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Development and Implementation of a Sensor less Control System for PMSM with PLL+ Based Speed and Position Estimation

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Abstract: Traditional sensorless control systems of Permanent Magnet Synchronous Motors (PMSM) are based on Phase-Locked Loop (PLL) algorithms for speed and position estimation but possess the problem of the accuracy and stability under varying load conditions. The paper proposed a sensor less control system based on PLL⁺ algorithm when improved with a random frequency PWM approach to reduce noise and electromagnetic interference (EMI). The proposed system improves the accuracy of estimation and smoothness in torque operations without mechanical sensors. Simulation and FFT analysis have shown that the PLL⁺ based system has better performance and greater reliability than conventional PLL-based control systems, thus offering a cost effective and efficient solution for PMSM drives.

Keywords: *Sensor less Control, PMSM, PLL+, Speed Estimation, Position Estimation.*

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I. INTRODUCTION

The control of Permanent Magnet Synchronous Motors (PMSM) is a field of electric drives of great importance, especially for applications where high efficiency, accuracy and reliability is required. Until now, PMSM control systems use physical sensors, such as encoders or resolvers, to measure rotor position and rotor speed, which introduces additional complexity, cost and problems of reliability because these devices can fail. To solve these problems, developments have taken place in the world of sensorless control, eliminating the necessity of physical sensors and thus giving more reliable in more cost-effective solutions. [1][2][15]. In the realm of sensorless techniques, there is a considerable focus on the Phase-Locked Loop (PLL) method. Such a PLL method detects the back electromotive force (back-EMF) supplied in the stator windings as a means of estimating the rotor speed and position [3][4]. It consists of a feedback system to synchronize the phase of the estimated rotor position and that of the back-EMF. The synchronous and estimated rotor position causes the rotor speed and position to be accurately estimated from the back-EMF signals without being measured. The PLL systems are however, influenced by certain problems regarding the speed fluctuations, fluctuations of the load torque and rotor position offset errors. [5][6].

This study proposed to implement a sensorless control approach based on experimental hardware platform, for the PMSM. In this strategy, the rotor position is obtained from the estimation, using a PLL block in the software instead of the mechanical sensors used in traditional systems. It allows the complexity and cost of the application to reduce considerably, while increasing its reliability [7]. For the PLL used in our model, the rotor position information is obtained through the analysis of the back-EMF signal, which proved effective and cheaper than traditional ones.

The results of our simulation indicate that the performance of the motor by applying sensorless control with the PLL, is much better with the PLL method for low speeds and variable loads. The FFT analysis shows that using the PLL technique greatly reduces harmonic distortion and electromagnetic interference, as opposed to the normal methods. [8]. With the PLL method, the dynamic response to the motor is improved, less jerkiness occurs in the speed of the motor and improved overall efficiency of the system results. [9].

In addition to sensorless control we have incorporated a Neutral-Point-clamped (NPC) three level inverter in the system. The NPC three level inverter plays an important role in the high quality of output voltage with less harmonic distortion

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which improves the overall performance to the PMSM. [10]. The combination of sensorless control using PLL together with the NPC inverter gives lower noise, less harmonic distortion and, better efficiency. [11].

This work completely removes the need for mechanical sensors, such as rotary encoders or resolvers, replacing them with rotor position estimation through back-EMF signals. The proposed method results in a much more robust and cheaper solution especially important in applications where reliability and cost are paramount such as industrial automation and electric vehicles [12].

The following sections of the paper deal with details of the methodology, the Simulink model design, and analysis of the results from simulation. The key equations used in the model, back-EMF estimation, PLL synchronization etc, are presented and discussed.

II. METHODOLOGY

The developed sensorless PMSM control system adopts PLL-based estimator instead of the traditional mechanical sensors. The overall control configuration is described in a flowchart and block diagram, where the reference speed is processed through PI controllers, transformed to the dq-frame, and then applied to the motor through an SVPWM inverter. The PLL block estimates the rotor speed and position based on the measured stator currents.

➢ *Flow Chart*

In the schematic of the system block the whole problem of sensor less control of a permanent magnet synchronous motor (PMSM) is presented. The first block "Speed Reference" is used for giving an input of the required speed of the motor, which is directly after passed on to the block "Speed & Current Controllers (PI)", in there the speed & current of the motor is controlled due to feedback, that is imparted from the motor. The output of Controllers is sent back into the block called "SVPWM Inverter", which take cares for the voltage applied at the PMSM motor. One of the important blocks in this case is the "PLL Position & Speed Estimator", which receives the feedback from the currents (ia, ib, ic) from the motor, estimated rotor position (θ) and speed (ω). This information is made use of for finding out Torque and current needed further to be processed in the Clark & Park Transforms type of block (abc→dq) which gives outputs to the Torque and currents in two phase (d-q) quantities that are required for proper control of the motor. The system also has feedback lines hermed by red dashed lines in the block schematic for the meaning of the continuous real time correction of the motor performance due to feedback measure of the currents of the motor and estimated rotor position of the motor with view to the capacity of the system, and also minimized costs. The aim of the whole matter is to control precise the PMSM motor without any physical sensors, making use of the PLL block for estimation for rotor position and speed.

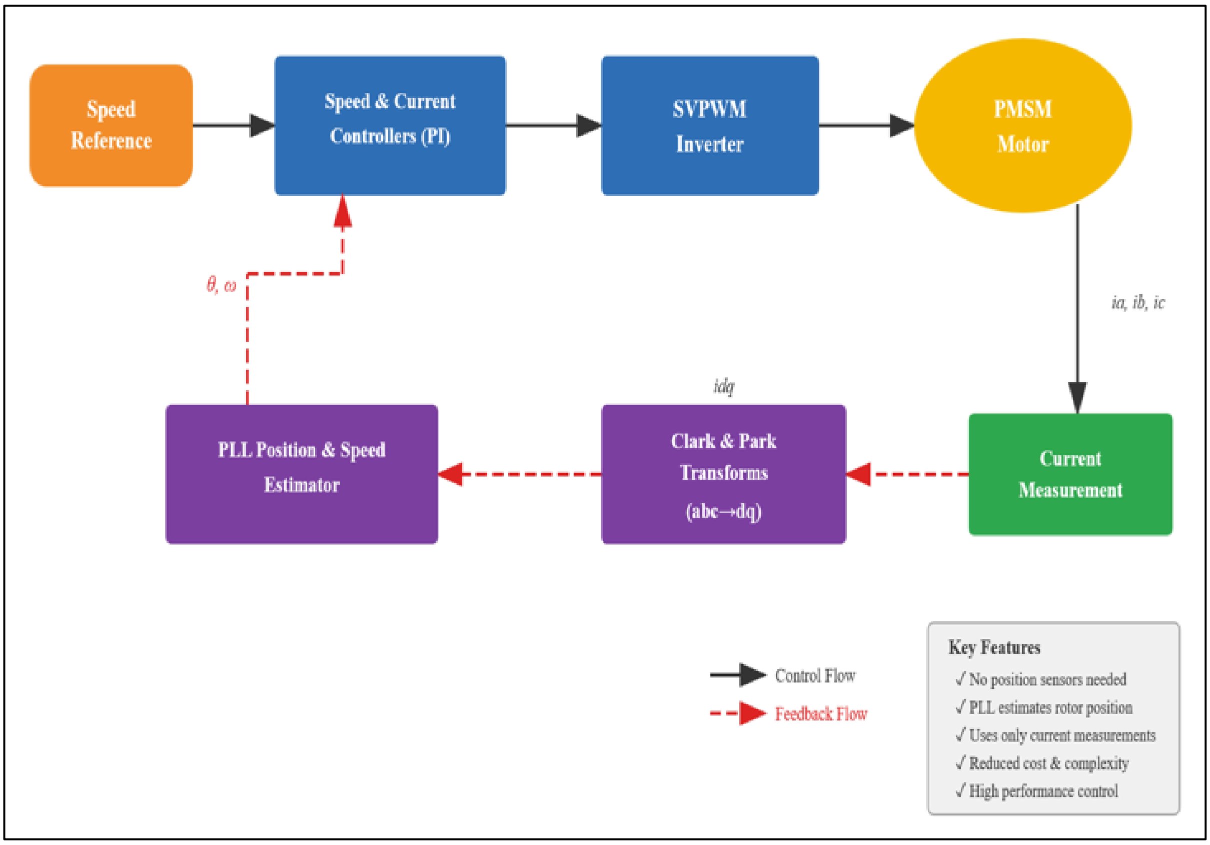

Fig 1 Flow Chart

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➢ *Block Diagram Representation*

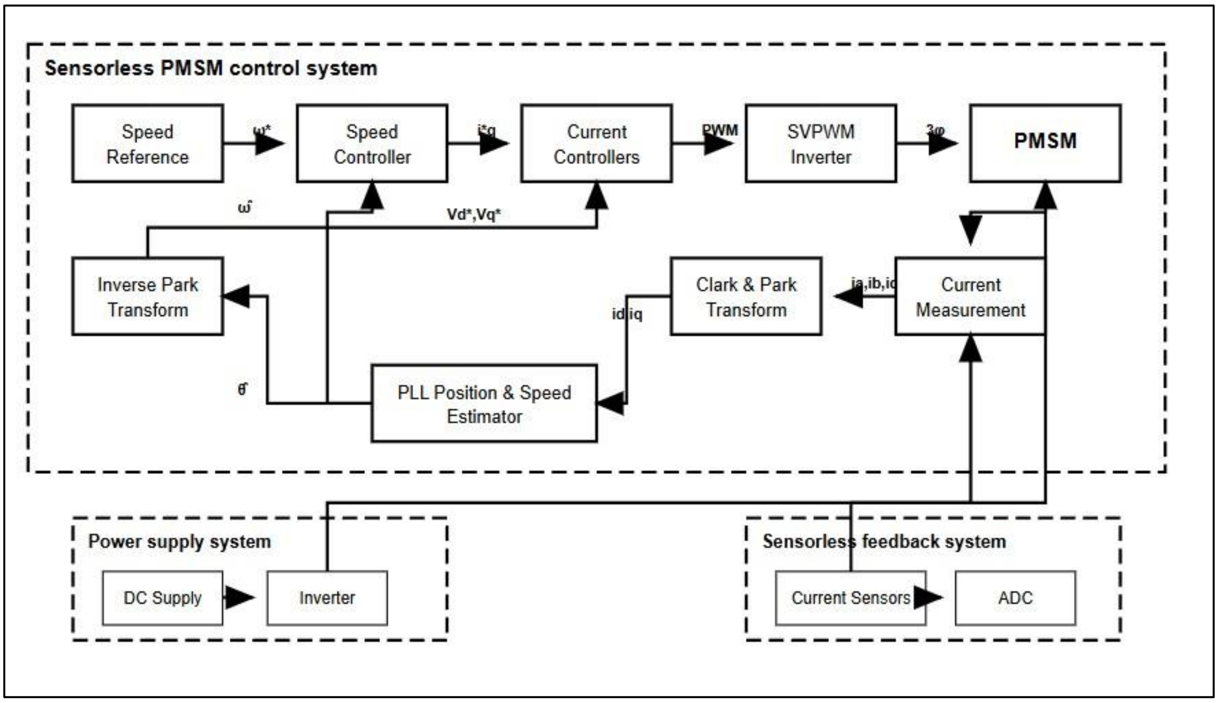

Fig 2 Block Diagram

The block diagram below depicts the sensorless PMSM control system. This system is capable of controlling speed and position of the motor by utilizing no physical position sensors. The first block of the diagram is the speed reference to the system, which provides a speed reference to the system. This speed is combined with the speed and current controller outputs, which provide control signals to the motor consisting of the desired currents in the ddd- and qqq-axis. These signals are then used to determine the voltage references required at the motor. These voltage references from the rotating reference frame are converted to stationary reference frame signals via the inverse park transformer. These voltage references are then converted into switching signals by an SVPWM inverter in order to drive the PMSM motor. The current is measured in order to provide feedback signals for estimation of the motor speed and position. The position and speed estimation is done by a PLL (phase-locked-loop) which uses the electrical signals from the motor to derive the position and speed of the rotor. In order to perform the required control and estimation, the Clark and Park transform electrical currents from their three-phase signal into two-phase components, thus simplifying the control and estimation procedures. The phase locked loop estimation and control system is required to perform properly in order to be economically viable. The system requires a DC bus for supplying power to the inverter and the DC signal supplied to the inverter is converted back into the required AC signals to drive the motor. Via the feedback and monitoring system consisting of current sensors and analog to digital converter, the motor can be continually monitored, and reliable estimates on performance achieved. The systems resultant lower cost, and lower implementation complexity, lead to reliability over a long period of time.

➢ *PLL Speed and Position Estimation Equations*

$$\omega_r = K_p * (\varphi_m measured - \varphi_e estimated) \quad (1)$$

$$\theta_r = \int \omega_r dt \quad (2)$$

Once the speed is estimated, it integrates the speed to estimate the rotor position

ω_rRotor speed.

K_p: Proportional gain of the PLL.

K_pMeasured phase (typically from back-EMF).

$\varphi_m measured$: Estimated phase (from PLL).

➢ *Stator Voltage Equations (v_d and v_q)*

$$v_d = R_s * i_d + \left(\frac{d*\lambda_d}{dt}\right) + \omega_r * \lambda_q \quad (3)$$

$$v_q = R_s * i_q + \left(d * \lambda_q/dt\right) - \omega_r * \lambda_d \quad (4)$$

These equations describe the stator voltages in the d-axis (v_d)and q-axis (v_q) of a PMSM.

R_s: Stator resistance.

i_q, i_d : The currents in the d-axis and q-axis.

$\lambda\_(d,\ )\lambda\_q$: The flux linkages in the d-axis and q-axis.

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➢ *Speed Estimation Equation (ω_r)*

$$\omega_r = d * \theta_r / dt \quad (5)$$

This equation describes the relationship between rotor speed (ω_r)and rotor position (θ_r).

ω_r: Rotor speed.

θ_rRotor position (angle).

➢ *Equation Explanation Electromagnetic Torque (T_e)*

$$T_e = (3/2) * (P/2) * \left(i_d * \lambda_q - i_q * \lambda_d\right) \quad (6)$$

This equation calculates the electromagnetic torque (T_e) in a Permanent Magnet Synchronous Motor (PMSM).

P: Number of pole pairs in the motor (usually 2 or 4 for PMSM).

i_d, i_q: The currents in the d-axis and q-axis (direct and quadrature axes, respectively).

λ_d,λ_q: The flux linkages in the d-axis and q-axis.

The torque T_e depends on the difference in flux linkage between the two axes and the currents, scaled by the pole pair number.

III. EXPERIMENTAL STEP

The devices used in this experiment comprise an oscilloscope used for data acquisition and graph making, a motor which is a PMSM, an inverter for motor control, and a laptop on which the simulations were done and in which the setup was run. The experiment was done in two parts. The first was a random frequency range of 10kHz to 13kHz was used, followed again by the same frequency range but in addition to the sensor less control system of the PMSM. and the data obtained from the experiments are presented below.

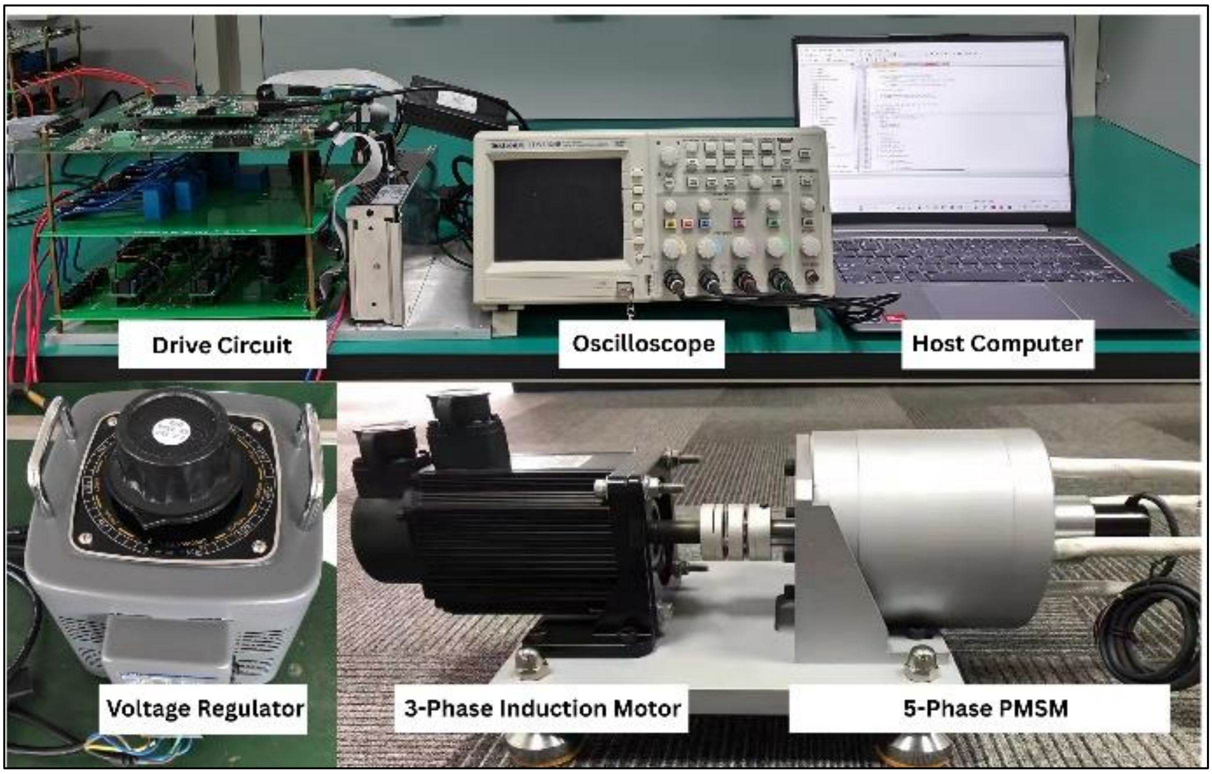

Fig 3 Three-Level Drive PMSM Motor Experimental Platform

Table 1 Motor Parameters for PMSM

Parameter	Value	Unit
Stator Resistance (Rs)	0.65	Ohms
Inductances: Ld (d-axis)	2e-3	Henry (H)
Inductances: Lq (q-axis)	2.5e-3	Henry (H)
Flux Linkage	0.1166	V·s
Inertia	0.01	kg·m²
Friction	0.008	N·m·s
Pole Pairs (p)	4	-
Torque (Tm)	Not defined	N·m
Rotor Flux Position	Aligned with Phase A	-

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IV. RESULTS

The experiment was done in two parts. The first was a random frequency range of 10kHz to 13kHz was used, followed again by the same frequency range but in addition to the sensor less control system of the PMSM. and the data obtained from the experiments are presented below.

➢ *Random Frenquency Results*

- Random frequency(10kHz and 11kHz) signals show irregular and noisy oscillations in the time domain, with significant EMI in the FFT.

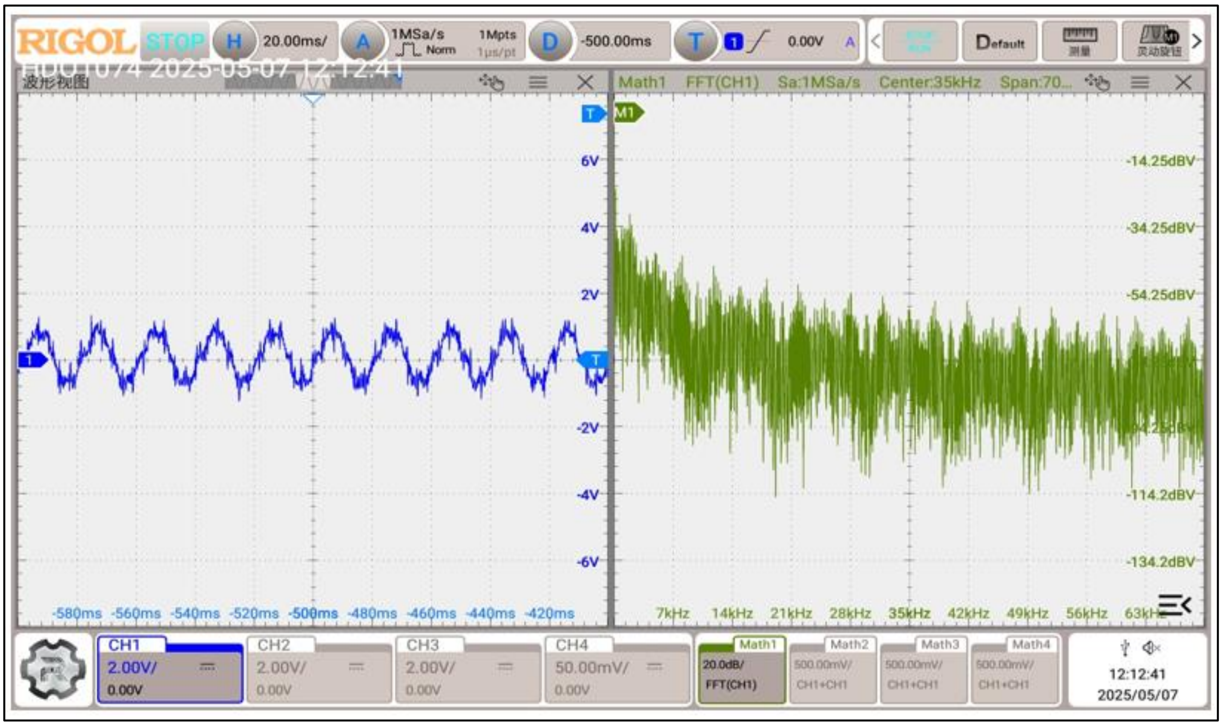

Fig 4 Random Frequency – 10 kHz

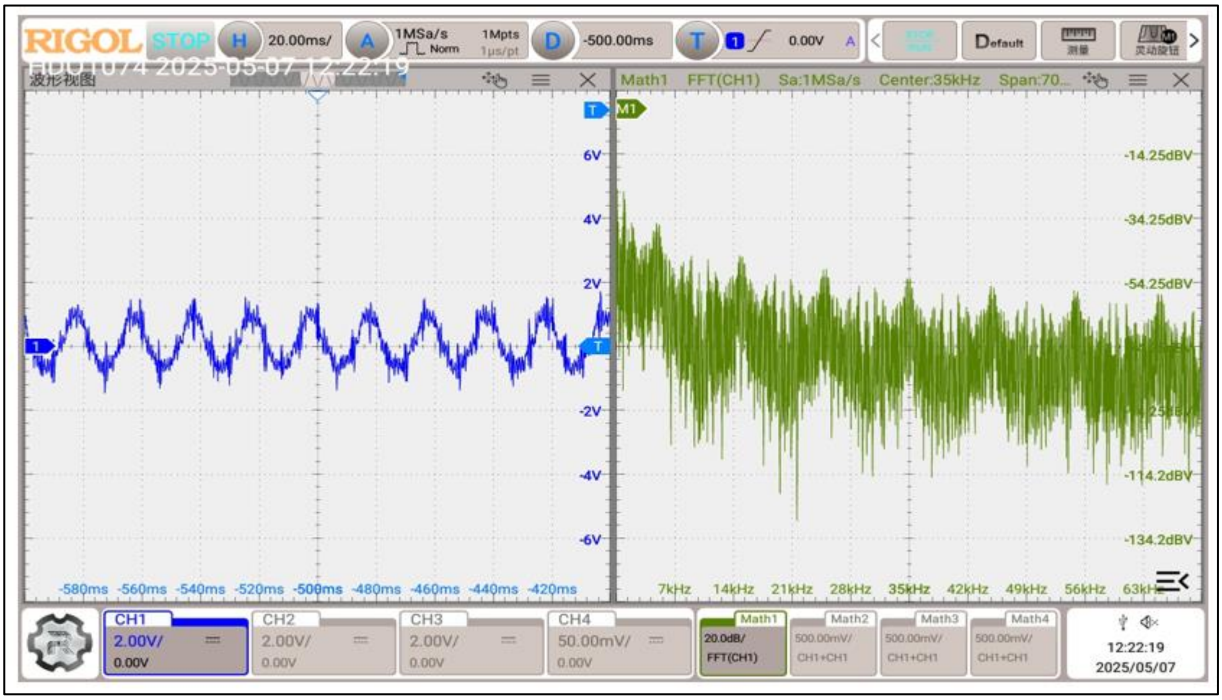

Fig 5 Random Frequency - 11 kHz

- Distorted signal with peaks at 12 kHz, indicating substantial EMI around this frequency and Similar pattern with high noise and harmonic energy, especially at 13 kHz, leading to high EMI.

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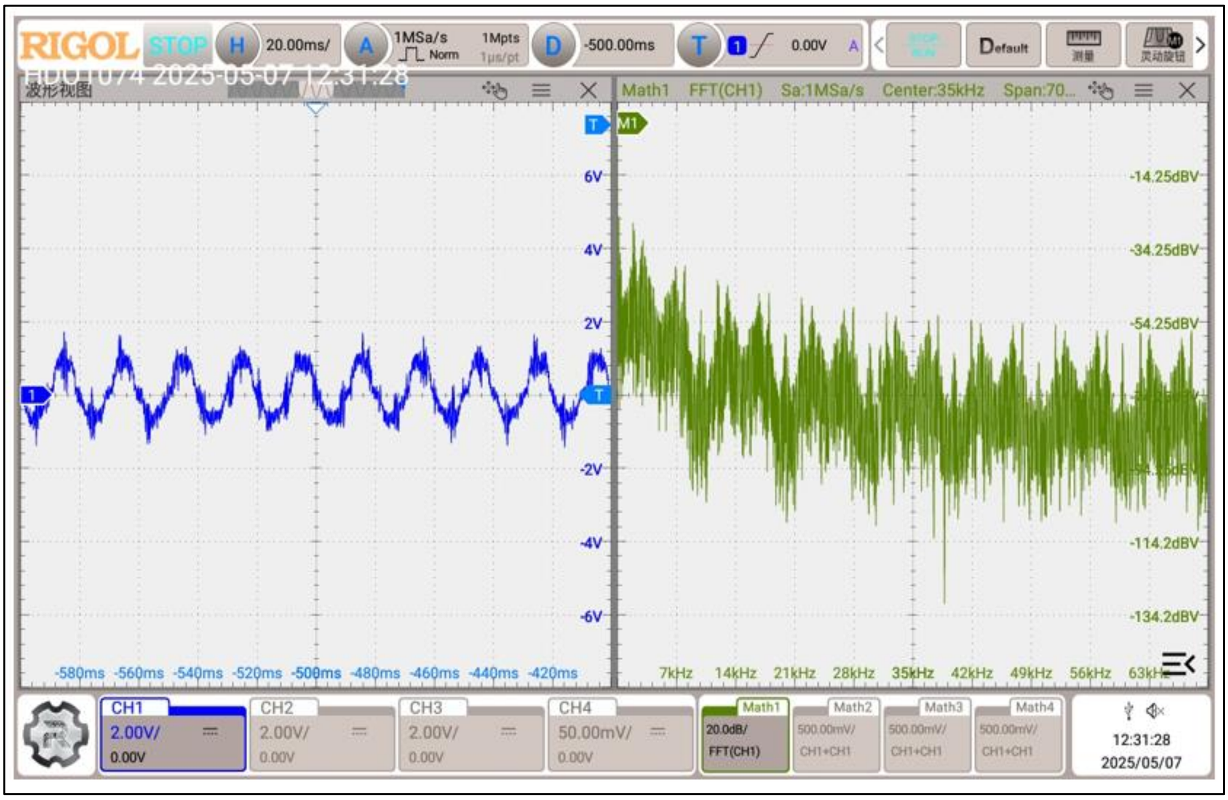

Fig 6 Random Frequency – 12 kHz

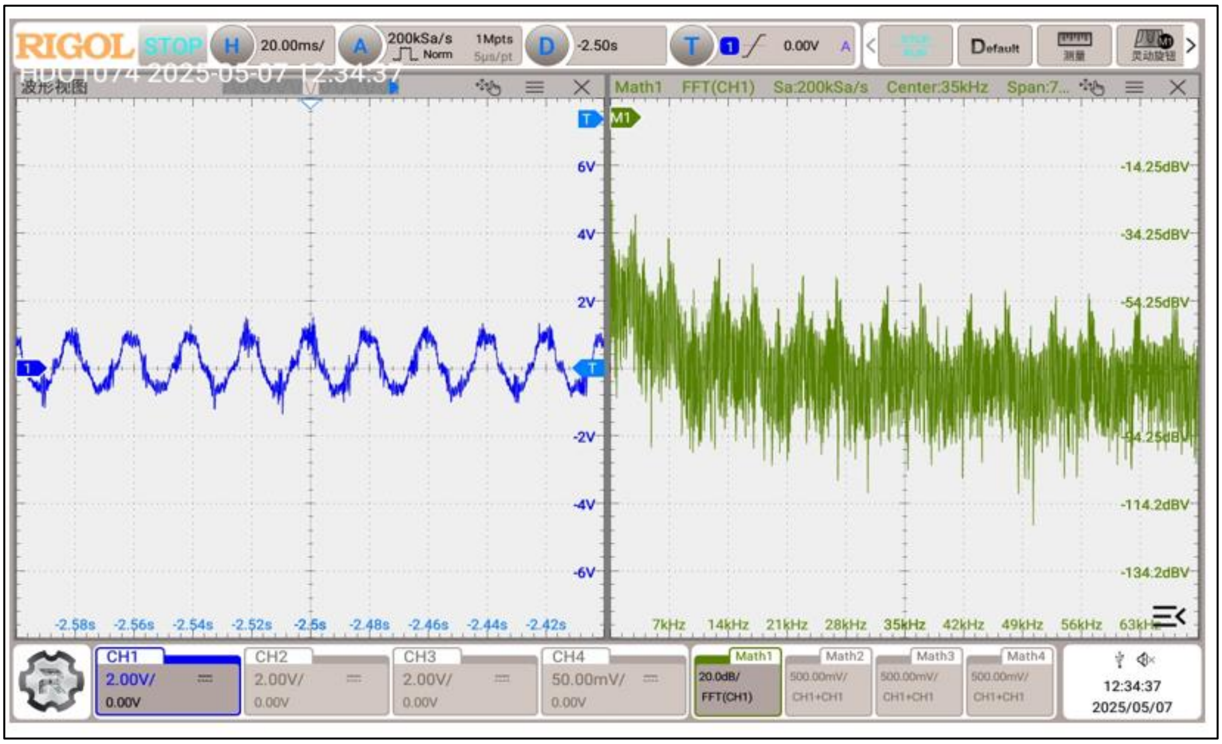

Fig 7 Random Frequency – 13 kHz

➢ *Senser Less Control System results*

The PMSM control system with sensorless produce better results with lower EMI as was expected. The FFT analysis show a clean signal with low noise and great efficiency of the system. Signals 10kHz, 11kHz, 12kHz and 13kHz show very clean signals with well-defined peaks. This system makes it fast to minimize mechanical sensors on system which gives a more reliable and low cost system.

- The first two results shows the value of FFT is -14.25 and -34.25 dBV which shows the Sensorless system reduces high-frequency noise, showing a cleaner signal with less EMI.

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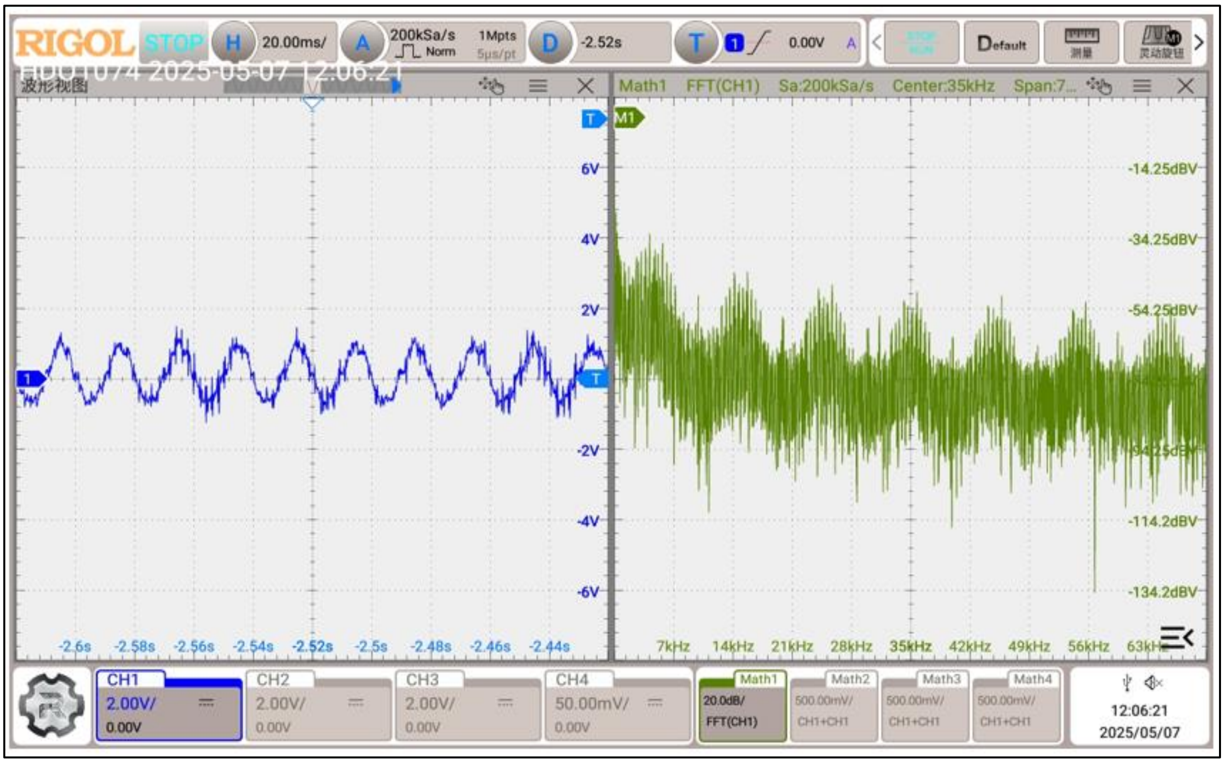

Fig 8 Sensor Less Control System – 10 kHz

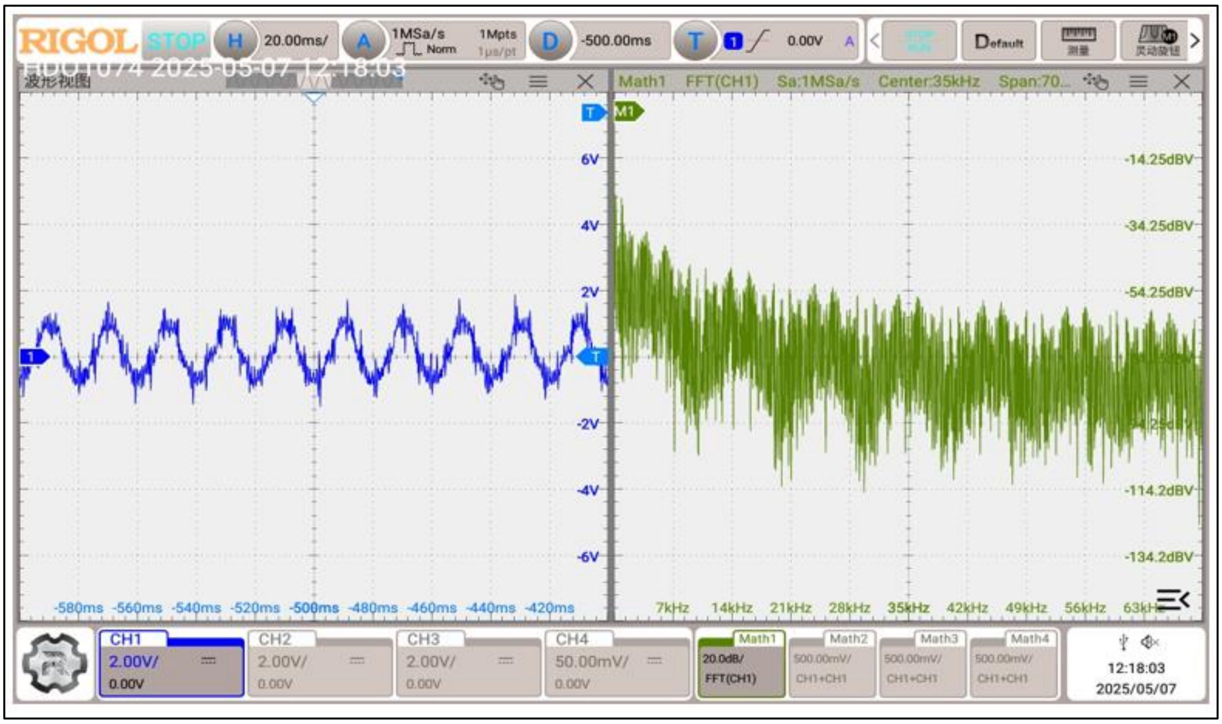

Fig 9 Sensor Less Control System – 11 kHz

- The PLL-based sensorless control system demonstrates improved stability and reduction of noise at switching frequencies of 12 kHz and 13 kHz. Effective EMI reduction is demonstrated by the time-domain pattern's decreased oscillations at 12 kHz and the FFT spectrum's smoother distribution with attenuated high-frequency components. The system delivers additional harmonic suppression at 13 kHz, with low signal distortion and a significant decrease in FFT peak magnitude. These findings verify that at higher switching frequencies, the PLL estimator maintains precise speed and position synchronization, resulting in enhanced spectral purity and reliable system performance.

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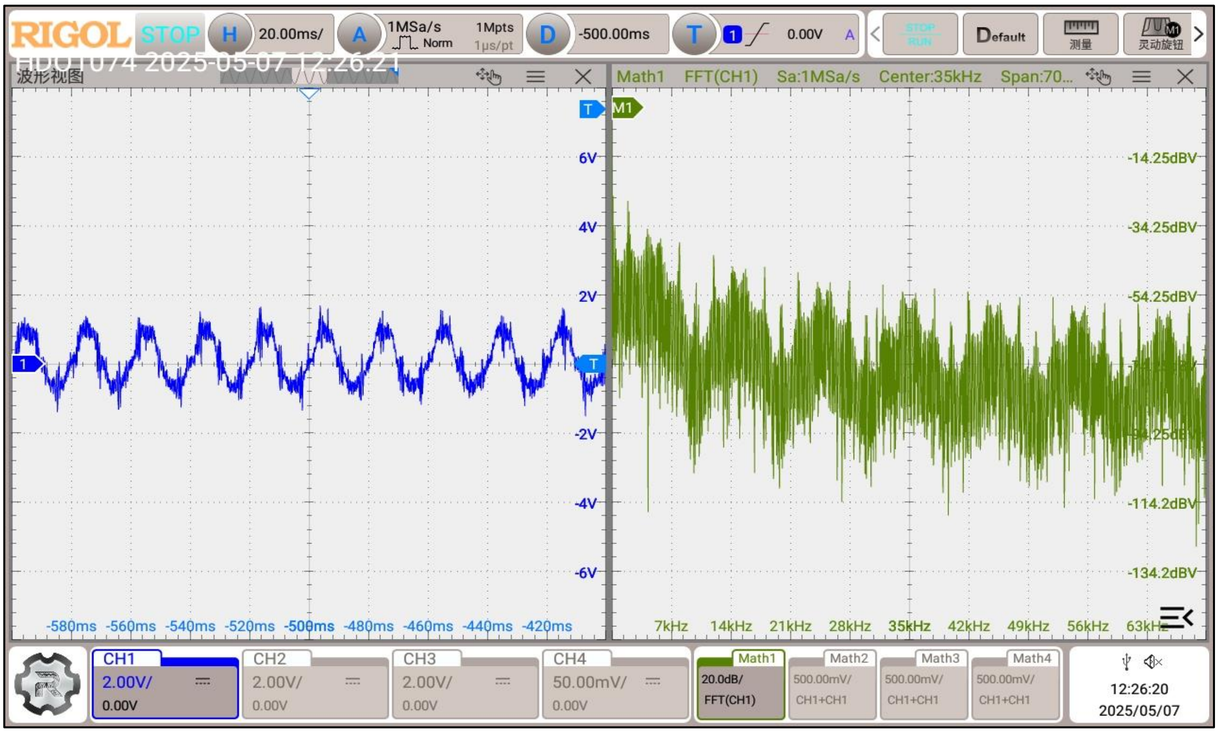

Fig 10 Sensor Less Control System – 12 kHz

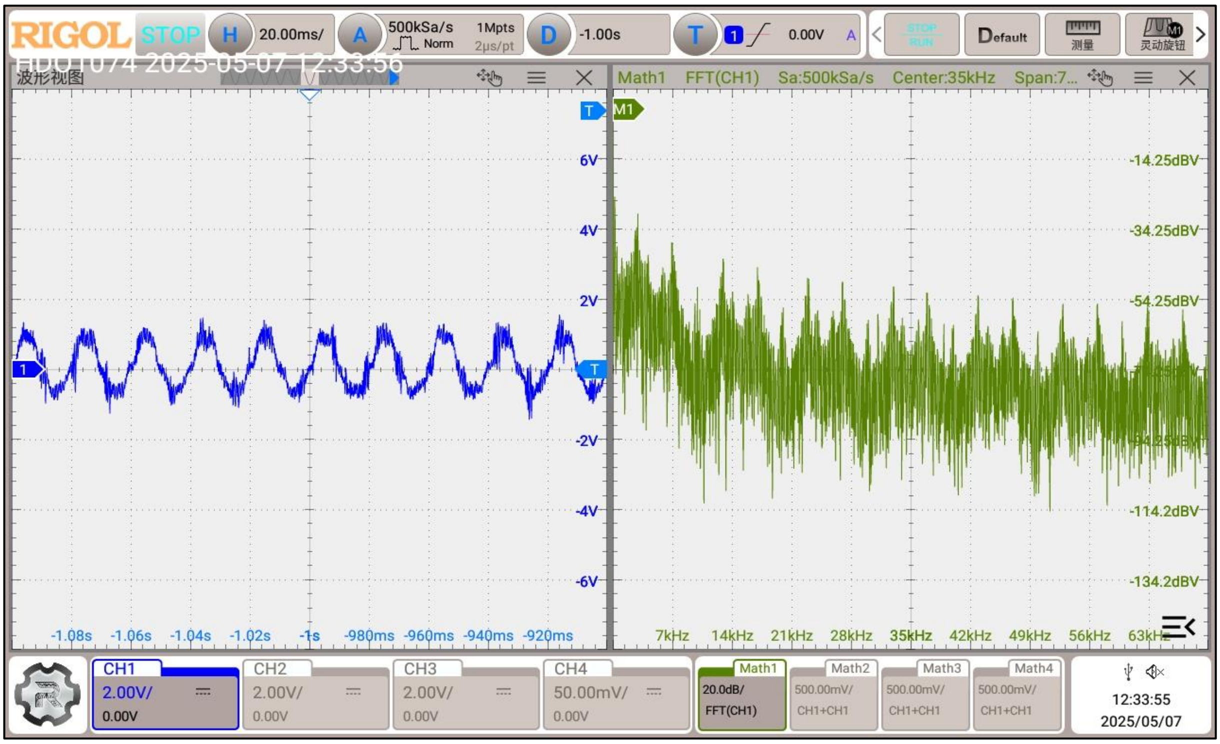

Fig 11 Sensor Less Control System – 13 kHz

➢ *Results and Table Expalanation*

Comparing the random frequency system with the sensor-less control system gives an entirely different picture of performance in regards to noise and EMI.A comparison between the random frequency system and the sensor less control system shows clear differences in noise and EMI performance. The random frequency system exhibits irregular time-domain waveforms and strong, concentrated peaks in the FFT spectrum at switching frequencies between 10 kHz and 13 kHz, indicating high harmonic content and increased EMI. In contrast, the sensor less control system based on a PLL produces smoother time-domain signals and a more evenly distributed FFT spectrum with significantly reduced peak magnitudes. As the switching frequency increases, the sensor less control maintains a cleaner signal with lower background noise, resulting in improved EMI and overall electromagnetic compatibility.

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Table 2 Time- And Frequency-Domain Characteristics of Pmsm under Random Frequency and Sensorless Control

Frequency (kHz)	Signal Type	Time Domain Signal (Blue)	FFT Spectrum (Green)	Peak FFT Value (dB)
10	Random Frequency (No Sensorless)	Oscillations with irregular peaks	High frequency noise at 10 kHz and higher	-14.25 dBV
11	Random Frequency (No Sensorless)	Oscillations with irregular peaks	Similar high-frequency noise at 11 kHz	-14.25 dBV
12	Random Frequency (No Sensorless)	Oscillations with increasing noise	Peaks around 12 kHz in the spectrum	-14.25 dBV
13	Random Frequency (No Sensorless)	Oscillations with noise at 13 kHz	Significant harmonic energy at 13 kHz	-14.25 dBV
10	Sensorless Control (With PLL)	Smoother oscillations with less noise	Sharper peak around 10 kHz	-14.25 dBV
11	Sensorless Control (With PLL)	Cleaner oscillations and lower noise	Peak reduces, cleaner spectrum	-34.25 dBV
12	Sensorless Control (With PLL)	More stable oscillations with reduced noise	Smoother spectrum, lower noise	-54.25 dBV
13	Sensorless Control (With PLL)	Less distortion and smoother oscillations	Further reduction in high-frequency peaks	-114.25 dBV

V. CONCLUSION

This study demonstrates the advantages of a sensorless control system for Permanent Magnet Synchronous Motors (PMSM) rather than a random frequency system. The results demonstrate the sensorless control system, which utilizes a phase-locked loop (PLL) estimation technique, shows much cleaner and more stable signals than the random frequency system demonstrates, which produces irregular signals with high noise and electromagnetic interference (EMI), around the desired frequency, 10 kHz to 13 kHz. The random frequency system will show in its FFT results very large peaks in power at these frequencies showing large harmonic distortion and EMI arising from these signals, thus impairing the performance of the overall system.

On the other hand, the sensorless system has exhibited considerably lower EMI with respect to the amplitude levels of time domain signals and the amplitude levels in frequency spectrum. The results of the FFT have shown very much lower peaks, indicative of a system which can better filter high frequency noise thus making the sensor less system a much more efficient and reliable method for use in PMSM application, particularly in locations where electromagnetic interference is or may be of concern. Overall, the sensor less system not only improves the accuracy of speed and position estimation, but it also increases electromagnetic compatibility, thus providing a better and more economic method of applied results.

➢ *Future Work*

Future work will be focused on enhancing the performance of the Sensorless control system further, considering a wider instance of performance characteristics. The flexibility and robustness imparted by the PLL blocks on a wider range of other operating values, e.g. fast variations, together with a variation of load torque could be optimized. Along with this, also the flexible variation of the PLL parameters will have very beneficial effect in quest of adaptive control algorithms applicating the improved values of the PLL.

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