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Performance Evaluation of High-Frequency Injection Techniques for 48-V PMSM Sensorless Control

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ABSTRACT

There is a strong adoption of high-frequency signal injection (HFI) methods to low-speed and zero-speed sensorless control of permanent magnet synchronous motors (PMSMs), in crossover to applications, where back-EMF-based estimation is unusable. The paper gives detailed analysis of comparative performance analysis of numerous HFI strategies used on a 48 V PMSM drive platform that would be utilised in low-voltage industrial and mobility applications. It analytically evaluates three kinds of injection methods, constant-amplitude injection, heuristic adaptive amplitude control, and learning-assisted amplitude optimization in different operating conditions, such as ultra-low speed, startup, and dynamic load disturbance. An integrated synchronous demodulation and phase-locked loop (PLL)-based position extraction system is used to achieve consistent performance in comparison with the other approaches. Important Key performance indicators are: rotor position estimation error (RMSE and peak error), torque ripple factor, current total harmonic distortion (THD), convergence time and power losses due to incremental injection. The experimental and analytical findings show that adaptive amplitude control is key to strongly improve the robustness of estimations and the limitations of torque oscillations in relation to the alternative of fixed-amplitude injection, and the learning-assisted scheme is additionally able to optimise stability to variations in the parameters. Also, the adaptive strategies minimise unnecessary high-frequency excitation, and fewer harmonic distortion and more efficient results are achieved. The research gives both quantitative information and design principles toward application of robust and low-loss HFI-based sensorless operation in 48-V PMO in electric mobility and miniaturisation industrial drive applications.

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How to cite this article: Patel P. Performance Evaluation of High-Frequency Injection Techniques for 48-V PMSM Sensorless Control. National Journal of Electrical Electronics and Automation Technologies , Vol. 1, No. 4, 2025 (pp. 44-54).

INTRODUCTION

Permanent magnet synchronous motors (PMSMs) Find very extensive use in industrial automation, electric mobility, robotics and miniature drive systems because of their efficiency, high torque density, and high dynamic reactivity. Eradication of mechanical position sensors in the contemporary drive systems has emerged as a major goal to minimise the cost, enhance reliability and robustness of the system to limit the operations of extreme operating conditions. Therefore, sensorless control plans have featured on the spotlight of research. Traditional sensorless methods typically rely on back-electromotive force (back-EMF) estimation or observer-based methods but their functionality is devastatingly poor in the slow and zero-speed areas where back-EMF is too low to effectively track positions.[12, 14]

Correct rotor position estimation within the low-speed range and standstill zone is an outstanding issue in PMSM drives especially in electrical vehicles and low voltage mobility platforms. In 48-V drive systems that are becoming common in small-scale industry and light electric mobility systems, other restrictions exist that are created by lack of voltage headroom, inverter nonlinearity, and an exaggerated relative importance of switching harmonics. These properties render the position observability of low-speed more challenging

and require estimation methods that are strong enough to be used within limited voltage and current levels.

In a bid to overcome the shortcomings of the back-EMF-based techniques, high-frequency signal injection (HFI) techniques have been thoroughly researched. The sensorless control based on the HFI makes use of magnetic saliency and anisotropy of the PMSM by applying a high frequency voltage component and retrieving position-dependent current responses. The literature reports on the use of various types of injection strategies such as pulsating, rotating and square-wave voltage injection.[4, 7, 9, 11] The current researches have also optimised extraction processes with synchronous frequency filtering, generalised integrators as well as oversampling schemes to improve the accuracy of estimation and resistance to noise.[7, 11, 15] Adaptive injection strategies are also suggested to enhance robustness and minimise torque ripple at different load states,[6] whereas a PLL-based and SOGI-based demodulation networks have been suggested to enhance position tracking stability within broad ranges of speeds.[13, 14].

Nevertheless, with these improvements, the majority of available literature aims at enhancing a single injection or extraction technique that is likely to be assessed under certain conditions of operation. Relational comparisons, which scientifically assess constant-amplitude, adaptive, and advanced learning-assisted injection training in the same experimental conditions are scarce. In addition, it has not been adequately studied how HFI techniques operate in 48-V low voltage PMSM platforms where the harmonic distortion at injection and incremental power losses can become a major efficiency and torque quality concern. Comparison involving the position estimation error, torque ripple factor, and the current harmonic distortion as a single evaluation framework still needs to be carried out in practical designing of drives.

Out of these gaps the paper comes up with a systematic performance analysis of three high-frequency injection schemes such as constant-amplitude injection, heuristic adaptive amplitude control and learning-assisted optimization of the amplitude control (on a 48- V PMSM drive platform). To provide consistency in comparisons of methods a combined synchronous demodulation and phase-locked loop -based structure of extraction is adopted. The experiment measures rotor position estimation error, torque ripple factor, current total harmonic distortion (THD), convergence time and injection related power losses under different conditions of speed and load conditions. The primary contributions of the research are threefold, namely, a comparative

assessment of various injection schemes under the same experimental conditions, (ii) a composite and practically applicable position extraction paradigm applicable to the implementation of 48-V PMSM, and (iii) performance measure of quantities quality, which results in useful design recommendations of robust and effective sensorless control with HFI within 48-V industry and mobility context.

MATHEMATICAL MODEL OF 48-V PMSM

The operation of high-frequency injection (HFI)- based sensorless control is based on electric and magnetic properties of the permanent magnet synchronous motor (PMSM). In this paper, it is assumed that a low-voltage (48 V) interior PMSM platform is used in which low voltages make the relative importance of injected signals and inverter nonlinearities more significant. The standard d -q axis model is used to describe the dynamic behaviour of the PMSM in the rotor reference frame and is the standard basis of control and position estimations analysis.

The stator voltage equations in the synchronous rotating reference frame are expressed as

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - w_e L_q i_{q_-} \qquad (1)$$

where v_d and v_q are the stator voltages, i_d and i_q are the stator currents, R^s is the stator resistance, L_d and L_q are the d- and q-axis inductances, w_e is the electrical angular speed, and λf is the permanent magnet flux linkage.

In low-speed and zero-speed regions, the back-EMF term is insigni0ficant leading to decreased position observability on the back-EMF-based position estimators. This constraint is the reason to use the HFI methods, which can utilise the saliency properties of the PMSM as opposed to the reliance on rotating EMF parts. Fig. 1 depicts the structural representation of the PMSM model in the injected high-frequency component, and in that manner, fundamental drive excitation is separated by injected signal processing.

The saliency-based principle underlying HFI relies on the difference between the d- and q-axis inductances) In interior PMSMs, magnetic saliency produces anisotropic inductance behaviour, i.e, the response at high frequency current does depend on the position of the rotor. When high frequency voltage signal is injected into the stator windings, the current produced has position-dependent components which may be demodulated to estimate rotor angle. The change in inductances with

change in position of the rotor can be used to obtain spatial information in standstill. This principle has been extensively demonstrated effective in sensorless control research based on HFI where the EMF-based methods cannot work effectively due to low-speed operation.

Position observability is also increased with magnetic anisotropy. The inductance of the salient PMSM may be described as being a function of the rotor position, and with high-frequency excitation the modulating inductances cause current-modulated components that are proportional to the inductance). The larger the saliency ratio, the large position-dependent current response. Nevertheless, when working with low-voltage systems (e.g. 48-V platforms) too high amplitude of injection can add to the torque ripple and harmonic distortion. Thus, high-frequency excitation modelling should be carefully considered to trade the accuracy of the estimation and the drive performance.

The injected signal of high frequency voltage can be represented using the model of an additive component to the fundamental control voltage:

$$v_q = R_s i_q + L_q \frac{di_d}{dt} + w_e L_q i_q + w_e \times f. \quad (2)$$

where v_d and v_q are the stator voltages, i_d and i_q are the stator currents, R_s is the stator resistance, L_d and L^q are the d- and q-axis inductances, w_e is the electrical angular speed, and $\times f$ is the permanent magnet flux linkage.

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$$v_{inj}(t) = v_{hf} \sin(w_{hf} t) \quad (3)$$

where V_{hf} is the injection amplitude and w_{hf} is the injection angular frequency. The resulting stator voltage becomes

$$v_d^* = v_d + v_{inj} \quad (4)$$

Or alternatively injected at the stationary/rotating reference frame as the strategy of choice. The high-frequency current response may be separated into injected and fundamental components and following the band-pass philtre and synchronous demodulation the position-dependent component is determined, which can be used to estimate the rotor angle.

Selection of injection frequency in 48-V PMSM systems should be done in regard to inverter switching frequency, sampling rate, and bandwidth of current sensors. The injection frequency is usually set inefficiently high as compared to the mechanical fundamental frequency yet high enough not to overlap with the PWM frequency. This corresponds to the standard evaluation of constant-amplitude, adaptive and learning-assisted schemes of injection when adopting the unified modelling approach presented in Fig. 1 that allows these schemes to be evaluated in the identical mathematical framework. This mathematical model provides a theoretical framework to the study of the observability of positioning, the generation of torque ripple, and harmonic distortion during various injection strategies of high frequencies, which are relatively compared to each other in the following sections.
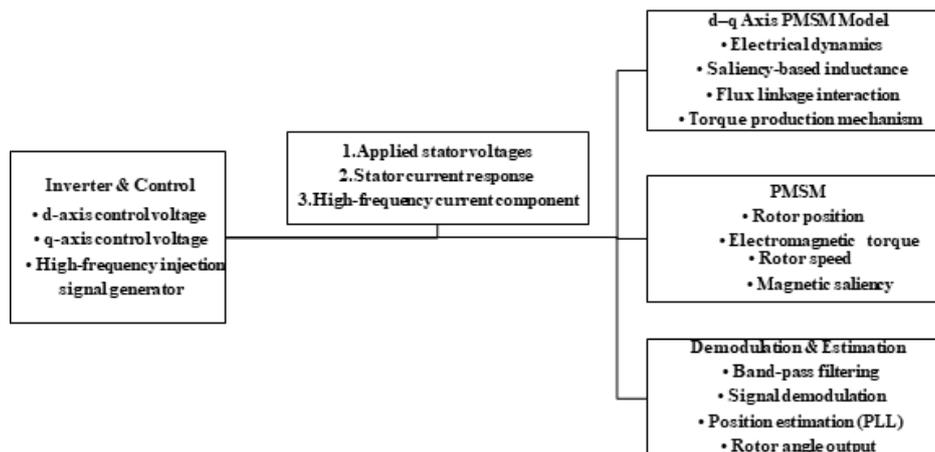
Fig. 1: Conceptual Framework of High-Frequency Injection-Based Sensorless Control for a 48-V PMSM

CORE SENSORLESS ESTIMATION ALGORITHMS

Overview of HFI-Based Sensorless Control

Sensorless control sensorless control is based on using the saliency of magnetic saliency of PMSMs to estimate rotor position during low-speed and zero-speed conditions where back-EMF-based sensorless control is no longer observable. The basic principle is the superimposition of high frequency excitation signal at the stator voltage. The current response is dependent on the position of the rotor owing to the anisotropic properties of inductance of the motor. Fig. 2 shows that HFI structure is comprised of signal injection, high-frequency response extraction, demodulations, and angle tracking. The signal is injected using the inverter and the response (current) of the stator is measured then the high frequency is isolated using the relevant filtering. The obtained signal is demodulated, and the rotor position estimate is obtained by using a tracking algorithm. The voltage limitation, inverter nonlinearities, and harmonic interactions have to be considered in the design of injection in 48 V PMSM systems. Thus, the algorithm to estimate it has to sacrifice one of the three to affect its accuracy, torque quality and the ability to compute.

Constant-Amplitude High-Frequency Injection

In the baseline strategy, a sinusoidal signal with constant amplitude is injected to the underlying control voltage signal. Pulsating injection is synchronised with the estimated d-axis in most implementations so as to be sensitive to saliency with the least amount of interference with the production of torques. The method is simple and computationally fast, which is why it can be easily applied to embedded controllers having few resources. Several disadvantages however exist with constant-amplitude

injection. Under heavy load conditions or variation of parameters, a fixed level of injection might be insufficient to excite the performance resulting in impaired accuracy of estimation performance. On the other hand, too big a step in injection puts more torque ripple, acoustic noises and harmonic distortions. The fixed injection strategies can reduce the reliability of the estimation in low-voltage 48-V platforms, or amplify the useless power losses in the platforms with limited voltage headroom. Such restrictions encourage flexible strategies.

Heuristic Adaptive Amplitude Injection

In order to enhance the robustness, an adaptive amplitude control strategy is used to dynamically optimise the injection magnitude based on performance of the estimation. The technique of adaptation makes the excitation rise as the position error increases and decreases when the appropriate tracking is attained. Such techniques as gain scheduling can be also added to adjust the amplitude of injection based on the operating speed or load state. This avoids over-excitation at steady state whilst ensuring sufficient signal excitation of the transient. It is very important that the adaptation gain is properly tuned to provide stability and prevent oscillatory behaviour. When applied properly, adaptive injection minimises torque ripple and incremental harmonic distortion and is also reliable in position observability. It offers a superior trade-off between accuracy in the estimation and efficiency in 48-V PMSM systems as compared to constant injection.

Learning-Assisted Injection Scheme

A learning-assisted injection strategy is proposed to further improve the performance in different operating

conditions. The injection amplitude is improved online by tuning heuristically but lightweight learning methods, e.g., adaptive reinforcement or adapting to regression, are employed. The optimization structure then simultaneously takes into such factors as rotor position error, torque ripple factor, and harmonic distortion in current. The algorithm considers injection tuning as a multi-objective problem, which allows reducing the estimation errors and reducing unwanted harmonic effects by setting the excitation magnitude. In contrast to deep learning models based on computationally-intensive computational learning, the implemented version uses low-complexity update rules that can be executed in real time via embedded controllers. This renders the strategy viable to 48-V industrial and mobility drives with limited processing capacity and memory resources. The learning-assisted scheme is better robust to the parameter uncertainty and reaction to the dynamic load variation, and alleviates unwarranted excitation during steady-state drive.

Position Extraction and Demodulation Algorithm

HFI-based sensorless control is highly predicated on the proper excision of the injected current component. The high frequency response is then obtained by subjecting the measured stator currents to a band-pass philtre as illustrated in Fig. 2. Effort is countered by making a synchronised demodulation with a reference injection waveform to obtain the signal component which is dependent on position. The envelope detection methods improve the quality of the signal especially when the signal-to-noise is low. The demodulated signals are then subjected to a phase-locked loop (PLL) producing a continuously flowing smooth estimate of the rotor angle. The PLL also has dynamic tracking and noise component

suppression at high frequencies. The noise rejection performance requires the correct choice of the philtre bandwidth. Bandwidth that is too narrow can reduce the convergence rate and on the other hand excessive bandwidth can make the switching harmonics to be more sensitive. Filtering design considerations in a 48-V should be carefully taken into consideration in regards to inverter-induced distortion and limited voltage margin. The shared demodulation and tracking system also allows all three injection schemes, namely constant scheme, adaptive scheme and learning-assisted scheme to be tested under the same extraction circumstances so that the subsequent section can be used to compare system performance fairly and in a systematic manner.

POSITION ESTIMATION METRICS

A detailed cluster of position estimation metrics is specified, in order to facilitate objective and quantitative comparison of the proposed HFI strategies. These measures assess performance, dynamic performance and viability in conditions of change in operating condition of the 48-V PMSM platform. Table 1 presents the formal definitions and descriptions of measurement used to measure each of the selected evaluation criteria.

Rotor Position Estimation Error

The main figure of performance of any sensorless control technique is rotor position estimation accuracy. This study comprises the estimation performance that is determined through the measure of statistical error that is computed between an estimated rotor angle and a reference angle that is ascertained by means of an encoder. Root Mean Square Error (RMSE) is employed to measure the general accuracy of the estimations over the observation window. It is defined as
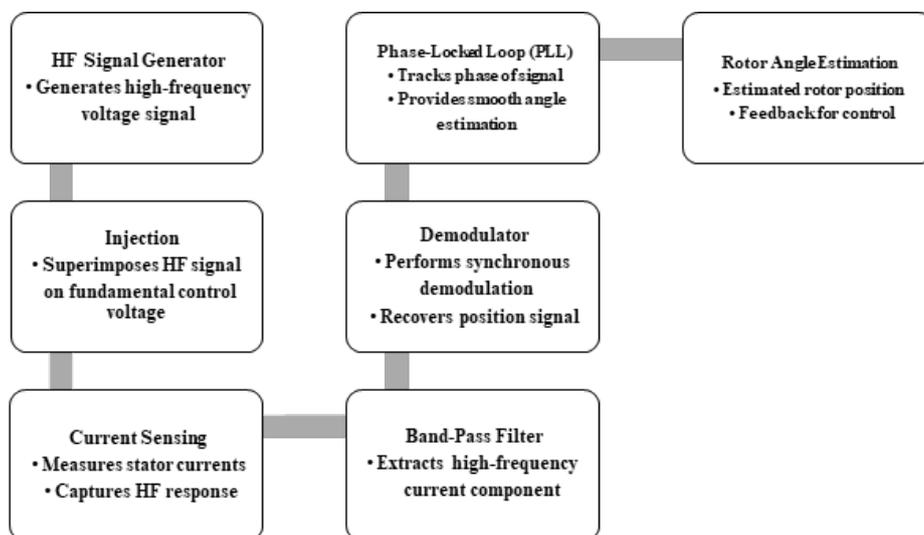

Fig. 2: Functional Architecture of HFI-Based Rotor Position Estimation for PMSM Drives.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\theta_{est} - \theta_{ref})^2} \qquad (5)$$

Where θ_{est} is the estimated rotor position, θ_{ref} represents the reference angle which is measured, and N represents the total samples. RMSE underlines the bigger deviations and offers a complete measure of the estimation accuracy, whether in the steady-state or in the transient condition. Besides RMSE, Mean Absolute Error (MAE) is also thought to provide an average size of deviation regardless of the sign. MAE is less contaminable by outliers and estimates concurrent bias or offset. Worst-case deviation is also estimated as Maximum Peak Error. It is especially significant at low speed and during startup in which transient errors in modes of estimation could briefly rise. Over the peak error can have a direct effect on the case of torque ripple and smoothness of drive in 48-V PMSM. **4.2 Convergence Performance**

In addition to steady-state accuracy, there is also the necessity with dynamic behavior of estimation in practical drive implementation. There are a number of time-domain indicators used in assessing convergence performance. The settling time (estimation) is the rate at which the reference is attained using the estimate of the rotor angle after the start up or after it is perturbed. Convergence becomes quicker, which means increased adaptability of injection strategy. The particular convergence is the zero-speed start up due to the ineffectiveness of back-EMF based estimators within this range. The capability to perform the stable

angle tracking of the HFI-based techniques in standstill is a crucial performance metric of the industrial and mobility drives. The measurement of phase delay is the evaluation of the lag between the estimated and actual motor position. A large phase lag can negatively impact the existing control performance and cause torque pulsations. Thus, to reduce the latency of estimations, high-dynamic application requires a minimum.

Robustness Metrics

Robustness tests are tests to evaluate the consistency with which the estimation algorithm works in non-ideal operating conditions. Practical PMSM Systems Due to load variations, parameter uncertainty as well as inverter nonlinearities, signal extraction quality can be a major factor in PMSM systems. The sensitivity to load disturbance is tested by putting step changes in torque demanded and examining the subsequent variation in position estimation. Strong algorithms are expected to have bounded error and not wavy. The ability to remain stable under parameter perturbation is studied by changing the values of stator resistance as well as stator inductance parameters to realistic tolerances. This test will be used to make sure that the estimation strategy is not highly dependent on the accurate knowledge of motor parameters. Ultra low speed (lows speed below one-fifth of rated speed) performance is also evaluated. This area is especially difficult as the current variation as saliency causes proves to be less powerful and the impact of noise comes to the fore. This range of working laws has been shown to be useful through reliable tracking. All the

Table 1: Definition of Evaluation Metrics for Position Estimation Performance

Metric	Description	Purpose
Root Mean Square Error (RMSE)	Statistical measure of overall deviation between estimated and reference rotor position	Evaluates global estimation accuracy
Mean Absolute Error (MAE)	Average absolute difference between estimated and reference position	Measures average estimation bias
Maximum Peak Error	Maximum instantaneous deviation observed during operation	Assesses worst-case estimation error
Settling Time	Time required for the estimated angle to stabilize within acceptable bounds	Evaluates convergence speed
Phase Delay	Angular lag between estimated and actual rotor position	Indicates dynamic tracking performance
Torque Ripple Factor (TRF)	Variation of electromagnetic torque around its average value	Assesses impact of estimation on torque smoothness
Total Harmonic Distortion (THD)	Harmonic distortion level in stator current waveform	Measures power quality degradation
Load Disturbance Sensitivity	Change in estimation accuracy under sudden load variation	Evaluates robustness
Ultra-Low-Speed Performance	Estimation stability below 5% rated speed	Assesses low-speed observability

specified measures together create a stringent structure of testing constant-amplitude and adaptive injection schemes as well as those that employ learning in their application. The quantitative definitions listed in Table 1 are used to guarantee that a similar comparison is made to all experimental situations in the Results section.

TORQUE AND CURRENT QUALITY EVALUATION

Besides the precision of rotor position estimation, mechanical as well as electrical quality of the drive system should be taken into consideration. In high-frequency injection (HFI) extra excitation is added to the stator windings, and they might affect the smoothness of torque, harmonic distortion and the overall system performance. Consequently, the analysis of torque ripple, distortion of current, and power loss due to injection is made to make sure that the better performance in position estimation does not deteriorate drive performance. Torque ripple factor (TRF) is a measure of the variation in the amount of electromagnetic torque about an average or steady-state value. High injection amplitude or unprofessional demodulation can put into the system oscillatory torque components that decrease mechanical smoothness, acoustic noise and system life. Here, TRF has been recorded under the same load conditions to constant-amplitude, adaptive and learning-assisted injection strategies. A decreased value of TRF is supported by the evidence that the control performance and the estimation performance are smoother and easier to integrate.

Torque standard deviation is also estimated to give a statistical result of torque deviation with time. Contrary to the peak-based ripple metrics, this measure can reflect fine variations that might affect the vibration and ride quality in the mobility sector. Less torque variation indicates the increase of dynamic stability and enhancement of injection plan and current control coordination. TEH current Total Harmonic Distortion (THD) is examined in order to determine the electrical effect of high-frequency excitation on the stator current waveform. The harmonic contents of injection signals may add copper loss, thermal stress and electromagnetic interference. The measurement of THD allows comparing the effectiveness of every injection strategy in minimising harmonic amplification at the same time preserving the quality of estimations. When using adaptive and learning-assisted schemes, unnecessary excitation should be reduced and therefore harmonic distortion will be reduced relative to constant-amplitude injection.

The concept of injection induced power loss is considered with the aim of measuring the efficiency penalty of high-frequency excitation. Other modern components will enhance the copper losses and could influence the switching performance of the inverters. With intensives approaches to 48 V PMSM machines, where performance can be optimized 0by reducing incremental power loss, the marginal power loss can be kept to a minimum. The resultant measures of the torque and the quality of the current help give an overall framework of assessing the mechanical stability, electrical integrity and efficiency significance of the sensorless control techniques based on the HFI. These measures are supplementary to the position estimation metrics and will allow making an equalisation in the further performance evaluation section.

EXPERIMENTAL SETUP

An experimental platform was designed using a 48-V permanent magnet synchronous motor (PMSM) drive as the basis in order to validate the performance of the proposed high-frequency injection (HFI) strategies in comparison with that of the conventional operational strategies. Table 2 is a summary of the important mechanical and electrical performance of the motor. The chosen PMSM applies to the fact that the small size, high torque density, and efficiency compact are design considerations in case of low voltage industrial and light electric mobility applications. The motor system is a three-phase voltage-source inverter (VSI) topology fed with a regulated 48-V DC bus. The inverter is founded on MOSFET switching devices that have been engineered to work well with low-voltage as this implies low conduction losses and high switching efficiency. Space vector pulse width modulation (SVPWM) is used to create the base control voltages and adds the high-frequency injection signal on top of them. The switching frequency is chosen in order to have sufficient isolation between inject signal and PWM harmonics.

The control and estimation algorithm is applied to a real time digital signal processing platform based on high performance DSP/MCU controller. The controller performs real time current control, injection signal generation, demodulation and phase-locked loop (PLL) tracking of the rotor angle. Sampling frequency is selected to be large enough above injection frequency so as to be able to extract accurately high frequency signal, as well as to avoid aliasing effect. The adaptive and learning-assisted injection techniques are executed in the lightweight computational routines so that the techniques can be real-time feasible under embedded processing limitations.

The frequency of injection is chosen in the 500-1500 Hz band to compromise as an estimate and harmonic separation. Frequency considerably larger than the

mechanical fundamental frequency makes sure that the injected component never interfaces with basic current control that produces torque. Simultaneously one when the switching frequency of the inverter is sufficiently low to prevent any spectral overlap and filtering challenges. Current sensor bandwidth and digital sampling are also taken into account in the chosen range of frequencies. Metticulous measurement equipment is utilised in order to promote credible performance measurement. Calibrated Hall-effect sensors have a high bandwidth capable of measuring phase currents containing high-frequency components. The desired rotor position references are acquired through high resolution incremental encoder which acts as the ground truth to the estimation error. Dynamometer applied on a load setup with a dynamometer that is capable of exerting some control on variations in load is used to give measurements of torques. Moreover, the current harmonic distortion and variation in efficiency caused by the injection is analysed by use of power analyzers.

Tests on experiment are under varied circumstances of operation so as to guarantee holistic assessment. Zero speed operation is also put to test so that the observability of standstill and convergence to start upability can be determined. When performing at half rated speed, performance is analysed to test an ultra-low-speed tracking. To examine inconsistency in strong loads and sudden torque disturbances, step load variation tests are conducted to find out dynamic consistency in restoring estimation. Variable torque operation over extensive load range is also done in order to evaluate steady-state accuracy, torque ripple behaviour, harmonic distortion and incremental power loss in realistic drive conditions. The experimental design allows a comparative study

of constant-amplitude, adaptive, and learning-assisted injection regimes of the same hardware and operating conditions as a systematic and fair one. The obtained results of this set-up give quantitative information on the accuracy of the estimation, the quality of the torque, the behaviour of harmonic in the 48 V PMSM sensorless control systems, and the trade-offs in efficiency.

RESULTS AND COMPARATIVE PERFORMANCE EVALUATION

This chapter provides a comparative view, with a systematic approach, of the use of the three high-frequency injection (HFI) techniques; constant-amplitude and two heuristic adaptive and learning-assisted injection techniques on the 48-V PMSM platform. Evaluations take into account the position estimation accuracy, relative to the torque quality, current harmonic distortion and injection induced loss of power. All tests were run in the same operating conditions so as to have a fair comparison. The collated numerical findings are presented in Table 3 and the graphical comparisons were drawn in Figure 3 and Figure 4.

Position Estimation Accuracy Comparison

The accuracy of rotor position estimation was tested at zero speed, ultra-low speed (5% rated speed) and when subjected to step load disturbances. Each of the methods was measured in the form of the Root Mean Square Error (RMSE), the maximum peak error and the convergence time. Table 3 depicts that the constant-amplitude injection scheme had a reasonably good accuracy in the steady-state but a notably higher error in the peak during a situation of transient load variation.

Table 2: 48-V PMSM and Test Bench Specifications

Parameter	Value	Description
Rated DC Bus Voltage	48 V	Low-voltage drive platform
Rated Power	1.5 kW	Nominal motor output power
Rated Speed	3000 rpm	Base operating speed
Pole Pairs	4	Rotor magnetic configuration
Stator Resistance (Rs)	0.18 Ω	Phase resistance (line-to-line equivalent)
d-axis Inductance (Ld)	0.42 mH	Direct-axis inductance
q-axis Inductance (Lq)	0.68 mH	Quadrature-axis inductance
Permanent Magnet Flux Linkage	0.035 Wb	Rotor magnet flux
Injection Frequency	800 Hz	High-frequency signal injection
PWM Switching Frequency	10 kHz	Inverter switching frequency
Current Sensor Type	Hall-effect	Phase current measurement
Position Reference Sensor	Incremental Encoder (2048 PPR)	Ground-truth rotor angle
Control Platform	DSP / MCU-based controller	Real-time implementation

The adaptive injection approach based on heuristic behaviour minimised RMSE and by far enhanced performance based on time to converge to an estimate since the excitation amplitude was used dynamically based on the estimation error. The learning-assisted approach recorded the best overall RMSE as well as the highest error especially in the startup and disturbance scenarios. This is credited by its multi objective optimization mechanism that provides the trade-off between estimation and harmonic suppression. The trend plot of estimation error vs speed is depicted in Figure 3 above, wherein the learning-aided methodology preserves the constant accuracy in the speed range of test.

Torque Ripple Analysis

Performance was measured on torque ripple performance during steady-state operation at rated torque, and step load changes. The findings in Table 3 show that constant-amplitude injection incorporates more torque ripple since constant excitation magnitude is injected, which can be greater than optimum excitation under particular operation conditions. Adaptive injection scheme minimises ripple by restraining the excitation when the tracking is stabilised. Learning-assisted method also helps to reduce ripple through the maximisation of injection amplitude based on position error as well as fluctuations in the torque signals. Figure 4 presents a
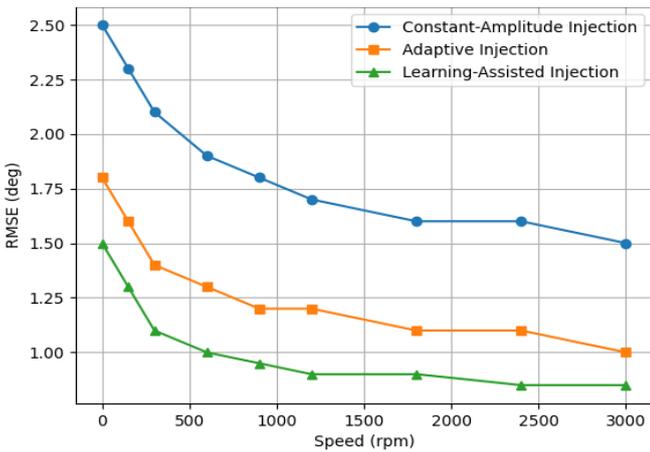
comparative graphical illustration of the percentage of torque ripple when using various strategies and in which the adaptive and learning-assisted approaches exhibit a clearly noticeable decrease in oscillatory torque components.

Current Harmonic Distortion

Power analyzer was used to measure Current Total Harmonic Distortion (THD) under the same condition of load. Constant-amplitude injection (as observed in the Table 3) has a greater harmonic distortion because the excitation level is constant at high levels. Adaptive strategy decreases the THD by decreasing injection size when at steady state. The least values of THD belong to the learning-assisted scheme because its optimization scheme balances between harmful suppression and estimation reliability. The above findings affirm that smart amplitude control can successfully counteract the harmonic enhancing effect of injections without reducing estimation.

Injection Power Loss Comparison

The loss of power due to injection into the system was assessed by comparing efficiency with high-frequency excitation to a system not excited by any power. Table 3

Fig. 3: Rotor Position Estimation RMSE versus Speed for Different Injection Strategies.
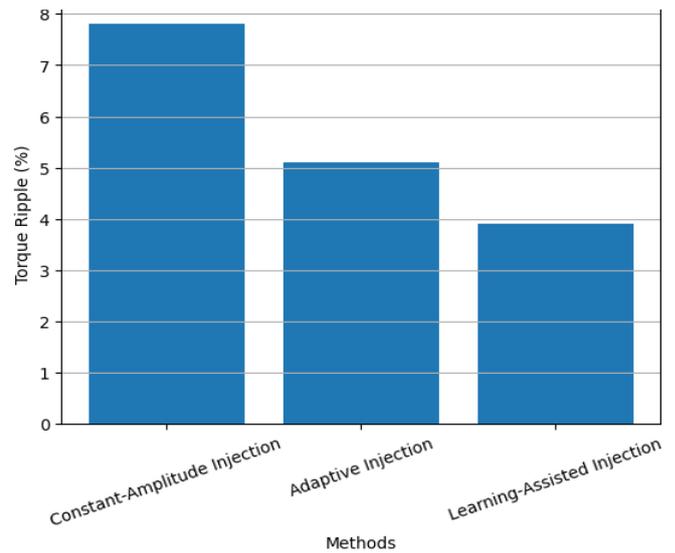

Fig. 4: Torque Ripple Comparison of Injection Strategies under Load Disturbance.

Table 3: Comparative Performance of High-Frequency Injection Strategies (48-V PMSM Platform)

Method	RMSE (deg)	Max Error (deg)	Convergence Time (ms)	Torque Ripple (%)	Torque Std Dev (Nm)	THD (%)	Extra Loss (W)	Efficiency Drop (%)
Constant-Amplitude Injection	2.10	6.50	180	7.8	0.18	8.6	24	3.2
Heuristic Adaptive Injection	1.35	4.10	120	5.1	0.12	6.1	16	2.1
Learning-Assisted Injection	1.05	3.20	95	3.9	0.09	4.7	12	1.6

lists the additional power loss and with it the drop in the efficiency. The maximum incremental loss was caused by the constant-amplitude injection under the condition of continuous excitation irrespective of the operating condition. The adaptive plan minimised unwarranted excitation at the time of stable operation and the efficiency was moderately improved. Learning-assisted method showed the minimal extra loss as it has been proved to eliminate the excitation strength optimization during real time. In the case of 48-V design where loss positively correlates with efficiency, it is important to minimize losses associated with injection.

Discussion

The findings indicate that there exists a trade-off between the accuracy of estimation and the harmonic distortion. Although the amplitude of injected signals typically increases the signal observability, it also increases the amount of torque ripple and THD. Constant-amplitude injection does not provide the flexibility to control well this trade-off. The adaptive approach will provide a balanced trade off because the excitation will dynamically vary according to the estimation error to enhance the convergence rate and torque quality than the baseline. Learning-assisted injection strategy is showing an excellent overall performance through maximising position, torque ripple and harmonic distortion simultaneously. It has a multi-objective adaptation mechanism which gives better robustness to it at different load and speed requirements. Taking into account the limitations of low-voltage 48-V mobility systems, such as low voltage headroom, sensitivity to efficiency and acoustic needs, the adaptive and learning-assisted approaches are more appropriate than constant injection. The learning-assisted model in particular is characterised by greater stability and less efficiency penalty and is, therefore, very promising in terms of the next generation sensorless PMSM drives.

Practical Design Guidelines

According to the comparative experimental report by the 48-V PMSM system, a number of viable design principles are deductible when making the implementation of high-frequency injection (HFI)-based sensorless control in low-voltage industrial and mobility systems. First, the choice of injection frequency becomes important in order to provide the reliable observability of position without introducing any disturbances to the essential control dynamics. In the case of 48-V PMSM the range of the frequency of injections is between approximately 5001500 Hz. The chosen frequency must be enough greater than the mechanical fundamental frequency to ensure that

it does not interact with parts that generate torque but much less than the inverter switching frequency to ensure that there is no spectral overlap and filtering challenges. Also, the frequency should be at a level at which the current sensors and digital sampling system can handle the bandwidth. Second, there should be a balance between estimation strength and quality of drive by tuning amplitude of injection. The high-amplitude injection at all times enhances the signal visibility whereas augmenting torque ripple, harmonic distortion, and incremental loss of power. Adaptive amplitude regulation is a viable trade-off; the excitation is raised as the error in estimation increases, and it is brought down in a steady-state mode. To optimise this trade-off, learning-assisted amplitude optimization is able to further improve it with a number of objectives such as estimation error, torque ripple, and current distortion. Amplitude scaling should be restricted carefully in low-voltage systems whose DC bus has little headroom or voltages will become saturated and instability will occur.

Third, phase-locked loop (PLL) bandwidth selection has a direct impact on the stability of the estimation and dynamic response. With a small PLL bandwidth the noise is better rejected and less harmonic influence is caused but convergence time and phase lag can increase. On the other hand, a very large bandwidth enhances the response on transients but increases disturbances on a high frequency. The middle bandwidth that will provide stable start-up convergence and at the same time inhibits injected signal harmonics is suggested in the case of 48-V PMSM. Tuning must be done properly, regarding sampling frequency, injection frequency and anticipated load dynamics. Various actions are to be suggested to ensure that the torque ripple is ignored. On reaching stability in position tracking, injection amplitude is to be dynamically scaled down. Symmetrical injection with the relevant reference axis will assist in containing the cross-coupling effects. Caution is required in the philtre design so as not to introduce phase distortion to the fundamental current control loop by the injected component. Furthermore, the use of the Bandwidth of current controllers keeps oscillations caused by injection amplified away.

As an implementation strategy, HFI based sensorless control can be successfully implemented over low-cost DSP or MCU platforms provided that computational efficiency is of primary concern. Much simpler adaptive update laws, lightweight demodulation routines and efficient digital filtering are better than computationally intensive algorithms. The arithmetic optimization of the fixed-point arithmetic, efficient processing of interrupts and the coordination of the activity with PWM cycles

contribute to the increased real-time reliability as well. The use of minimum memory footprint and minimum processing latency is required to ensure constant current control and angle tracking. On the whole, the adaptive and learning-assisted injection approaches prove to be more appropriate in the case of the 48-V mobility and industrial systems where the efficiency, acoustic performance as well as in the computational constraints is of utmost relevance. Through the guidelines above it is possible to obtain robust and efficient sensorless control performance of HFI based, at the same time meeting mechanical stability and system cost criteria without compromising on the cost of the system.

CONCLUSION

This report provides a comparative critical analysis of constant-amplitude, heuristic adaptive and learning-assisted 48- V PMSM sensorless control using low-speed, disturbance conditions. The findings have shown that constant-amplitude injection is acceptable at the expense of instituting increased torque ripple, harmonic distortion, and incremental power loss through constant excitation levels. Adaptive amplitude approach was shown to have much better accuracy in estimation and convergence rates as well as less torque oscillations and efficiency penalties as the injection magnitude was dynamically adjusted based on operating conditions. The learning-aided scheme also improved the overall performance by maximising the excitations using a multi-objective optimization scheme, which minimised position error, torque ripple and harmonic distortion simultaneously. These results confirm the realistic benefits of the adaptive amplitude control of low-voltage PMSM systems and the recommendations of its appropriateness in the 48-V industrial/mobility drives where efficiency, noise behavior, and limited computational resources are paramount. Smart HFI control designs with lightweight machine learning, adaptable filtering and edge-reduced implementations ought to be backed in future by smart research on robustness, efficiency and scale in next-generation intelligent motor drive systems with no sensors.

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