

Article

Rotor Position Alignment of FSTPI Based PMSM Drive Using Low Frequency Signal Injection

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Abstract: A PMSM drive with an incremental encoder or using sensorless control requires alignment to a predetermined rotor position (initial position) or initial rotor position detection at start-up. It is desired to lock the rotor to a known state (usually zero angle) at start-up if the initial rotor position detection is not available or difficult to obtain. In this work, a simple and proper zero angle initial rotor position alignment of four-switch three-phase (FSTP) inverter-based PMSM drive is proposed. Low-frequency voltage signal is applied to the d -axis voltage reference of the open-loop FSTPI based PMSM drive scheme without requiring complex trigonometric calculations, PI current regulators and current sensing. Therefore, fluctuated capacitor voltages at the DC-link are obtained allowing current flow through phase a locking the rotor with zero angle, properly. The proposed method has been implemented using a low-cost FSTP voltage source inverter (VSI) for PMSM drive with a floating-point TMS320F28335 DSP. The effectiveness and the feasibility of the proposed zero angle initial rotor position alignment method for PMSM driven by FSTP inverter have been demonstrated through experimental results.

Keywords: permanent magnet synchronous motor (PMSM); four-switch three-phase (FSTP) inverter; reduced switch inverter; initial position alignment; signal injection

1. Introduction

In many applications such as in light electric vehicles and consumer products, low power is desired. The utilization of a cost-effective three-phase inverter is crucial to decrease the cost of the drive system. This can be achieved by eliminating two semi-conductors in the inverter topology making it four-switch three-phase inverter, as shown in Figure 1a [1–4]. For sensorless operations where the initial rotor position detection is not available or starting from an unknown rotor position is not possible, aligning or locking the rotor to a predetermined position is inevitable for proper starting of PMSM [5]. Additionally, for sensed operation of PMSM drives where incremental optical encoder is used as the position sensor, the initial rotor position is not known, therefore the alignment procedure is mandatory [6]. The precise rotor position must be identified before starting the motor and after the DC-link is at full capacity.

The PMSM has to be energized by a selected voltage vector or sequence of voltage vectors to align the rotor to the predefined position. In studies using sensorless control and incremental encoders in

sensor based AC drives, methods for determination of initial rotor position and alignment to zero angle have not been investigated for the FSTP inverter. Locking the rotor to a known position (especially zero angle), as shown in Figure 1b at start-up is easily performed in classical six-switch three-phase (SSTP) inverters using conventional techniques, however zero angle alignment with classical methods do not work in case of an FSTP inverter due to the fact that the DC-link voltage is at full capacity and one phase (phase a which is set to align with zero position and d -axis rotor flux linkage vector) of the PMSM is mounted to the midpoint of the split capacitors in the DC-link, as shown Figure 1a such that all the four non-zero voltage vectors aligned with the $\alpha\beta$ -axes. Therefore, simplified space vector pulse width modulation (SVPWM) generation in FSTP based inverter is achieved [7–9].

In the classical rotor alignment procedure of the PMSM drive with vector control scheme, enough d -axis constant current is injected to overcome the load, inertia and friction in the vector controlled scheme whilst q -axis current reference is set to zero with zero position input applied to the co-ordinate transformations such as Park and inverse Park prior to startup, therefore the rotor flux is aligned with the stator flux which is set to zero degree position [10]. The main disadvantages of such conventional techniques are that they are mainly dependent on PI regulators and can be easily applicable to six-switch inverter based PMSM drives without causing severe degradation at the startup procedure. Moreover, with the classical rotor position alignment method, dynamic performance strongly relies on the bandwidth of the current control loop and the parameters of the d - and q -axes current regulators. High and low frequency pulse signal injection methods are investigated for the sensorless control of PM machines in classical six-switch three-phase inverters [11–13]. However, these studies are intended to estimation of initial rotor position. In the FSTP inverter fed PMSM drive, classical alignment procedure with d -axis current regulator with zero position applied to the co-ordinate transformations that is used for three-phase six-switch (SSTP) inverter generates improper voltage vectors that does not perform alignment to zero angle when phase a (d -axis zero angle position) is attached to the mid-point of the split capacitors.

In [14], a simple sector determination scheme for a normalized SVPWM is proposed for the FSTP inverter without voltage or position sensors such that the complex calculations are eliminated in the controller. Although, the sector determination algorithm is developed for SVPWM, no discussion has been given on obtaining a zero angle initial rotor position alignment. Current and torque ripple minimization incorporating SVPWM are also reported in [8] for FSTP inverters where the compensation techniques are employed for PMSM drives to reduce the unbalancing and current and torque distortion in FSTP inverters. However, the main focus in this work is to reduce the oscillation observed in current and torque waveforms due to the nature of FSTP inverters. Therefore, in this study, no details have been given on the encoder type or about the initial rotor position detection methodology. A study in the literature given in [15] discusses the initial rotor position alignment issue of the FSTP inverters. The solution to this problem explained in [8], which is locking the rotor with line-to-line voltage is possible but does not acquire zero angle alignment.

In this paper, the proper rotor position alignment methodology to a predetermined zero angle position is developed for the FSTP driven PMSM drive. It is shown that the rotor position can be aligned to zero electrical degree position properly using low-frequency d -axis synchronous reference frame voltage in which the desired constant virtual zero position is applied to the co-ordinate transformation (inverse Park transformation) without using classical closed loop dq -axes current regulators. Thus, correct zero position alignment is achieved in a short amount of time for the FSTP inverter based PMSM drive at start-up. The proposed initial zero angle rotor position alignment method is simple and therefore is eligible for real-time implementation of cost effective four-switch PMSM drives.

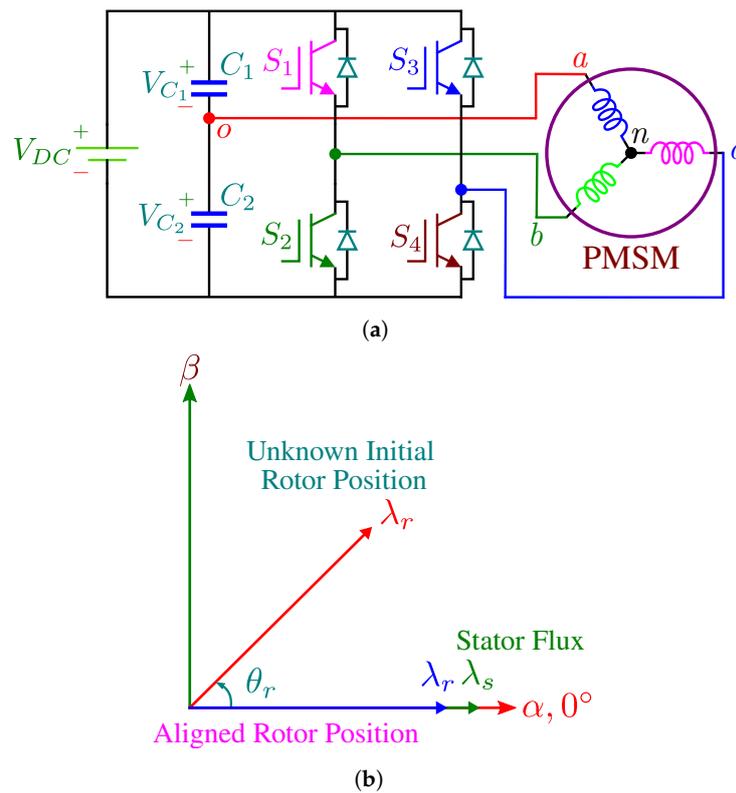


Figure 1. PMSM drive using four-switch three-phase (FSTP) VSI with stator and rotor flux linkage vectors: (a) Phase-*a* is wired to the middle of the two DC-link capacitors; (b) rotor alignment process.

2. Definition of Problem and the Proposed Signal Injection-Based Initial Zero Angle Rotor Position Alignment Method for FSTP Inverter

The simplest approach to align/lock the rotor to a known initial position in the FSTP inverter fed PMSM drive before starting is performed by applying a constant voltage vector to the stator phases to produce a stationary magnetic field and the rotor aligns itself naturally onto this stator field. However, one phase (phase *a*) is mounted to the mid-point of the capacitors for the FSTP topology, therefore under constant voltage input no current will flow through phase *a* which does not allow aligning the rotor position to the desired zero angle.

Fluctuations in the two capacitor voltages V_{C1} and V_{C2} exist that produce a deviation of the non-zero voltage vectors from their previous position, as shown in Figure 2. This can easily be overcome in the SSTP inverter where all phases can be controlled by the corresponding switches on each of the inverter legs. In the proposed alignment scheme at the startup process for FSTP inverter based PMSM drives, the pulse width modulated low-frequency *d*-axis voltage reference signal is injected to phase *a* through phase *b* and *c* allowing current to be flown in phase *a* and therefore proper rotor position alignment to zero angle is achieved.

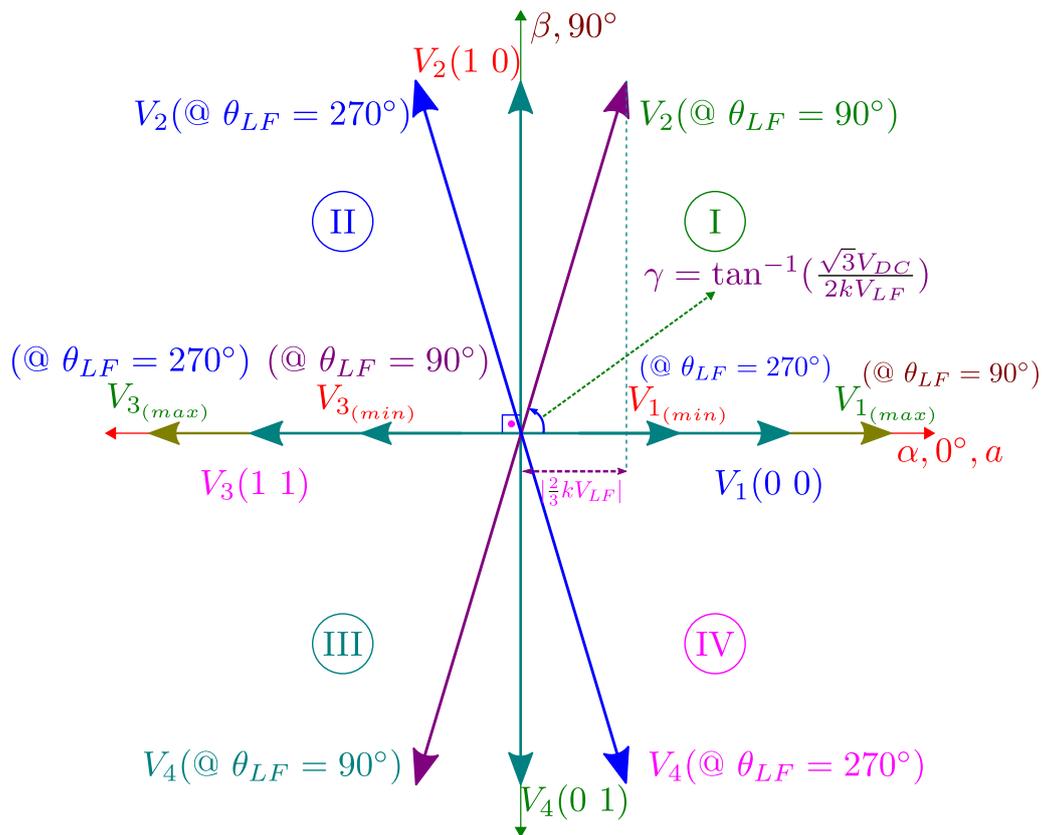


Figure 2. Non-zero voltage vectors of the FSTP VSI under low-frequency signal injection (LFSI) applied to the *d*-axis synchronous reference frame.

3. Mathematical Analysis of the Proposed Zero Angle Initial Rotor Position Alignment Scheme

For proper zero angle rotor position alignment in FSTP inverter based PMSM drive, open-loop voltage control with *d*-axis low-frequency ($f_{LF} = 50$ Hz) reference signal $V_d^* = V_{LF} \sin(\omega_{LF} t)$ is injected along with $V_q^* = 0$ to the drive scheme, as shown in Figure 3. By injecting the fluctuated voltage signal to the *d*-axis, constant $V_{DC}/2$ voltage with fluctuated AC components are generated on the upper and lower capacitor voltages given by

$$\begin{aligned} V_{C1} &= V_{DC}/2 - kV_{LF} \sin(\omega_{LF} t) \\ V_{C2} &= V_{DC}/2 + kV_{LF} \sin(\omega_{LF} t) \end{aligned} \tag{1}$$

where k is the resultant AC voltage amplitude constant $k = \frac{1}{2C|Z_{EQ}| \omega_{LF}}$ in the DC-link capacitors due to the motor parameters, capacitor values, and the injected signal frequency. $|Z_{EQ}|$ is the equivalent impedance when phase *a* is energized and phase *b* and *c* are shorted under voltage signal injection. As a result, current flows in phase *a* and therefore alignment to zero position is achieved. The magnitude of V_{LF} and injected signal frequency f_{LF} determine the time elapse to lock the rotor to the desired zero angle position. Using Equation (1), the four active voltage vectors under low-frequency *d*-axis signal injection case are tabulated in Tables 1 and 2.

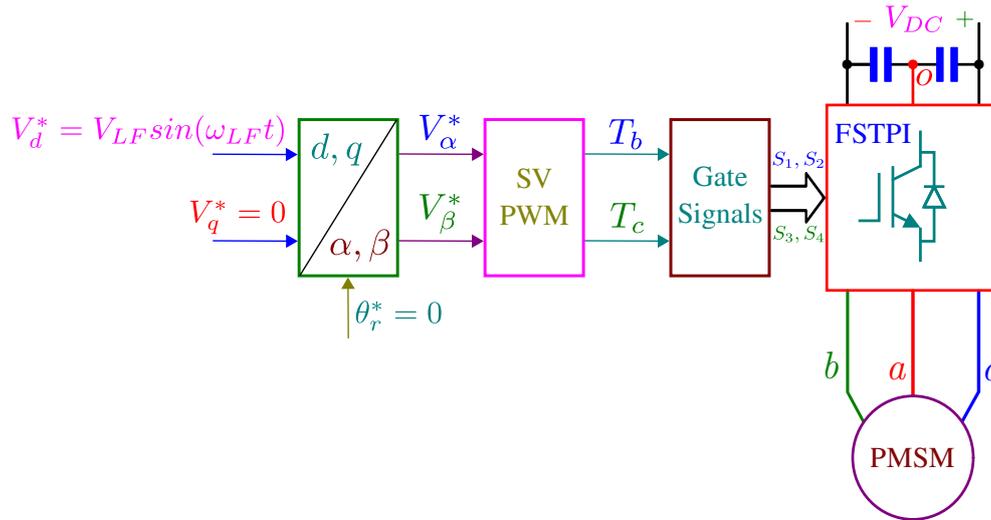


Figure 3. Block diagram of the proposed LFS injection based zero angle initial rotor position alignment for FSTP inverter-fed PMSM drives.

Table 1. Non-zero voltage vectors of FSTP inverter with DC-link fluctuations under LF signal injection.

Voltage Vector $V(S_1 S_3)$	Voltage Space Vector (\vec{V}_s)
$V_1(0\ 0)$	$V_{DC}/3 + (2/3)kV_{LF}\sin(\omega_{LF}t)$
$V_2(1\ 0)$	$(2/3)kV_{LF}\sin(\omega_{LF}t) + j(V_{DC}/\sqrt{3})$
$V_3(1\ 1)$	$(2/3)kV_{LF}\sin(\omega_{LF}t) - j(V_{DC}/\sqrt{3})$
$V_4(0\ 1)$	$-V_{DC}/3 + (2/3)kV_{LF}\sin(\omega_{LF}t)$

Table 2. Non-zero voltage vectors of FSTP inverter with DC-link fluctuations under LF signal injection at $0^\circ, 90^\circ, 180^\circ,$ and 270° .

$V(S_1 S_3)$	$ \vec{V}_s (@ \theta_{LF} = 0^\circ, 180^\circ)$	$ \vec{V}_s (@ \theta_{LF} = 90^\circ, 270^\circ)$
$V_1(0\ 0)$	$V_{DC}/3$	$(V_{DC} \pm 2kV_{LF})/3$
$V_2(1\ 0)$	$V_{DC}/\sqrt{3}$	$(\sqrt{3V_{DC}^2 + 4k^2V_{LF}^2})/3$
$V_3(1\ 1)$	$V_{DC}/\sqrt{3}$	$(\sqrt{3V_{DC}^2 + 4k^2V_{LF}^2})/3$
$V_4(0\ 1)$	$V_{DC}/3$	$(V_{DC} \pm 2kV_{LF})/3$

Analysis of Inverter Capacitor Effect

Since the circuit given in Figure 4 has stator resistances, damping occurs in the system. Resonance will naturally be determined by the damping of the circuit irrespective of the applied low-frequency AC signal. If the circuit is underdamped, the system resonates otherwise the circuit operates as overdamped without resonance. The circuit in Figure 4 has a damping factor calculated as

$$\zeta = \frac{3R_s}{2} \sqrt{\frac{C}{3L_s}} \tag{2}$$

Since the damping factor $\zeta = 2.4042$ is greater than 1, the system behaves as overdamped without oscillation. The critically damped condition of the circuit occurs at

$$C = \frac{12L_s}{9R_s^2} \tag{3}$$

where R_s is stator resistance, L_s is stator inductance and $C = C_1 = C_2 = 380 \mu\text{F}$ considering the electrical machine parameters are constant. The Semikron SEMITEACHTM inverter that has been used in this

system has two 2200 μF capacitors. Since the calculated damping factor in Equation (2) is greater than 1 with the already built-in capacitors in the inverter, the system acts as overdamped without oscillation.

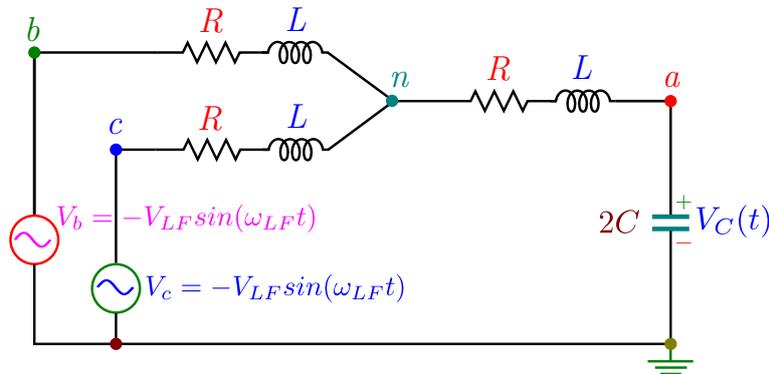


Figure 4. Electrical circuit of the zero angle LFS injection for FSTP inverter based PMSM drive.

4. Determination of *k* Constant

Applying inverse Park transformation in Figure 3 of the open-loop voltage control of FSTP inverter based PMSM drive, reference $\alpha\beta$ -axes voltages are obtained as

$$\begin{aligned} V_\alpha^* &= V_d^* \cos 0^\circ - V_q^* \sin 0^\circ = V_d^* \\ V_\beta^* &= V_q^* \cos 0^\circ + V_d^* \sin 0^\circ = 0 \end{aligned} \tag{4}$$

Assuming 0° electrical position occurs at the border of Sector I and IV, duty ratios T_b and T_c in the SVPWM calculations can be derived as

$$T_b = 1 - X - (1 - X - Y)/2 \tag{5}$$

$$T_c = T_b - Y = 1 - X + (Y + X - 1)/2 - Y = (1 - X)/2 \tag{6}$$

where $X = \sqrt{3}/2V_\alpha^*$ and $Y = V_\beta^*/2 = 0$. Actual leveled duty cycles are expressed as

$$\begin{aligned} T_b = T_c &= 2(T_b - 1/2) = \\ &= 2((1 - X)/2 - 1/2) = -X = \\ &= -\sqrt{3}/2V_\alpha^* \end{aligned} \tag{7}$$

Therefore, *b*- and *c*-axes LFS injection based voltages applied to the motor terminals are given as

$$V_b = V_c = -V_{LF} \sin(\omega_{LF} t) \tag{8}$$

An equivalent circuit of the zero angle alignment of PMSM drives with LFS injection based on an FSTP inverter can be drawn in terms of inverter and motor parameters, as shown in Figure 4 where *L* and *R* are the motor inductance and resistance. *C* is the capacitor of the FSTP inverter. DC voltage ripples on capacitors can be obtained by solving the circuit illustrated in Figure 4. The amplitude of the equivalent impedance of Figure 4 can be derived as

$$|Z_{EQ}| = \sqrt{\left(\frac{3R}{2}\right)^2 + \left(\frac{3\omega_{LF}LC - 1}{2\omega_{LF}C}\right)^2} \tag{9}$$

Solving $V_C(t)$ in Figure 4 yields

$$V_C(t) = \left(\frac{1}{2C |Z_{EQ}| \omega_{LF}} \right) V_{LF} \cos(\omega_{LF} t) \quad (10)$$

5. Implementation and Experimental Results

To validate the feasibility of the proposed scheme, an experimental platform of the FSTP inverter for PMSM drive is set up which is shown in Figure 5. Comparative experimental studies of the proposed smooth initial rotor position alignment method and the classical method have been conducted on a 1 kW FSTP inverter fed PMSM drive. The stator resistance and inductance of the PMSM are 3.4Ω and 3.3 mH , respectively. The rotor magnetic flux linkage is 0.095 Wb . The DC-link voltage measurements are performed by Tektronix TPP0200 model passive voltage probes with 300 V max. range and up to 200 MHz bandwidth. The voltage probes are used with the voltage amplifiers. The current probe used in the system is Fluke 80i-110s with $\pm(3\% + 50 \text{ mA})$ accuracy at 10 A and $\pm 100 \text{ A}$ range. Rotor position and speed are obtained by HEDSS ICU4809 incremental encoder with 2500 ppr with up to 120 kHz response frequency. Figures 6–9 illustrate the experimental results of the mechanical rotor positions and DC-link capacitor voltages using conventional and the proposed methods under fan type load, respectively.

Figures 10 and 11 represent phase a current and mechanical rotor speed using the proposed method under $V_{DC} = 400 \text{ V}$ with C_1 and C_2 are $2200 \mu\text{F}$, respectively. In Figure 6, classical rotor alignment with the proper constant d -axis voltage value using virtual zero angle is applied as a reference with q -axis voltage is set to zero. The rotor is deviated too much from the desired zero angle from the initial position of 20 mechanical degrees. Its final position is around -90 mechanical degrees, as shown in Figure 6.

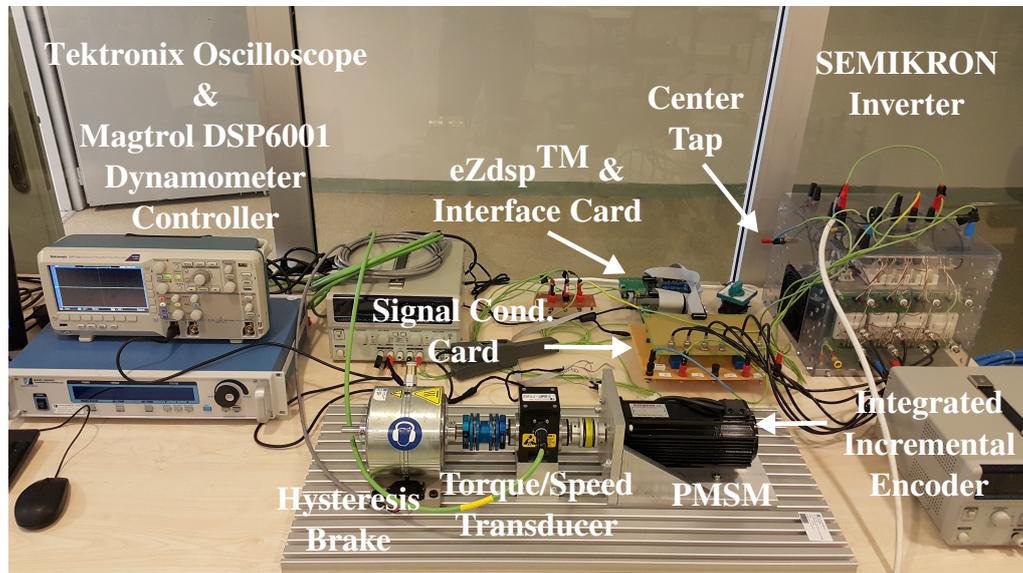


Figure 5. A 1 kW experimental test-bed.

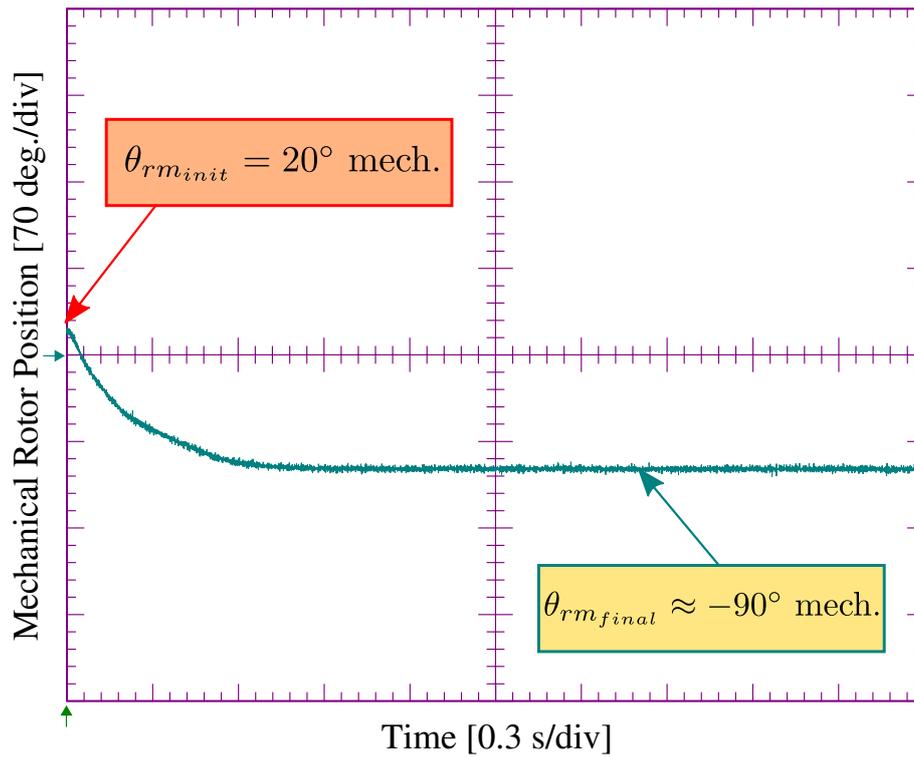


Figure 6. Mechanical rotor position of the PMSM drive under classical alignment procedure at start-up. Operating at: 0.25 pu *d*-axis voltage and zero *q*-axis voltage with 10 kHz switching frequency under fan type loading condition.

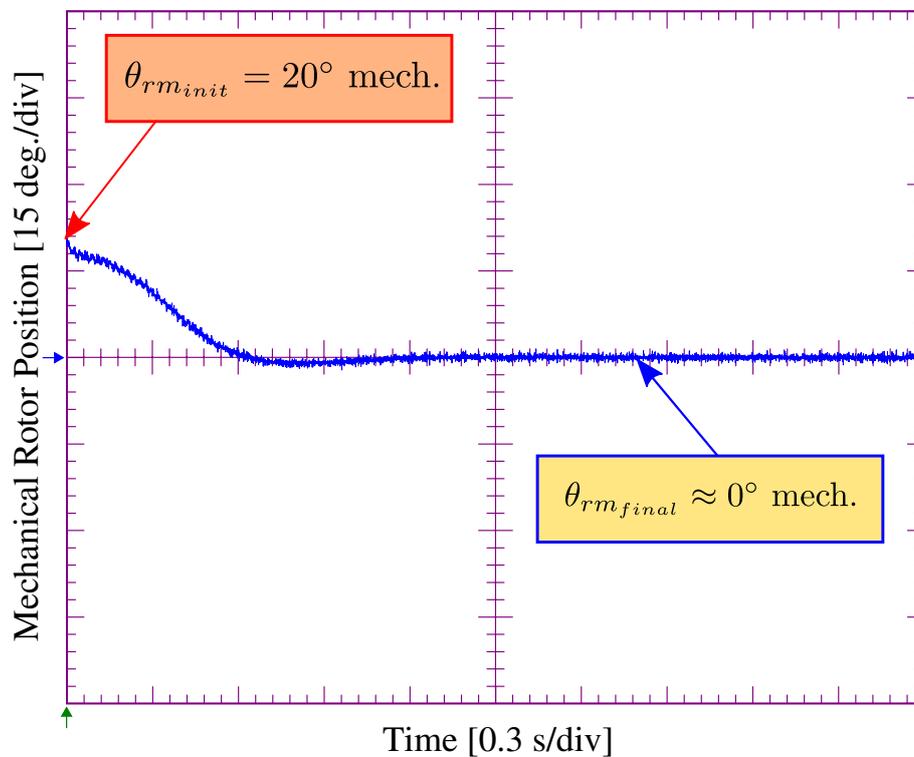


Figure 7. Mechanical rotor position of the proposed zero angle LFS injection based PMSM drive with FSTP inverter. Operating at: 0.25 pu *d*-axis voltage and zero *q*-axis voltage with 10 kHz switching frequency under fan type loading condition.

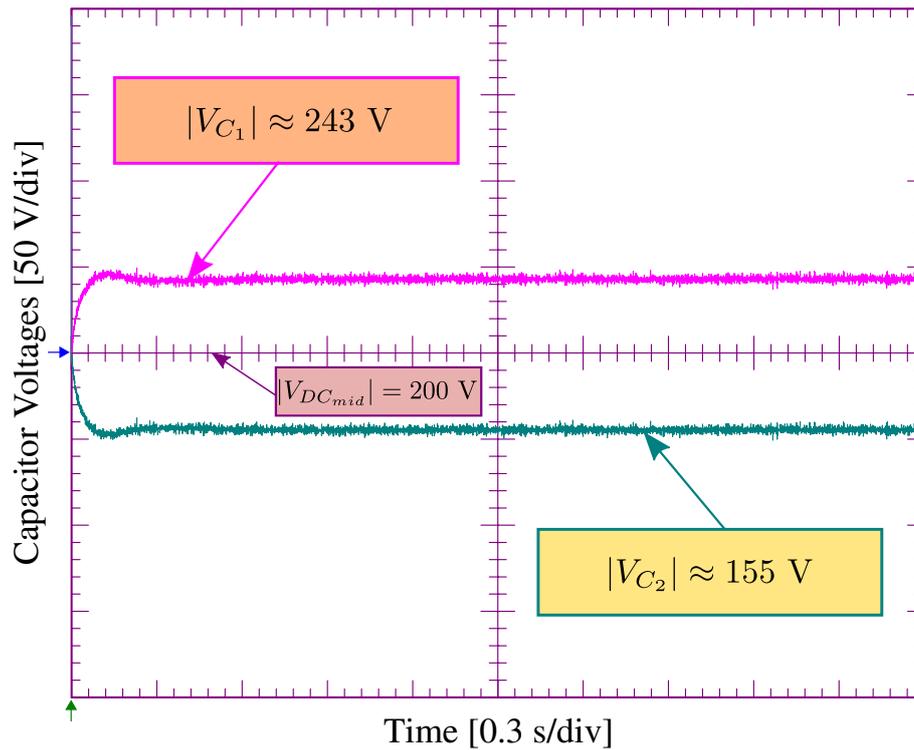


Figure 8. DC-link capacitor voltages of the PMSM drive under classical alignment procedure at start-up. Operating at: 0.25 pu d -axis voltage and zero q -axis voltage with 10 kHz switching frequency under fan type loading condition.

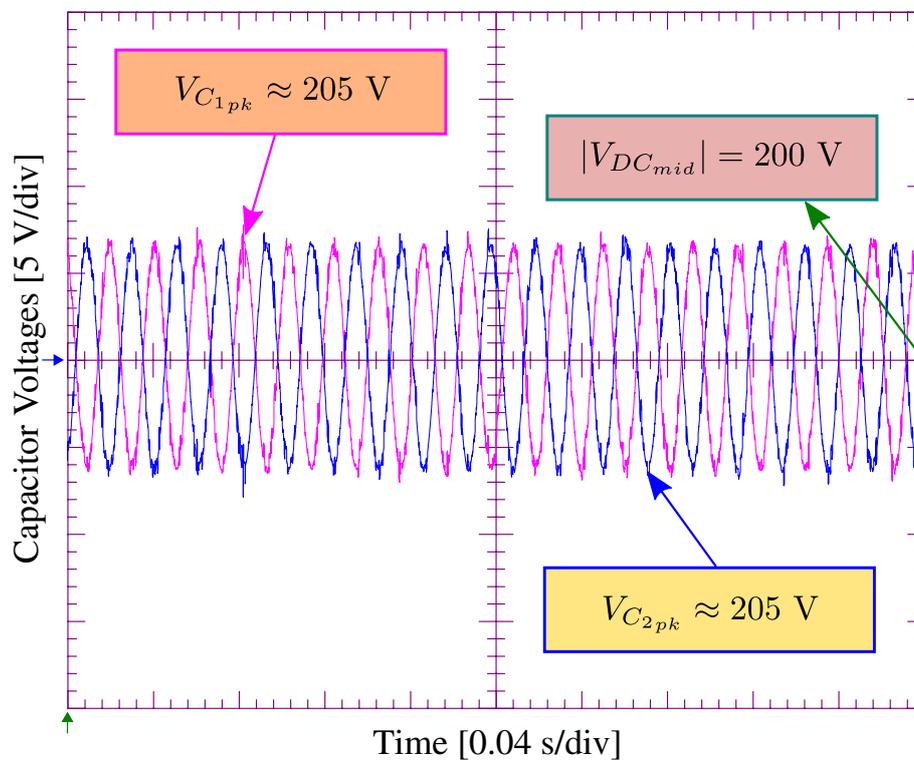


Figure 9. Steady-state DC-link capacitor voltages of the proposed zero angle LFS injection based PMSM drive with FSTP inverter. Operating at: 0.25 pu d -axis voltage and zero q -axis voltage with 10 kHz switching frequency under fan type loading condition.

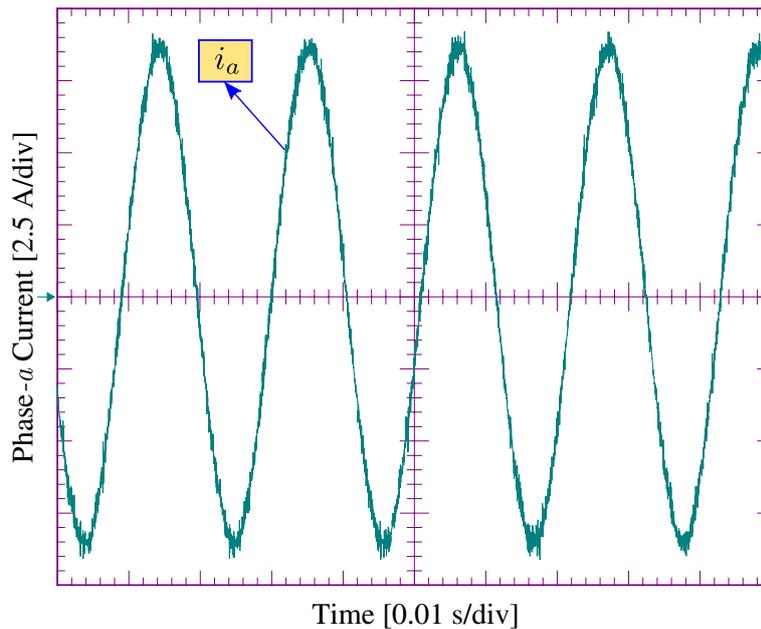


Figure 10. Phase a current at steady-state of the proposed zero angle LFS injection based PMSM drive with FSTP inverter. Operating at: 0.25 pu d -axis voltage and zero q -axis voltage with 10 kHz switching frequency under fan type loading condition.

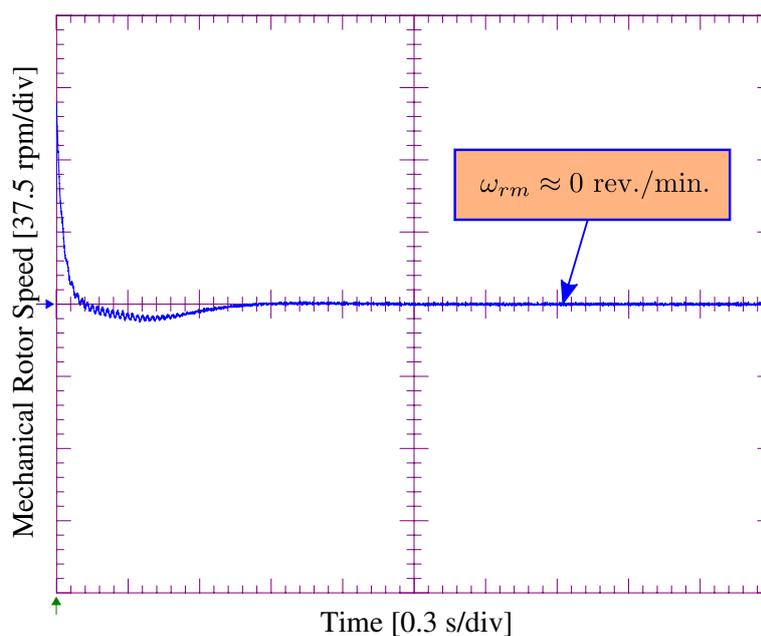


Figure 11. Mechanical rotor speed of the proposed zero angle LFS injection based PMSM drive with FSTP inverter. Operating at: 0.25 pu d -axis voltage and zero q -axis voltage with 10 kHz switching frequency under fan type loading condition.

It is seen in Figure 7 that under $f_{LF} = 50$ Hz LFS injection with 0.25 pu d -axis voltage amplitude reference, proper zero angle alignment is successfully achieved. Initial rotor position is set to 20 mechanical degrees. After 1.2 s, the rotor locks to the zero mechanical degree position with the proposed method as opposed to the classical one in which the alignment procedure to zero angle is not successful, as shown in Figure 6. The rotor is aligned to a negative position using the classical alignment method. Since only DC capacitor voltages exist in the classical zero angle alignment method, no current flows through the phase which is mounted to the center point of the capacitors. Therefore, the alignment procedure is unsuccessful.

With the proposed scheme, LF signal allows fluctuation on the DC-link offset voltage, as shown in Figure 9 enabling current flowing through the center tap connected to phase a which results in proper zero rotor angle alignment. The amplitude of the fluctuated DC-link voltages matches with the k value that is theoretically calculated in Equation (10). The frequency of oscillated DC-link voltages equals to the injected LF signal frequency.

Steady-state phase a current waveform is given in Figure 10. It is seen that no low frequency fluctuations are reported on the phase current. This will not cause mechanical oscillation in the motor when the rotor is locked with the zero angle. When the rotor is aligned to the proper zero position, the speed of the rotor is dropped to zero as well at the same time with the position, as shown in Figure 11.

The sensitivity analysis based on the input applied voltage amplitude V_{LF} and the injected signal frequency f_{LF} versus the time duration of the alignment are depicted in the Table 3. It is observed in the sensitivity analysis that when the V/f ratios is around 0.005, the faster alignment is achieved. The motor current increases when the input voltage amplitude is selected higher than 0.25 pu which is selected to be the optimum voltage amplitude. If the inertia and/or load of the system are higher than expected, a proper offset can be added as a bias to the injected signal to achieve zero angle alignment. Since the application of this method is only used for the initial alignment procedure, it will only run for a few seconds.

Table 3. The sensitivity analysis results based on the input applied voltage amplitude V_{LF} , the injected signal frequency f_{LF} versus the time duration of the alignment.

V_{LF} (pu)	f_{LF} (Hz)	Alignment Time (s)
0.1 pu	50 Hz	11 s
0.1 pu	40 Hz	9 s
0.1 pu	30 Hz	2.8 s
0.1 pu	20 Hz	2.2 s
0.2 pu	50 Hz	2.2 s
0.2 pu	40 Hz	1.5 s
0.2 pu	30 Hz	1.9 s
0.2 pu	20 Hz	2 s
0.25 pu	50 Hz	1.2 s
0.25 pu	40 Hz	1.3 s
0.25 pu	30 Hz	1.4 s
0.25 pu	20 Hz	1.5 s

As can be seen in Table 3 that higher V_{LF} values with proper injected frequency (close to the motor nominal operating frequency) considering the V/f ratio generate more $V_C(t)$ at the DC-link and the alignment time is reduced. The optimum V_{LF} amplitude is selected to be 25% of the nominal voltage at 50 Hz (nominal operating frequency of the motor).

The proposed zero angle rotor position alignment method at start-up could be used in applications such as centrifugal pump, fan and blower where initially light load or no-load occur including permanent magnet synchronous generators that are mounted on small scale wind turbines. Since the basis of the proposed method is an open-loop, alignment time depends on the system inertia, applied voltage, and the frequency of the injected signal. After the alignment procedure is completed, switching to the closed-loop control algorithm is enabled which drives the four-switch PMSM system. If the desired zero rotor position has not been achieved while the speed is not close to zero for a certain amount of time, the applied frequency is lowered properly to speed up the alignment procedure.

6. Conclusions

A simple and smooth zero angle initial rotor position alignment scheme using low-frequency signal injection (LFSI) that is applied to the d -axis voltage reference is proposed for FSTP inverter-fed open-loop PMSM drives at start-up. Therefore, by having the AC signal injected to the d -axis synchronous voltage reference frame, fluctuated capacitor voltages V_{C_1} and V_{C_2} are obtained allowing current flow through phase a locking the rotor at a zero angle. The proposed method does not require complex trigonometric calculations and PI current regulators, and it is desirable for real-time implementation of reduced cost four-switch three-phase PMSM drives. Experimental results validate the effectiveness and the feasibility of the proposed alignment method for PMSM driven by an FSTP inverter.

Author Contributions: S.B.O. conceived the idea of the research, supervise this research study and participated in all of the study phases; O.C.K. and A.A. contributed software development and writing—original draft preparation; O.H. provided guidance, reviewed the results and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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