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Review on improving Accuracy in Position Estimation For SynrmSensor Less Control Systems By Optimizing And Mitigating Dead-Time Harmonic Currents

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Abstract-

This review investigates recent advancements in mitigating dead-time harmonic distortion and rotor position estimation errors in the sensorless control of Synchronous Reluctance Motors (SynRMs). The objective of this study is to analyze how various control and compensation techniques improve current waveform linearity, torque smoothness, and estimation accuracy under inverter non-idealities. The methodology involves a comparative evaluation of recent research focusing on dead-time compensation algorithms, optimized PWM schemes, adaptive observers, and AI-based estimation approaches. These studies were systematically reviewed to assess their experimental validation, implementation feasibility, and performance improvements across different motor configurations. The results reveal that adaptive and AI-driven compensation methods effectively minimize harmonic distortion and enhance sensorless estimation reliability, especially in low-speed regions where back-EMF signals are weak. However, limitations persist in achieving robust real-time adaptability and scalability for high-power applications. The review concludes that integrating intelligent hybrid control architectures with hardware validation can lead to more efficient, accurate, and reliable SynRM drives, paving the way for the next generation of sustainable industrial motor systems.

Keywords- Dead-time compensation, Sensorless control, Synchronous Reluctance Motor (SynRM), Harmonic distortion, Adaptive estimation

I. Introduction

Synchronous Reflex Motors (SynRMs) are a good alternative to classic induction and permanentmagnet drives because they are easy to use, work well, and are cheap. Because they don't need rare-earth minerals like Permanent Magnet Rhythmic Motors (PMSMs) do. [1]–[4], For driving motors, SynRMs are better because they are excellent for the environment and cost-effective. They are becoming more widespread in business automation, electric automobiles, and green power systems because they have built-in benefits such less rotor loss, higher torque density, and greater efficiency when the load changes. But to get the best results out of SynRMs, need to know precisely when the rotor exists so it can control torque and flux well. Positional sensors like encoding or resolvers used to be used to get this kind of knowledge. But these types of sensors make it more expensive, challenging to use, as well as prone to break while the weather is poor.

Because of this constraint, sensorless control systems have been made that use measured voltages and currents to infer where the rotor is. This makes the systems less dependent on hardware while yet keeping control accuracy. Over the past ten years, sensorless control techniques have changed a lot [5]–[8]. They use mathematical models, observers, or signal-injection methods to figure out where the rotor is without physically measuring it.

Fig. 1 Synchronous Reluctance Motors (SynRMs) [9]

The Model Reference Adaptive System (MRAS), Extended Kalman Filter (EKF), and High Frequency Signal Injection (HFI) are some of the most well-known methods because they work well under a wide range of load and speed situations. Even with these improvements, getting a high level of precision in position estimation is still hard, especially in inverter-fed SynRM drives where things like dead-time effects and voltage distortions can cause big estimate mistakes. The inverter uses pulse width modulation (PWM) to change DC electricity into AC power so that the motor can work. A little delay called dead-time is added between switching transitions to keep power switches from short-circuiting. This dead period is necessary to safeguard the hardware, but it also causes unwanted voltage errors and harmonic currents, which change the current waveform and make the overall control performance worse.

When the system is moving slowly or carrying a light load, the induced back electromotive force (EMF) is small, and the system depends largely on accurate current measurement. This makes the problem of location estimate inaccuracy worse. Harmonic currents caused by dead time mess with the basic parts of the stator current, which causes oscillations and wrong feedback for the estimation algorithms. These harmonics not only make the torque less smooth, but they also hurt the control system's dynamic response and stability. As a result, location estimation techniques may have phase lag, drift, or offset problems, especially when the switching frequencies change or the loading circumstances are not linear. These kinds of errors can cause torque ripple, more noise, and lower system efficiency, which makes sensorless SynRM control less useful in industrial settings where precision is important [10].

Dead-time harmonic currents have effects that go beyond just distorting signals. They produce more damage, heat, and shorten the life of motor parts. Also, these harmonics make it harder to tune observers and filters in the estimating algorithms since they add noise components that overlap with the relevant signal spectrum. To get precise sensorless control, it's important to make up for dead-time effects. Numerous studies have investigated strategies to alleviate this issue, including dead-time compensation algorithms that modify the inverter output voltage and PWM optimisation approaches that reduce harmonic emission. Recently, adaptive and AI-assisted methods have been suggested that use neural networks and machine learning models to automatically fix voltage problems and guess how harmonics will behave when operating conditions change.

As the need for drive systems that are both high-performance and cost-effective grows, it is important to improve the accuracy of position estimation in SynRM sensorless control systems by optimising and reducing dead-time harmonic currents. This study seeks to furnish a thorough examination of current methodologies, emphasising their advantages, constraints, and relevance in practical contexts. This review has four main goals: first, to look at the basic link between deadtime effects and position estimation accuracy; second, to look at the mathematical and experimental models used to describe harmonic currents in inverter-fed SynRMs; third, to look at the best ways to reduce and improve these effects, including both traditional and AI-based methods; and finally, to find the gaps in current research and suggest ways to make estimation more reliable and control more reliable in the future[11].

This review examines the key factors affecting position estimation in SynRM drives, emphasising the interplay between inverter-induced harmonics and control algorithms. It combines information from both theoretical and experimental investigations to show how different tactics for compensation and optimisation affect the dynamics of the system and the accuracy of the estimates. The study also looks into how well different sensorless control methods work when there is dead-time distortion. It puts together what has been found in recent studies. The study intends to help researchers and engineers build sensorless control systems that are stronger, more flexible, and more efficient. These systems should be able to achieve the same level of accuracy as sensors without needing mechanical feedback devices. In short, to make position estimates more accurate for SynRM sensorless control systems, need a plan that comprises precise modelling, clever compensation, and advanced optimisation. One of the main issues in this subject is deadtime harmonic currents. They have an effect on both the estimation process and the entire drive's efficiency and stability. This paper seeks to elucidate innovative concepts and nascent technologies that can transcend current limitations, so promoting the advancement of the next generation of high-performance, sensorless SynRM drives through meticulous research and discussion.

II. Related work

Marčetić & Matić, et al. 2025 The paper presents a unified shaft-sensorless control methodology for PMa-SynRM drives, improving startup and low-speed regulation. The method employs rotor parking and high-frequency voltage injection to make it easier to find the rotor's position and increase dynamic torque performance. This lets fans and pumps perform well and dependably [9].

Cai & Luo, et al. 2025 A flux saturation model that deals with parameter nonlinearity and crosssaturation effects in SynRM sensorless control is suggested. This method improves the accuracy of rotor estimates and the system's stability by using hysteresis voltage to find model parameters. Experimental validation corroborates the model's efficacy and accuracy in real-time control applications [5].

Ilioudis,et al. 2025 A sliding mode observer (SMO) and a modified EMF observer are offered as a sensorless control method for SynRM drives. The method uses the specified γδ reference frame to make sure that the rotor speed and position are always measured correctly, no matter what. Simulations show that the method works effectively, finds a solution rapidly, and gives reasonable estimates [12].

González-Cagigal et al., 2025 The research compares the Extended Kalman Filter (EKF) with the Unscented Kalman Filter (UKF) in the model predictive control of PMA-SynRM drives. Simulation analysis looks at how well a system works, how fast it can compute, and how likely it is to make mistakes when measuring. The results show which Kalman filter method is superior for improving sensorless operation and dynamic performance [13].

Guo et al., 2024 displays a four-stage current oscillation (I-f) control scheme that is supposed to help Synchronous Repulsion Motors (SynRMs) perform better when the speed and current are low, which is when normal extended backward EMF or flux-based approaches don't work. To deal with energy saturation, the method uses an easy method to find inductance. It also adds high-frequency electricity injection to keep changing the rotor angle or current amplitude. This makes it easy to go to the low-speed zone while maintaining sensorless control steady. Experimental findings on a 5.5 kW SynRM show that the method works and is dependable for improving estimates of position and drive performance[14].

TABLE I. LITERATURE SUMMARY

Author/Year	Method	Results	Research gap
Polat & Yıldırım (2024) [15]	Dead-time compensation	Effective reduction of voltage distortion and	Limited exploration of real-time

	strategy using unipolar SPWM implemented on STM32F407G microprocessor.	harmonic components; validated through simulation and experimental comparison on resistive and inductive loads.	adaptation under variable load conditions and temperature fluctuations.
Lv et al. (2024) [16]	Reduced-order observer-based sensorless control with ADALINEbased dead-time compensation for SynRM drives.	Successful suppression of sixth current harmonic and improved low-speed estimation accuracy on a 3 kW SynRM platform.	Scalability to higher power systems and adaptive tuning under dynamic speed variations not fully investigated.
Li et al. (2024) [17]	Anti-disturbance extended state observer (A-DESO) for PMa-SynRM control to enhance noise suppression and dynamic response.	Improved robustness, reduced observation error, and better dynamic performance during load disturbances compared to conventional ESO methods.	Experimental validation under wide temperature and fluxweakening conditions remains limited.
Xu et al. (2024) [18]	Adaptive sliding mode observer using saturation function and adaptive law with PLL for rotor position estimation.	Reduced chattering and phase delay, achieving smoother and more accurate rotor position estimation for a 3 kW PMa-SynRM.	Real-time hardware implementation and robustness under severe nonlinearities not yet verified.

Wang et al. (2024) [19]	Pseudo-random highfrequency injection method with flux map modeling for zero and low-speed SynRM control.	Significantly reduced high-frequency noise and loss while maintaining estimation accuracy and dynamic stability in experiments on a 1.5 kW SynRM.	Further study needed on real-world acoustic noise behavior and long-term system reliability.

III. Fundamentals of SynRM Sensorless Control

The Synchronous Reluctance Motor (SynRM) operates based on the principle of magnetic reluctance, where the rotor tends to align itself along the path of minimum magnetic reluctance. Unlike induction motors that rely on induced currents or permanent magnet synchronous motors (PMSMs) that use magnets to establish rotor flux, the SynRM's torque production depends solely on the saliency of the rotor structure. The rotor of a SynRM consists of laminated iron with flux barriers designed to create an anisotropic magnetic path. When the stator windings are energized with a rotating magnetic field, the rotor experiences torque as it tries to align its direct (d-axis) and quadrature (q-axis) flux linkages to minimize magnetic reluctance. This phenomenon is mathematically expressed by the reluctance torque equation:

$$T_e = \frac{3}{2}p(L_d - L_q)i_d i_q$$

where T_e is the electromagnetic torque, (p) is the number of pole pairs, and L_d and L_q represent the inductances along the direct and quadrature axes, respectively. The difference between L_d and L_d (known as saliency ratio) determines the torque capability of the motor. Efficient control of SynRMs requires accurate knowledge of the rotor position to correctly transform stator currents into the synchronously rotating reference frame.

Traditionally, rotor position sensors such as encoders or resolvers provide this information, but they increase cost and reduce reliability in harsh industrial environments. To overcome this limitation, sensorless control techniques have been developed, which estimate rotor position and speed from terminal voltages and currents using mathematical observers or signal-processing algorithms. The accuracy of such estimation directly affects the overall performance, torque smoothness, and stability of the drive system [20].

A. Position Estimation Methods

Several position estimation approaches have been proposed for SynRM drives, broadly categorized into model-based and signal-injection-based methods.

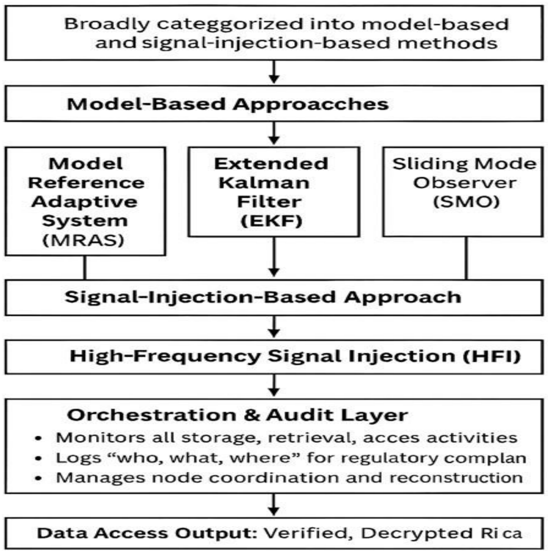

Fig. 2 Position Estimation Methods (Compiled by Researcher)

a) Model Reference Adaptive System (MRAS): The MRAS technique is one of the most widely used model-based approaches due to its simplicity and real-time applicability. It operates using two models: a reference model, which is independent of rotor position, and an adjustable model, which depends on the estimated rotor position. The estimation algorithm adjusts the rotor position until the outputs of both models converge. MRAS has strong dynamic performance, but it is susceptible to changes in parameters like stator resistance and inductance, especially when the temperature changes or the magnetic field becomes saturated.

b) Extended Kalman Filter (EKF): The EKF is a probabilistic observer that uses recursive prediction and correction processes to minimise the estimation error covariance and find both the rotor's position and speed. It can deal with noise in the system and uncertainty in the parameters, which makes it good for high-performance uses. But it is more complicated to compute than MRAS, because it needs to describe motor dynamics very accurately. The EKF provides superior estimation accuracy at medium and high speeds but may struggle under very low-speed or standstill conditions where signal observability decreases.

c) Sliding Mode Observer (SMO): The SMO is based on variable structure control theory and uses discontinuous control laws to drive the estimation error to zero in finite time. It exhibits strong robustness against disturbances and parameter variations, making it suitable for practical drives operating under uncertain conditions. However, the high-frequency switching nature of the SMO introduces a phenomenon called chattering, which may generate undesirable noise and require filtering techniques to smooth the estimated signals.

d) **High-Frequency Signal Injection (HFI):** In low-speed or zero-speed conditions where back EMF is negligible, model-based estimators like MRAS and EKF become unreliable. In such cases, HFI techniques are employed, wherein a high-frequency voltage signal is injected into the stator windings. The resulting current response depends on rotor position due to magnetic saliency. By demodulating this signal, the rotor position can be estimated even at standstill. HFI methods are highly effective at low speeds but may cause additional acoustic noise and energy loss due to the injected signal [21], [22].

Each of these methods has unique advantages and limitations, and their effectiveness largely depends on accurate modeling of the motor and inverter system. Often, hybrid estimation strategies that combine multiple approaches-such as MRAS-EKF or SMO-HFI-are used to achieve reliable estimation across the entire speed range [23].

B. Role of Inverter Non-Idealities in Estimation Errors

The estimating algorithms are based on the premise that inverters work perfectly, however realworld inverters don't always work that way, which makes things harder. In a PWM-controlled inverter, switching devices like IGBTs or MOSFETs are never perfect. They need a short dead time between switching transitions to keep the DC connection from short-circuiting. This dead period is necessary to preserve the hardware, but it changes the applied voltage vectors, which causes voltage distortion and harmonic current to form. These distortions change the current waveform that the controller sees, which messes up the input data that is utilised to figure out the position.

When the back EMF is low, like when the car is moving slowly, getting the current readings right is very important for the estimate. Even a small amount of dead time can generate large phase lag and bias errors in the expected position of the rotor. Also, switching delays, decreases in voltage between chips, and DC-link voltage variations in inverting devices make these problems even worse. [24]. To achieve high-precision sensorless control, it is necessary to employ dead-time compensation algorithms as well as PWM correction methods to mitigate these effects. To improve the accuracy of estimating position in SynRM drives, it is important to understand and simulate inverter non-idealities. The fundamentals of SynRM sans sensor rely on the accuracy of the motor model, the efficacy of the estimate methods, and the inverter's ability to mitigate distortions. Incorporating these effects into estimation techniques or compensating for them in real time can significantly enhance the stability and reliability of sensorless control. A thorough comprehension of these principles establishes the basis for enhancing control performance and alleviating harmonic disturbances, who will be further upon in the following sections. [25].

IV. Analysis of Dead-Time Harmonic Currents

In inverter-fed motors, dead time is the brief pause that occurs between the switching of additional power semiconductor devices, such as IGBTs or MOSFETs, throughout every inverter leg. This delay, which is normally a few microseconds, is built in on purpose to keep each switch from running at the same time. If they did, the DC bus could short-circuit and the inverter could break. This dead time is necessary to protect the equipment, but it also generates a problem known as voltage distortion, which makes harmonic currents flow through the motor windings. These harmonics cause the control system work less well, less efficiently, and less accurately. This is especially true for sensorless Synchronous Reluctance Motor (SynRM) drives, where position estimation relies significantly on correct voltage and current outputs [26].

A. Origin and Characteristics of Dead-Time Distortion

Dead-time distortion happens when the pulse width modulation (PWM) strategy's intended reference voltage is different from the actual voltage that is applied to the motor terminals during the switching operation. There is a tiny time interval, called "dead time," between each PWM transition. This is to make sure that one transistor turns off entirely before the next one turns on. During this time, the current from the motor keeps going through the freewheeling diodes in the inverter switches. The output voltage goes up or down slightly from its ideal value, depending on which way the current is flowing.

This change generates an inaccuracy in the phase voltage, which switches between positive and negative current and shows up as low-order harmonics in the stator current. Because of this, the motor current waveform is not a perfect sine wave; instead, it is distorted and uneven. There are a lot of things that affect how bad this distortion is, like the switching frequency, the PWM method (like Sinusoidal PWM or Space Vector PWM), the DC-link voltage, the dead-time duration, and the load current amplitude. When the fundamental voltage is low, even slight dead-time effects can have a big impact on current quality. This is especially true at low speeds or light loads [25]. These distortions add both low-frequency harmonics (usually the third, fifth, and seventh order) and high-frequency components that are connected to the PWM carrier frequency. The combined impact causes higher total harmonic distortion (THD), irregular phase currents, and lower overall drive performance.

B. Effects on Torque, Current Waveform, and Estimation Accuracy

The presence of dead-time harmonic currents has a big effect on how well the SynRM system works both electrically and mechanically. From a mechanical point of view, these harmonics induce torque ripple, which makes the developed torque oscillate. These oscillations show up as vibrations, noise that can be heard, and stress on the rotor and bearings, which causes wear over time and makes the machine run less smoothly. This can lead to motion control errors and lower system stability in precise applications like robotics or servo motors [27].

The distorted current waveform increases losses in both copper and iron, which lowers the motor's efficiency and makes the stator windings and inverter switches hotter. This thermal stress can make the part last less long and require more maintenance. Also, the current waveform symmetry is not balanced, which causes the magnetic flux to be unevenly distributed. This could make saturation effects worse and make the torque generating process even more difficult. The most significant effect is evident in sensorless control systems, where precise voltage and current measurements are essential for estimating rotor position. The Model Reference Adaptive System (MRAS), Extended Kalman Filter (EKF), and Sliding Mode Observer (SMO) are all sensorless algorithms that use the mathematical correlations between the stator voltage, current, and flux linkage to figure out where the rotor is. These algorithms get bad data when dead-time harmonics mess up the input current, which causes estimation mistakes, in MRAS-based systems, harmonic components cause a phase lag and offset between the reference and adaptive models, which leads to a position estimate that is either skewed or unstable. Dead-time noise causes state estimation to diverge in EKF-based systems, especially at low speeds when the back electromotive force (EMF) is minimal. In the same way, harmonic currents interfere with the injected signal response in highfrequency injection (HFI) methods used for low-speed estimation, which makes it harder to detect salient features. As a result, the motor may experience torque fluctuations, speed fluctuations, or even instability in the closed-loop control. These effects are especially strong when the speed is very low or the vehicle is practically stopped because the estimation is based almost entirely on the measured current and not the back EMF. In certain situations, even small voltage mistakes caused by dead time can lead to big differences in location estimate, which makes the system less reliable and responsive [28].

C. Mathematical Modeling and Experimental Insights

A lot of research has gone into modelling and experimentally characterising currents that are harmonic in inverter-fed drives in order to understand and lessen the consequences of dead time. Analytical models explain how dead time creates an equivalent voltage deviation that changes with the current polarity, which changes the applied timing voltage. Both simulations and realworld tests show that when the dead time gets longer, the distortion caused by harmonics in the stator current also gets worse, especially when the switching frequency is low or the load is small. [29]. Experimental tests utilising high-precision oscillator and spectrum analysers demonstrate that this current waveform displays unique low-order harmonic peaks in conjunction with high-frequency changing harmonics. The total harmonic distortion tends to go up a lot when the dead time is prolonged or the current sensing is unequal. Researchers have also discovered that even little variations in the switching features of inverter legs can lead to significant phase voltage mistakes, resulting in current imbalance and exacerbating torque symmetry issues

To combat these impacts, many strategies for dead-time compensating and harmonic protection have been proposed. These include ways to find out the current polarity and make up for the voltage, where the voltage produced by an inverter is modified in real time to make up for the mistake that occured during the dead period. More modern methods use algorithms called adaptive algorithms that modify the adjustment settings based on feedback from the load or the current in real time. Recently, AI and ML models have been used to rapidly predict and fix harmonic behaviour. This has made current waveforms better and made it easier to figure out. The examination of dead-time harmonic currents illustrates their significance to the efficacy and precision of SynRM sensorless control systems. The inverter needs dead time to be safe, but it also makes voltage errors that modify the shape of current waveforms, make torque ripple worse, and make it difficult to figure out where things are. These effects can be avoided by using strict modelling, experimental validation, and compensatory techniques. This will give modern SynRM drives smoother torque output, better efficiency, and more reliability.

V. Mitigation and Optimization Techniques

The negative impact of dead-time currents of harmonics on inverter-fed A lot of effort has gone into finding ways to increase the quality of the current, the smoothness of the torque, and the accuracy of position estimation in sensorless controllers because of synchronous unwillingness motor (SynRM) drives. These solutions are meant to fix or reduce the distortion caused by inverter non-idealities, which will bring back the precision of voltage and current waveforms. There are three primary types of strategies: algorithms for dead-time compensation, PWM and switching optimisation, and adaptive or AI-based methods for reducing harmonics. Depending on the needs of the system, including how hard the calculations are, how quickly they need to be done, and what technology is available, each category has its own pros and cons [30].

A. Dead-Time Compensation Algorithms

The goal of dead-time compensation algorithms is to fix the voltage faults that happen during the inverter's dead-time period. These algorithms change either the inverter's output signal or its control references to make up for the changes that happen because of switching delays. The easiest way to make up for something is to add or delete a modest voltage offset that is in line with the current flow. The algorithm lowers the output voltage a little when the current flows in a positive direction. When the current flows in the opposite direction, it raises the voltage by the same amount. This adjustment based on polarity brings the average output voltage back to its ideal reference. More complex algorithms use feedback signals like phase current, DC-link voltage, and switching states to dynamically estimate the real voltage error [31]. These approaches change the inverter's modulation signals in real time all the time, which greatly cuts down on low-order harmonics. Another good method is zero-current clamping detection, which finds the times when the phase current goes to zero and adds more compensation to keep the voltage output from going out of phase. Some researchers have also created compensating systems that use both model predictions and real-time data. These systems use both feedforward and feedback. Feedforward techniques use math models of the inverter to fix faults before they happen, while feedback schemes keep an eye on current distortion and change the compensation coefficient as needed. These methods work well to lower both torque ripple and total harmonic distortion (THD), especially when the load is light or the speed is low. Some people have also suggested hardwarebased ways to fix problems, like current polarity sensors and digital signal correction circuits. These methods make things more accurate, but they also make circuits more complicated and expensive. So, many modern drive systems have software-based compensation built right into the digital signal processor (DSP) or field-programmable gate array (FPGA). This lets them work well without needing extra sensors.

B. PWM and Switching Optimization

The goal of dead-time compensation algorithms is to fix the voltage faults that happen during the inverter's dead-time period. These algorithms change either the inverter's output signal or its control references to make up for the changes that happen because of switching delays. The easiest way to make up for something is to add or delete a modest voltage offset that is in line with the current flow. The algorithm lowers the output voltage a little when the current flows in a positive direction. When the current flows in the opposite direction, it raises the voltage by the same amount. This adjustment based on polarity brings the average output voltage back to its ideal reference.

More complex algorithms use feedback signals like phase current, DC-link voltage, and switching states to dynamically estimate the real voltage error. These approaches change the inverter's modulation signals in real time all the time, which greatly cuts down on low-order harmonics. Zero-current clamping detection is another good way to do this. It discovers the periods when the current phase goes to zero and adds extra compensation that prevents the voltage that emerges from falling out of phase. [32].

Certain investigators have also built compensatory systems utilising both model forecasts and data that is current. Such systems use both feedback and feedforward. Feedforward methods employ algebraic representations of the inverter to solve problems before they happen. Feedback methods, on the other hand, watch for current distortion and modify the compensated coefficient as needed. These methods work well to lower both torque ripple and overall harmonic distortion (THD), especially when the load is light or the speed is low. Some people have also suggested utilising hardware to fix problems, like current polarity indicators and electrical signal correction circuits. These methods make elements more accurate, but they make the circuits harder to understand and require more. Because of this, many modern drive systems have built-in software-based mitigation in the digital message processor (DSP) or field programmed gate array (FPGA). This makes them work smoothly without needing more sensors.

C. Adaptive and AI-Based Harmonic Reduction Methods

The rise of modern computing technologies has made it possible to use adaptive and AI-driven methods to reduce harmonics caused by dead time. Adaptive methods, on the other hand, change the compensation automatically by considering things like the load current, speed, or temperature. This is not the same as prior systems that used fixed compensation values. Adaptive model measurement control (MRC) and observational estimate approaches look at the output of an inverter and the feedback from the motor current to find changes that are caused by dead time. These systems automatically modify correction setting to keep harmony as low as feasible in different scenarios by comparing estimated and actual results. This method takes things a step further by using artificial intelligence (AI) or machine learning (ML). can use data sets that indicate how inverters perform with varying loads and speeds to train neural networks. After training, these models can find voltage patterns of errors in real time and change the PWM signals to repair them. This method has worked great for lowering both current THD or torque ripple as well as rendering the assessment of the rotor location more precise. [33].

Fuzzy logic controllers (FLCs) or adaptive neuro-fuzzy inference engines (ANFIS) have also been used to deal with the issue that dead-time distortion isn't linear. These systems use rule-based thinking to figure out exactly how harmonics function and give smooth compensation whenever things are confusing or change quickly. Can have intelligent automatic tuning output without having to do it by Researcher if include AI-based mitigation to the control loop. Reinforcement learning (RL) is another interesting field of study. [34]. In this case, the control system learns why to make up for things by interacting with the motor setting. To reduce distortion from harmonics and make its estimates more precise, the system updates its compensation policy based on realtime data. To reduce dead-time harmonic currents, need to use a mix of computational compensating, PWM optimisation, or adaptive intelligence. Standard dead-time compensation procedures are good at getting rid of low-order distortion and getting the voltage back to where it should be. On the other hand, optimal PWM techniques get rid of distortions that appear when switch. Adaptive and AI-driven methods offer a smart or scalable solution for sensorless SynRM drives in the future. They can learn and change how inverters work in real time. These technologies work together to make modern high-performance SynRM control systems' current waveforms cleaner, lower torque ripple, and make position estimation much more accurate.

VI. Comparative Evaluation and Discussion

TABLE II. COMPARATIVE ANALYSIS

Author/Year	Method / Technique	Results / Key Findings	Advantages
Joksimovic et al. (2023) [35]	Harmonic current suppression algorithm using feedback acquisition and internal model control for SPMSMs.	Effectively eliminates stator current harmonics and torque ripple within two fundamental periods; verified through simulations and experiments.	Fast harmonic suppression, enhanced torque smoothness, accurate control under nonideal back-EMF.
Huang et al. (2022) [36]	Dead-time compensation in highfrequency square-wave voltage injection (HFSVI) for SynRM sensorless control.	Successfully compensates dead-time effects and improves current vector and rotor angle estimation without using lowpass filters.	Filter-free implementation, enhanced estimation accuracy at low speed, simplified signal processing.

Attia et al. (2021) [37]	Confined Band Variable Switching Frequency PWM (CBVSF PWM) for inverter dead-time mitigation.	Achieves lower total harmonic distortion (THD) and suppression of low-order harmonics in output current.	Reduced THD, improved current waveform quality, effective in reducing negative effects of dead-time.
Nikmaram et al. (2021) [38]	Modified finite position set model predictive control (FCSMPC) using optimized adaptive error function for SynRM.	Enhances predictive control accuracy with fewer iterations; validated through simulation and experiments.	Reduced computational burden, improved rotor position estimation, robust predictive performance.

The comparative evaluation of the four studies highlights significant advancements in addressing harmonic distortion, dead-time effects, and sensorless control challenges in electric drive systems. Joksimovic et al. (2023) introduced an internal model control-based harmonic suppression algorithm that effectively minimized torque ripple and stator current harmonics within two fundamental cycles, demonstrating superior dynamic performance. However, its applicability is limited to surface-mounted PMSMs. Huang et al. (2022) contributed a novel dead-time compensation method for high-frequency square-wave injection-based sensorless control, eliminating the need for low-pass filters and improving position estimation accuracy, although its performance diminishes at higher frequencies. Attia et al. (2021) introduced the CB-VSFPWM technique to alleviate dead-time effects caused by inverters, resulting in reduced THD and enhanced current quality via simulation, however it lacks real-time validation. In the meantime, Nikmaram et al. (2021) improved predictive control for SynRMs by combining a finite position set technique with adaptive error optimisation. This improved the system steadier and less demanding on the computer. All of this research shows a clear trend to smart reward and predictive tactics that make control quicker and efficient. Future research should focus on the integration of these techniques with AI-driven optimised and real-time device validation to provide adaptability across diverse dynamic and nonlinear operating contexts.

VII. Conclusion and Future Directions

This research examined the challenges and remedies associated with dead-time harmonic distortion or position estimation inaccuracies in the sensor-less control of synchronised Reluctance Motors (SynRMs). The research indicated that inverter non-idealities, particularly dead-time effects, obscure the current waveform, disrupt the torque, and diminish the accuracy of estimates. All of these elements are very important for sensorless operation to perform properly and reliably. A number of mitigation strategies, including dead-time compensation algorithms, optimised PWM approaches, and adaptive or AI-based systems, have shown promising results in improving current linearity and reducing harmonic distortion. A comparative review of recent studies indicated a consistent evolution from conventional model-based control to intelligent, adaptive frameworks that dynamically compensate for nonlinearities and parameter fluctuations. Even with these improvements, it is still hard to make sure that high-power industrial drives are strong enough to handle different loads, can adapt in real time, and can be made bigger. Future study need to concentrate on amalgamating hybrid AI-assisted estimation and compensating frameworks with experimental hardware validation to attain near-sensor precision and improved drive efficiency. In the end, precise modelling, smart compensation, and adaptive optimisation could work together to get past current problems and make the next generation of SynRM sensorless control systems that are cheaper, use less energy, and are better for the environment. Future research should concentrate on AI-integrated adaptive compensation, real-time hardware validation, hybrid estimation models, and optimisation for high-speed, low-noise SynRM drives to improve accuracy, robustness, and energy efficiency.

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