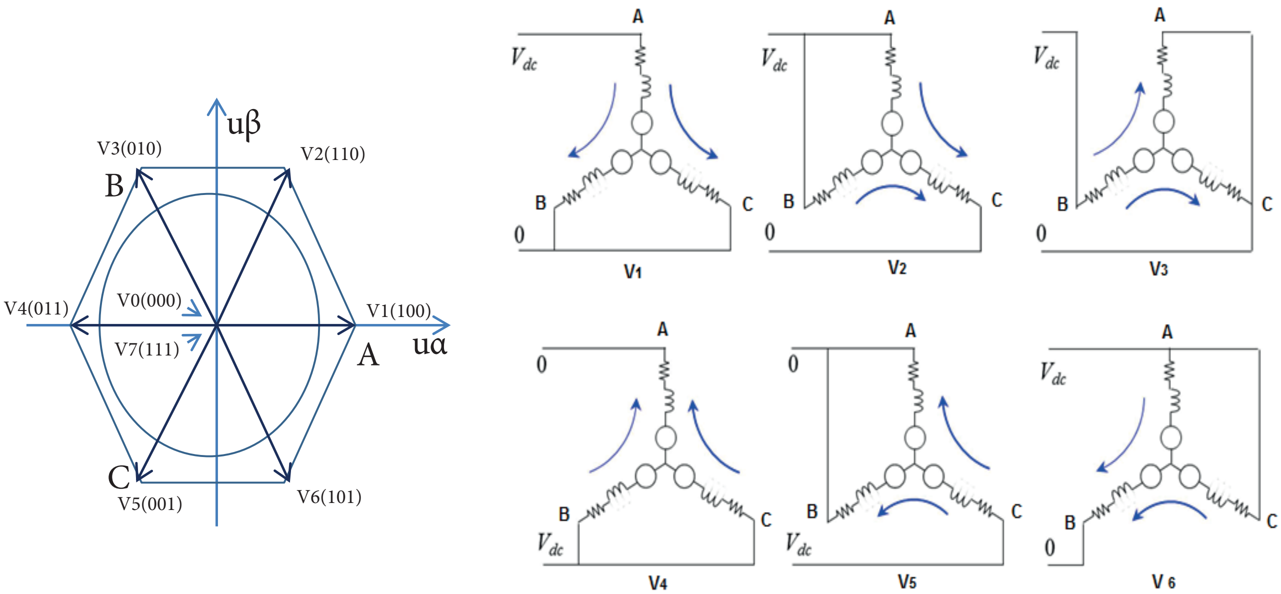

Figure 2. Applied voltage vectors.

Although this method is satisfactory in most cases, it may not work in certain situations. If the initial rotor position is very close to the stator phase-A when the V_1 vector is applied to the stator, the resulting torque may be too low to rotate the rotor. In this case, there is a difference between the actual rotor position and the measured position by the incremental encoder. This difference will reduce the torque during the motor control, but because the reduction is small, it may not be important. However, if the rotor initially is in the opposite direction of the phase-A axis (negative A), the applied vector V_1 will not be able to rotate the rotor, but this time the difference between the measured and actual position values will be 180°, causing the motor control to fail. There are various methods proposed in the literature to solve this problem. Applying the six vectors shown in Figure 2 subsequently to rotate the rotor one full turn [16] and applying $V_3 = \{0, 1, 0\}$ and $V_1 = \{1, 0, 0\}$ methods [17] can be listed as the most common methods for alignment. In the former method, the rotor starts to rotate with the first vector applied in a different direction from the starting position and stands in the last phase. In the latter method, first the V_3 vector is applied to bring the rotor to phase-B, and then vector V_1 is applied to align with phase-A. If the rotor initially is in phase-B or negative B it may not rotate with the first applied vector, but it rotates and aligns with phase-A when the second vector, V_1, is applied. This method can be improved by applying the V_2 vector between vectors V_3 and V_1 to better control the process.

The amplitude and duration of the vector to be applied to bring the rotor to a desired position are important. If the vector amplitude is not large enough, the rotor may not rotate, or if it is too large, the rotor may rotate suddenly and uncontrollably. Depending on the inertia of the rotating system, sudden movements can damage the system or cause oscillations. For this reason, the magnitude of the voltage vector to be applied must be calculated depending on the parameters of the motor and the load. However, it is not always possible to determine an optimum voltage because the torque to rotate the rotor may also vary depending on external factors such as temperature, friction, etc. In order for the alignment to be completed properly, the application of the relevant vector must be continued for the time required for the rotor to reach the phase, or to stop the oscillations of the rotor when it aligns with the phase. For these reasons, it is important to control the vector to be applied during the alignment process.

There are other less common methods to determine the starting position of the rotor, too. For example, a method based on the relative position information read from the incremental encoder was presented in [18]. In this method, a constant I_q reference value in the standard FOC algorithm is applied and the change in the resulting angle θ is measured. A second value of θ is determined by repeating this method with another I_q reference. The initial position of the rotor can then be calculated by proportioning the two angle values and the two applied I_q references. When the motor has low friction and low inertia, the required I_q is low, causing an increase in position calculation error.

2.2. Proposed method

The problem with the most commonly used method to align the rotor with phase-A is that when the voltage is applied the rotor may move in an uncontrolled manner. For this reason, applying a controlled voltage is proposed in this paper. Adding a new controller complicates the processor software. Therefore, one of the controllers used in the classical FOC algorithm is used to control the voltage for alignment. Figure 3 shows the abc, $\alpha\beta$, and dq axis frames and the relative positions of the stator current and the rotor. If the rotor angle θ is 0°, the d-axis is aligned with the motor phase-A, as shown in Figure 3. In the proposed method the θ angle is always assumed to be 0°. In this case, applying a voltage to the d-axis is the same as applying voltage to phase-A of the motor. In the proposed method, the magnitude of the voltage applied to the d-axis is determined by the speed controller used in the FOC algorithm. The speed controller ensures that the rotor stays under control throughout the alignment process.

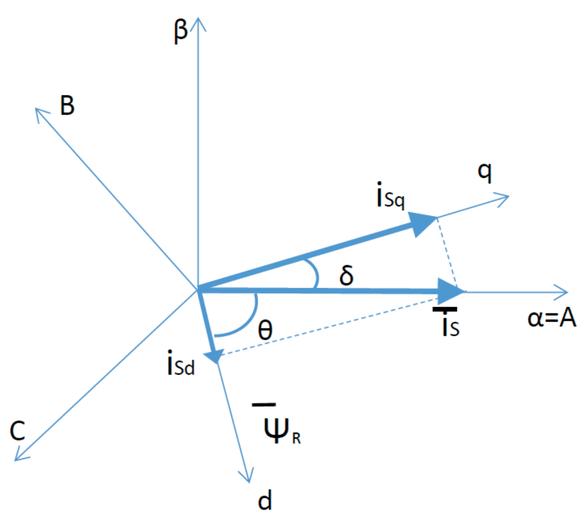

Figure 3. The axis locations.

The FOC algorithm needs to be modified for the proposed control. The proposed modification is depicted in Figure 4. The modifications have been marked in Figure 4. First of all, the rotor angle θ is assumed to be $0°$ for the d-axis to align with phase-A. Unlike the constant torque angle algorithm, the output of the speed controller generates the I_d reference instead of the I_q reference. The I_q reference is set to 0. The speed reference given here is determined by the characteristics of the motor. The magnitude of this speed reference affects the length of the alignment process. A high speed reference may shorten the alignment process, but it may cause the rotor to move suddenly. Therefore, an appropriate speed reference value must be selected according to the system specifications.

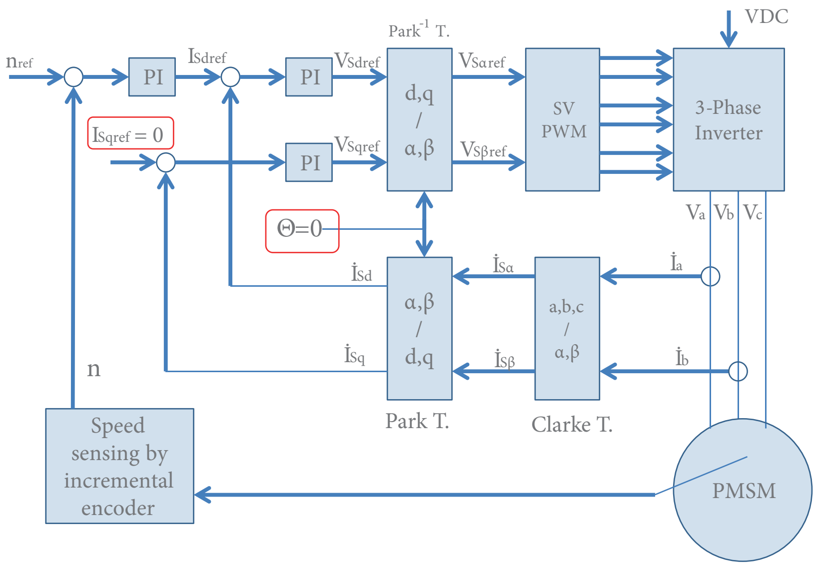

Figure 4. The algorithm of the proposed method.

The I_d current reference generated by the speed controller produces a torque that will bring the rotor into phase-A. Since the value of I_d is varied by the speed controller, the rotor always stays under control. It will stay aligned with phase-A after the alignment is completed even if the I_d current increases, since stator currents will not be able to generate torque. The speed controller keeps increasing the I_d reference, but since the rotor does not move the controller understands that the rotor is aligned with the phase-A when it detects that the I_d reference passed a certain value while the rotor is not rotating. When the alignment operation is completed, the incremental angle encoder value can be reset. The normal operation starts and the classical FOC algorithm is initiated.

The flowchart of the proposed alignment algorithm is shown in Figure 5. For the initial setting the rotor angle θ is assumed to be $0°$, the output of the speed controller is used as I_d reference, and I_q reference is set to zero. After the initial setting the alignment can start by applying a constant speed reference. Afterwards, there are three possible situations. If the rotor does not move because the initial rotor position is either at $0°$ or $180°$, I_q reference is applied to change the rotor position. If the rotor starts rotating in a negative direction because of an initial rotor position between $0°$ and $180°$, the speed control reference is multiplied by –1. If the rotor starts rotating in the positive direction because of an initial rotor position between $180°$ and $0°$, no intervention is necessary until the end of the alignment. The end of the alignment process is recognized when the speed becomes zero, at which time the output of the speed controller has its maximum value.

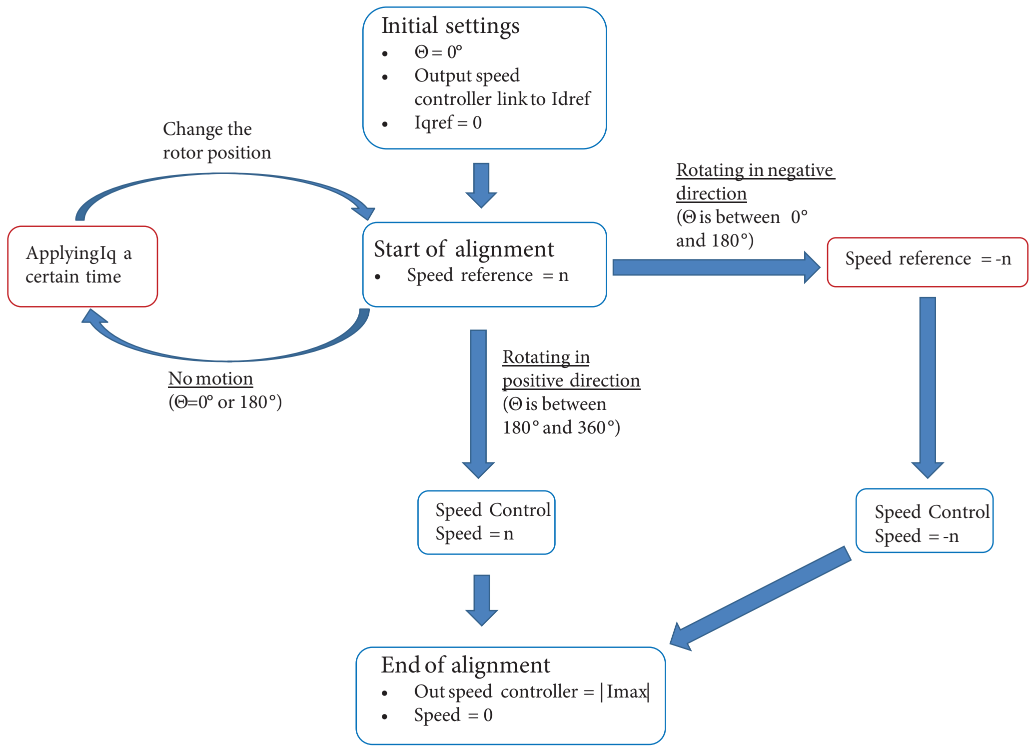

Figure 5. The flowchart of the proposed method.

2.3. Problematic cases of using proposed alignment method and their solutions

Although the proposed algorithm is simple and can be applied successfully, it is possible that various problems may be encountered depending on the initial position of the rotor. Solutions exist for these problems and they will be explained here. Possible problems and their solutions are as follows:

- If the rotor is initially at a position between 0° and 180°, application of I_d current starts the rotor to move to phase-A (0°) in the negative direction. In this case, the controller increases the output value because of the negative speed feedback from the speed controller. As the output value of the speed controller increases, the rotor accelerates in the negative direction. The rotor can swiftly pass phase-A, but since the applied flux is on phase-A, the rotor goes back to phase-A. The motion is oscillatory and eventually the rotor is aligned with phase-A as shown in Figure 6. This uncontrolled movement of the rotor is not desirable. To avoid this problem, the sign of the speed reference is changed if the rotor speed is initially sensed in the negative direction. The rotor is aligned with phase-A in the negative direction without any oscillation in the rotor speed or position. For experimental results, the reader is referred to Section 3.

- If the rotor is in the opposite direction of phase-A (minus A) (180°) at the beginning, there is no torque due to the 180° angle between the stator current flux (in phase-A) and the rotor flux. Because the rotor does not move, the output of the controller increases. When the value of I_d reference reaches a certain value, the alignment algorithm detects that the alignment is complete. In this case, the rotor position is measured incorrectly to be 180°. Due to the 180° error, in the case of normal operation the required flux is generated on the negative rather than positive q-axis. It causes rotation in the reverse direction. Because of the motion in the opposite direction, the controller increases the I_q reference value and the rotor rotates at maximum speed in the reverse direction. To solve this problem, a new statement is added

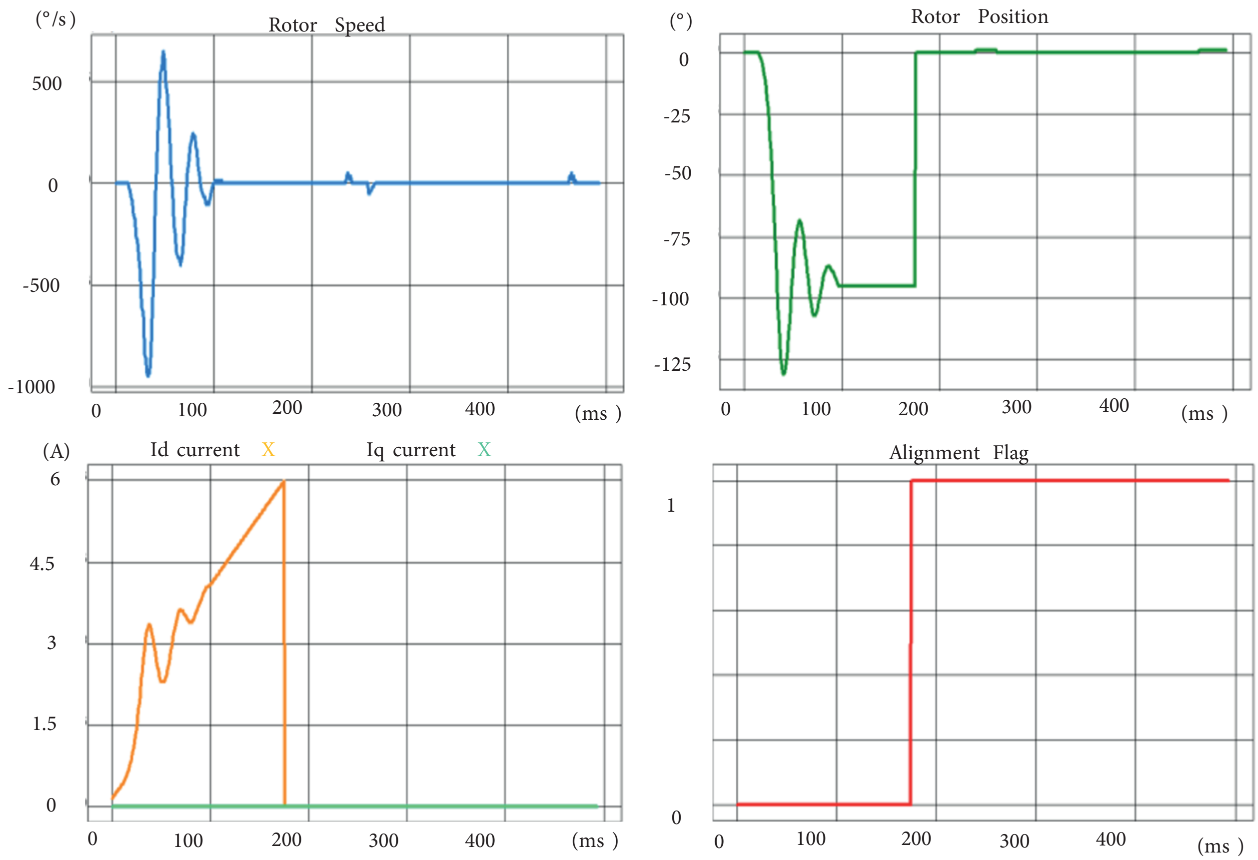

Figure 6. The results obtained when motor initial position is about 90° relative to phase-A when the speed reference is not changed; upper row speed (left), position (right). Lower row: d-axis and q-axis currents (left), alignment flag (right).

to the alignment method. If the rotor speed does not exceed a certain value after the alignment procedure starts, it is understood that the rotor is initially at 0° or 180°. If the rotor is at 0°, there is no problem. If the rotor is at 180°, the problem described occurs. For this reason, if the rotor does not rotate during the alignment, the output of the speed controller is applied to I_q reference instead of I_d reference for a certain period of time and the rotor position is changed from 0° or 180°. Then the method described above is applied and the rotor is aligned with phase-A. For experimental results, the reader is referred to Section 3.

3. Experimental results

The proposed method has been tested in the laboratory. Two different motors, a DC power supply Agilent E3634A and AVAR servo driver unit, which include a Texas Instruments TMS320F28335 digital signal processor and MOSFET inverter block, have been used in the experiments. A motor with incremental encoder is used for the first application of the proposed alignment method. The experimental setup is shown in Figure 7. Parameters of the motor are given in Table 1.

The rotor speed, rotor position, d and q axis currents, and the alignment complete flag graphics have been recorded for each experiment. These graphs are given separately for the following cases in which different

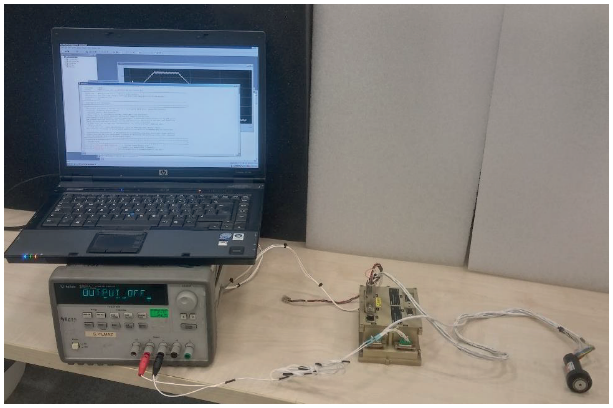

Figure 7. The experimental setup of the motor with incremental encoder.

Table 1. Parameters of the motor with incremental encoder.

Producer and model	MAXON – EC22
Rated voltage	24 V
Rated speed	32200 rpm
Line-line resistance	612 mohm
Line-line inductance	0.0542 mH
Number of encoder pulses per revolution	512
Number of pole-pairs	3

starting positions of the rotor have been tried. The results obtained when the motor initial position is about 90° relative to phase-A are shown in Figure 8. The results obtained when motor initial position is about 180° relative to phase-A are shown in Figure 9. The results obtained when motor initial position is about −90° relative to phase-A are shown in Figure 10. In these figures, the upper left graphs give the rotor speed, the upper right graphs give the rotor position, the lower left graphs give the stator current in dq axis frame, and the lower right graphs are the alignment flags that mark the end of the alignment process. As seen in Figure 8, the sign of the speed reference is changed if the rotor speed is initially sensed in the negative direction. The rotor is aligned with phase-A in the negative direction without any oscillation in the rotor speed or position. As seen in Figure 9, the algorithm recognizes that there is no motion for nearly 250 ms and applies the I_q reference for a few milliseconds. Afterwards, the alignment procedure starts again and the alignment is completed at nearly 550 ms.

3.1. Comparison of alignment methods

In this section, the proposed alignment method is compared with the alignment method in which V_3 and V_1 vectors are applied. This method is also called the B-A method because it requires the application of a voltage first to phase-B and then to phase-A. In order to compare the methods, a motor with a resolver has been used to measure the rotor position correctly. The experimental setup is shown in Figure 11. Parameters of the motor given in Table 2. In order for the comparison to be clear, the motor was loaded with a high inertia load. Several experimental measurements have been taken but only graphs for about 90° and 180° initial position relative to phase-A are given in this paper. All the other results are similar to those shared here. The rotor position and rotor speed results of the B-A and novel methods are given Figure 12 and Figure 13.

The following conclusions can be made from the test results.

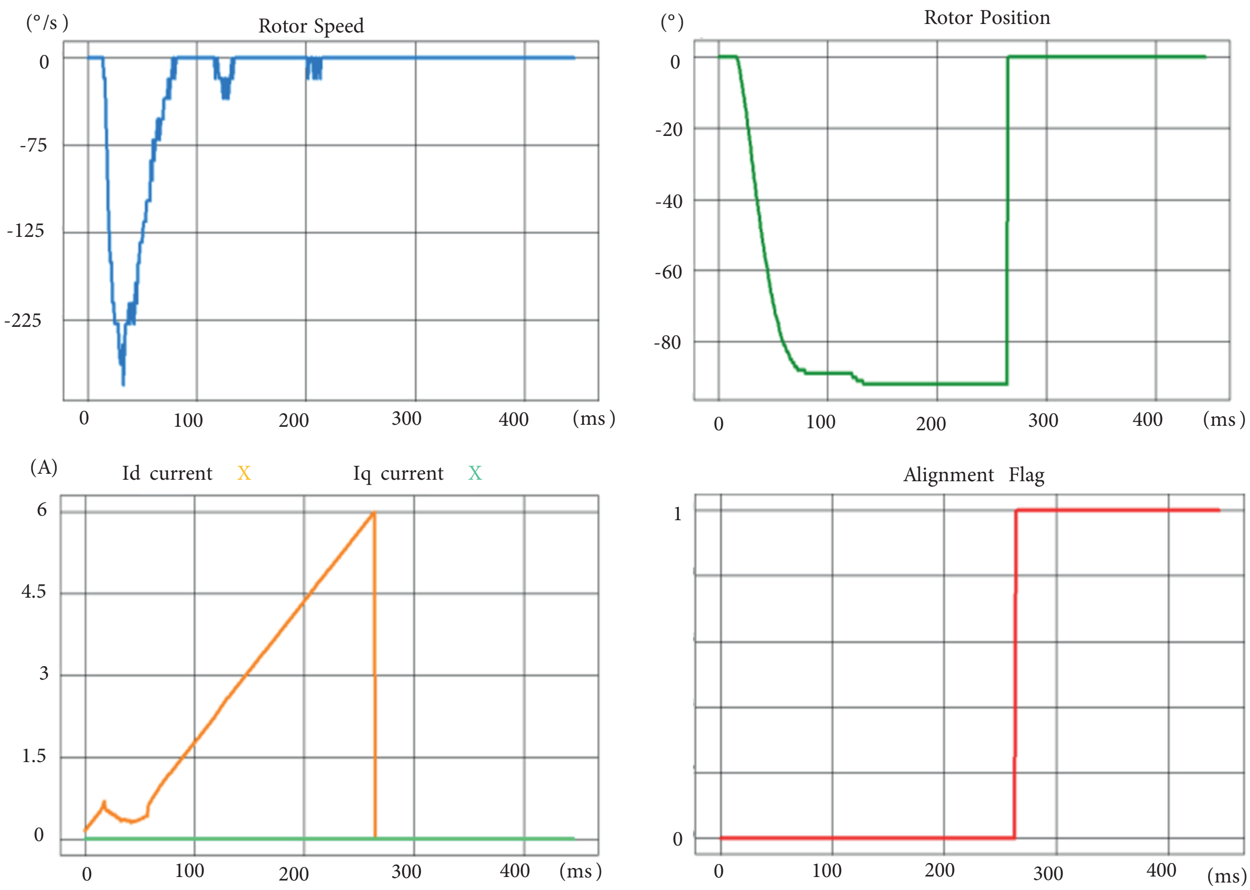

Figure 8. The results obtained when motor initial position is about 90° relative to phase-A; upper row speed (left), position (right). Lower row: d-axis and q-axis currents (left), alignment flag (right).

Table 2. Parameters of the motor with resolver.

Producer and model	KOLLMORGEN - D061A
Rated voltage	230 Vac
Rated speed	500 rpm
Line-line resistance	2.9 ohm
Line-line inductance	6.8 mH
Number of pole-pairs	1

- Since the duration of the alignment process is not known beforehand, the time to apply the voltages is determined by giving a certain margin of error when applying the B-A method. In the experiments performed, this time was chosen as 1 s for each voltage. For this reason, the alignment process for all cases, regardless of the starting position of the rotor, takes 2 s in total with the B-A method. On the other hand, the alignment process varies depending on the starting position of the rotor in the proposed method. However, in the case where the rotor is farthest from phase-A, it takes less than 1 s (≈0.9 s). This is shown in Figure 13. When the initial position is about 90° relative to phase-A the alignment takes about ≈ 0.45 s, which is less than half. This is shown in Figure 12. By increasing the speed reference

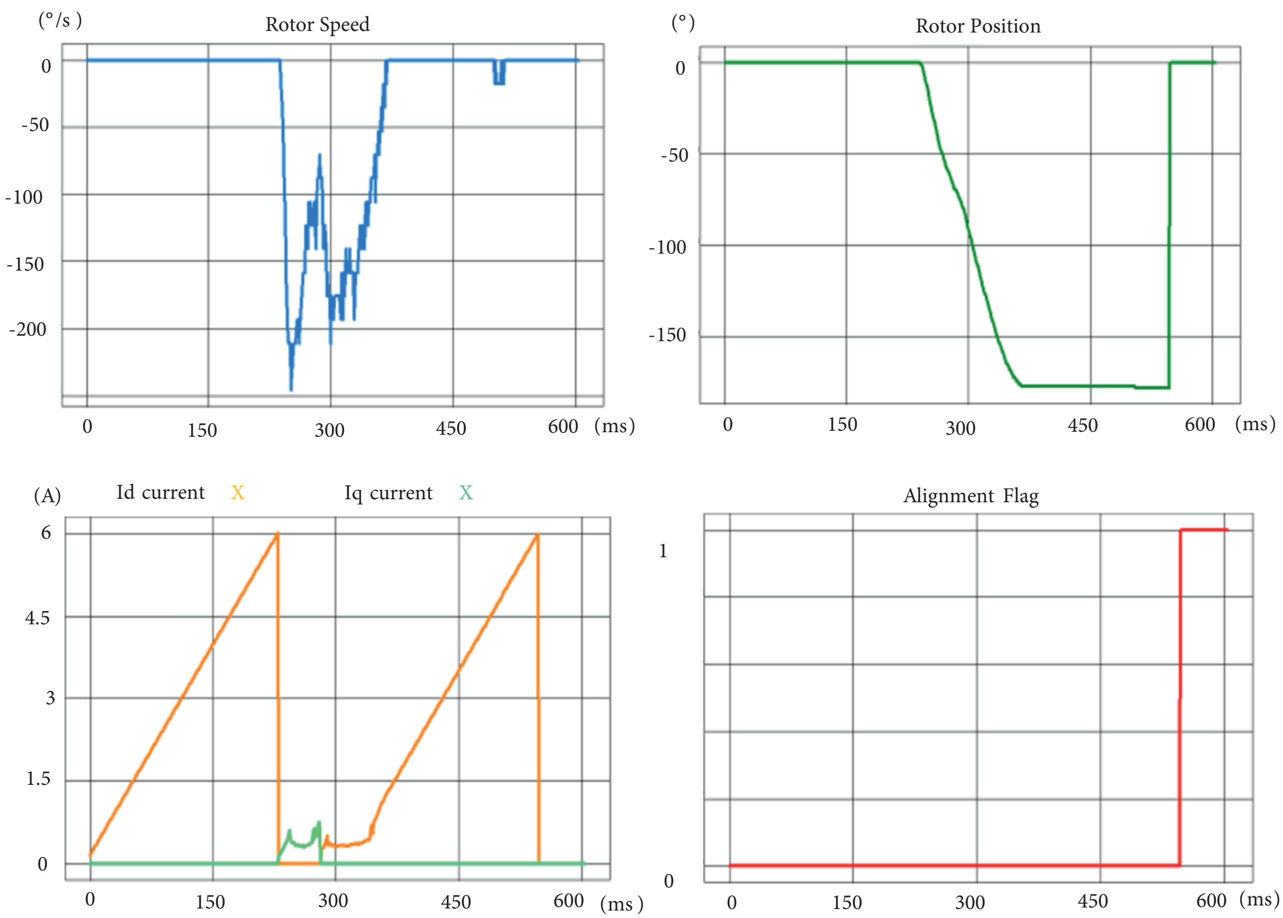

Figure 9. The results obtained when motor initial position is about 180° relative to phase-A; upper row speed (left), position (right). Lower row: d-axis and q-axis currents (left), alignment flag (right).

value given in the proposed method, the alignment process can be completed in a shorter time.

- In the B-A method, the applied voltage can be increased in order to reduce the alignment time. However, the increase in voltage may cause the rotor position overshoot or oscillation around 0°. The position overshoot is seen in Figure 12 and Figure 13. Since the motion is controlled in the proposed method, no such oscillations will occur.

- The speed of the rotor instantly increases to 1500 $°/s$ in the B-A method, as seen in the graphs of Figure 12 and Figure 13. In the proposed method the speed is controlled and does not exceed 400 $°/s$. Although the maximum speed of the rotor in the proposed method is slower than the maximum speed of that in the B-A method, the alignment is completed in a shorter time.

- In the B-A method, the voltage value varies due to the torque required to align the rotor depending on the environmental conditions and the load change. Changing conditions can cause a misalignment because the voltages applied in the B-A method are constant. In the new method, due to the use of the speed controller, the applied voltage varies according to the changing conditions and the alignment process is performed successfully.

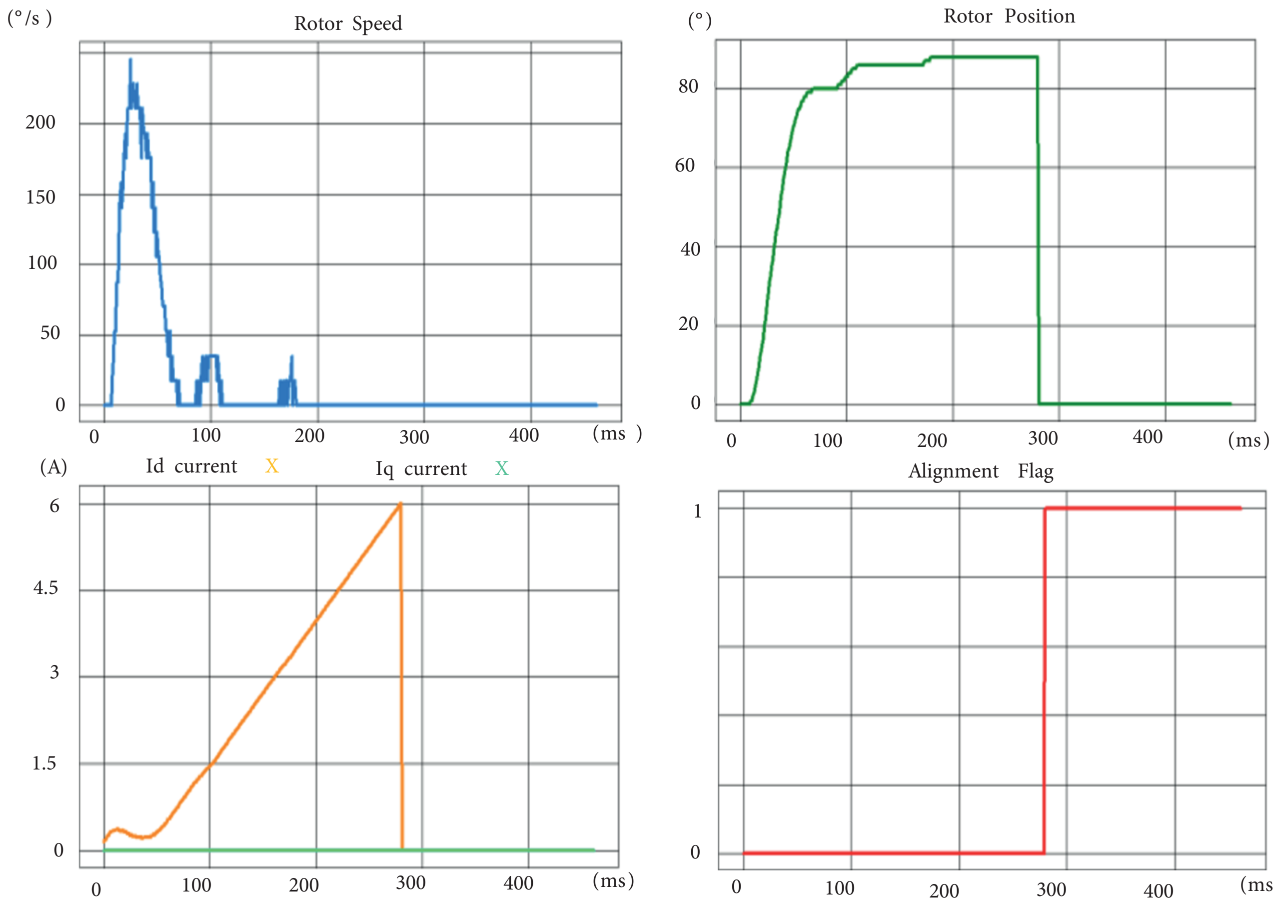

Figure 10. The results obtained when motor initial position is about minus 90° relative to phase-A; upper row speed (left), position (right). Lower row: d-axis and q-axis currents (left), alignment flag (right).

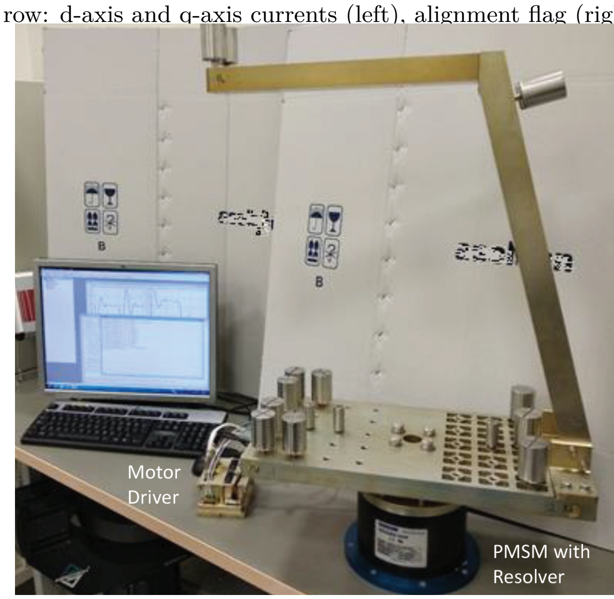

Figure 11. The experimental setup for the motor with resolver.

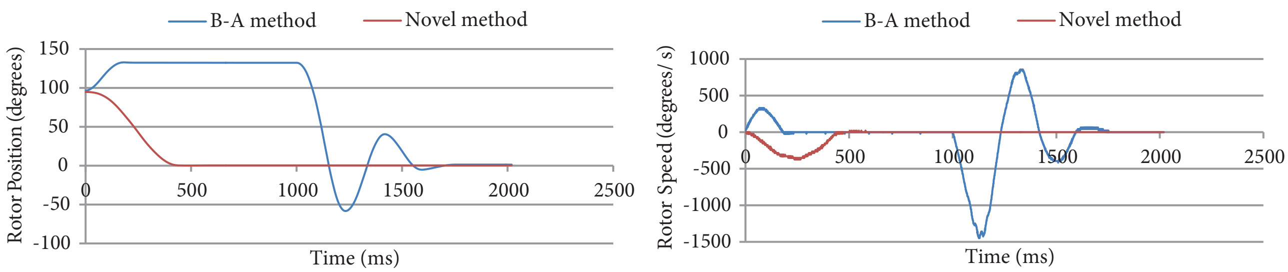

Figure 12. The results of B-A and novel methods applied to the motor with resolver. Initial position is about 90° relative to phase-A. Upper: rotor position. Lower: rotor speed.

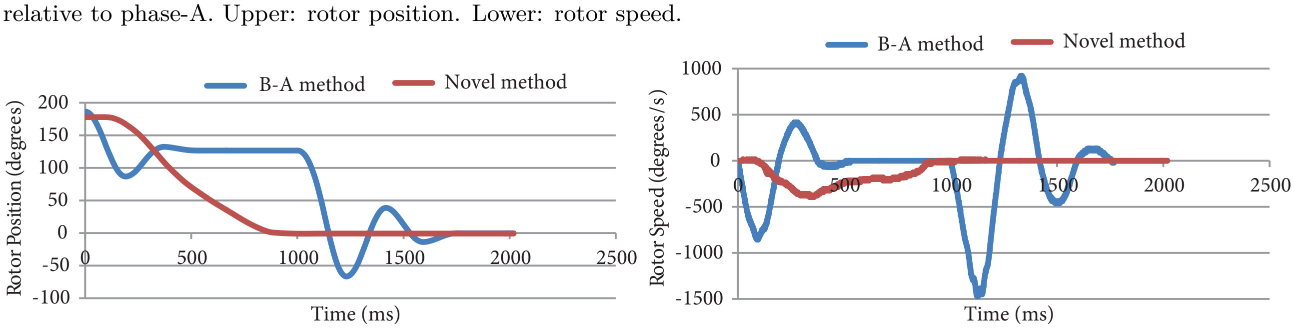

Figure 13. The results of B-A and novel methods applied to the motor with resolver. Initial position is about 180° relative to phase-A. Upper: rotor position. Lower: rotor speed.

4. Conclusion

Knowing the rotor position is very critical when controlling PMSMs. There are several methods to determine the rotor initial position or to align the rotor to a known position if an incremental encoder is used. In this paper, a new method utilizing a modified version of the FOC to determine the initial rotor position is proposed. The proposed method is more reliable than the existing ones since the motion is under complete control and it is not affected by environmental conditions. Experimental work shows that the proposed method eliminates the sudden movement and oscillation problems that are frequently observed in other methods. The useful life and the reliability of the system may be extended by the prevention of sudden movements. In addition, since the alignment process is shorter, the motor control can be started earlier with the proposed method.

It has been observed that there are some special cases needing attention depending on the initial position of the rotor with the proposed method. In these special cases undesired results may be faced. Solutions have been developed for these possible problems and the proposed algorithm has been revised accordingly. Experimental results show that these problems were eliminated.

The work presented in this paper shows that incremental encoders with small size and low cost could be used more reliably by using the proposed alignment method in position control systems.

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