

Metaheuristic-Based Observer Design for Electromagnetic and Load Torque Estimation in PMSMs: A Comprehensive Review

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Article's Information	Abstract
<p>Received: 23.10.2025 Accepted: 18.03.2026 Published: 31.03.2026</p>	<p>Due to their efficiency and torque density, they are commonly used in electric vehicles and robotics. The catch is that except for mechanical sensor input, torque and speed estimation in austere environments remains the single most difficult obstacle. This paper presents an exhaustive survey of observer-based torque estimation methods for PMSM drives to analyze state-of-the-art contributions and highlight the leading field research directions.</p> <p>While observer-based techniques, such as EKF, UKF, MRAS, SMO and Luenberger observers have been widely applied to handle this issue; adaptive based nonlinear and AI based observers are arising to face such problems. This was important for observers loops implementation in transients, making load torque observers interesting from academic point of view and they are trending around the recent research as to their better disturbance rejection during dynamic conditions. Metaheuristic optimization algorithms, including PSO, GA and GWO, have also been employed to auto-tune the observer's and controller's parameters in order to enhance estimation accuracy and dynamic performance.</p> <p>These type of optimised based works have been used with Modern control techniques such as Field Oriented Control (FOC) and Model Predictive Control (MPC) to achieve better results. We subsequently offer a critical perspective on the observer designs, state estimation techniques, and control approaches, with the objective of furnishing some useful guidance on the existing voids and future research directions. Although, some progress has been achieved, most of these developments are based on simulated studies and underline the need of real-time implementation and hardware in the loop validation, high level of uniqueness in drive system.</p>
<p>Keywords: PMSM, LTOs, Metaheuristic Optimization, FOC, MPC.</p>	
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1. INTRODUCTION

However, in parallel, the permanent magnet synchronous motor (PMSM) has become an integral part of robotics, electric vehicles, and high-performance drive systems due to its small size and large torque-to-weight ratio and energy efficiency [1]. Further rise of PMSM drives can also be related to the development of energy-efficient and sustainable technology solutions [2]. In reality, direct measurements of the electromagnetic torque and rotor velocity require expensive, sensitive devices (torque transducers or encoders). Furthermore, when placed under harsh conditions, these sensors can affect the system's reliability and maintenance costs. Consequently, many sensorless estimation methods and computational observers have been employed to achieve accurate torque and speed estimation while avoiding hardware complexity [3]. Although a considerable number of studies have tried to determine T_e during permanent magnet synchronous machine (PMSM) operation, TL estimation is also an essential task, as it informs how much external mechanical power has been applied onto the shaft in the pneumatic machine. This task is significant because the correct estimation of load torque directly affects the robustness of drives, ensures functioning at variable loads, and the design of sophisticated fault diagnosis and prognosis algorithms [4].

To overcome this, Load Torque Observers (LTO) were proposed, combining measurable electrical signals, such as stator currents and voltages, with a mathematical model of the motor to estimate TL. To this end, several state observer methods have been studied for PMSM state estimation (torque, speed, or load torque). Some of the most widely used methods are the observer methods, such as:

- Extended Kalman Filter (EKF): Due to its suitability to process measurement noise as well as nonlinear system dynamics, it was proposed and used as a real-time state observer for PMSM drives [5].
- Model Reference Adaptive System (MRAS): Observers based on MRAS have attracted much attention because of their relatively straightforward structure and adaptability in terms of low or medium speed [6].
- SMO, this observer is well known for its robustness to parameter variation and external disturbances. However, care should be taken to minimize the chattering effect [7].
- Load Torque Observers (LTOs): More recently, observers were introduced to explicitly estimate load torque through adaptive structures such as [8], enhancing control performance under unknown or varying loads.

Moreover, for readout PMSMs the parameters must be tuned in complex control techniques (Field Oriented Control (FOC), Model Predictive Control (MPC)) excluding that of observer. This works because the process starts in the Seventree company with a bullet list of those candidate tunings that is actually executed outside Jenkins in a thin form factor called either rapid tuning or an optimization tool. The crossword abovehigh-dimensional optimization problems Chandler Sarah is not only more efficient than traditional manual one [9]. [10] — which showed that the adoption of novel metaheuristic optimization algorithms can significantly enhance PMSM systems in aspects such as performance stability, energy efficiency & reliability. This review paper contributes in the following ways:

- Presenting a systematic taxonomy of observer-based torque estimation methods in PMSM drives.
- A complete overview of load torque observer (LTO) design and its implications for drive performance.
- Utilizing metaheuristic optimization algorithms to maximize observer and controller parameters.
- Indirect search on PMSM observer based control system

The structure of this paper is as follows. In Section II, background of electromagnetic torque estimation, load torque estimation, and observer design is provided in the context of PMSM systems. Section III contains system description, mathematical modelling of PMSM, observer based estimation methods and optimal control strategies. Within PMSM observer-control systems high-level, types of observance, control methods, and optimization algorithms are organized (cf. Section IV). Section V describes the hardware

implementation requirements and issues related to these experiments. The paper ends with Section VI which organizes prospects for future research.

2. RELATED WORK

Sensorless control of Permanent Magnet Synchronous Motors (PMSMs) and torque estimation based upon observer techniques has been well-studied using a great amount of research work during the last 5 years. The breadth and depth of this field has expanded with numerous observer paradigms developed ranging from classical linear observers to nonlinear observers to disturbance observers, and, more recently, artificial intelligence-based estimation approaches. In addition, fewer linearization approaches have been gradually utilized to optimize parameters of state observers and controllers. Among all the estimation objectives multiple, load torque estimation has drawn more and more attention recently as the great effect external load disturbances can exert on the dynamic property and stability of PMSM drive system. This stresses the need of an adjustment of load torque to improve disturbance rejection, control robustness, and seamless operation over a wide range of operating conditions. The next subsections summarize these developments and represent state-of-the-art PMSM torque estimation based on observer principles.

2.1. Traditional observers and contemporary developments

Many PMSM state estimation methods have been investigated in the literature based on observers like electromagnetic torque, rotor speed and load torque.

- Extended Kalman Filter (EKF): This is still one of the most widely used observers for PMSM applications due to the fact that it can handle nonlinear dynamics as well as measurement noise. More recently, new and low-order dynamical systems ECG respect the fact that computation of EKF complexity can be avoided potentially in view of degradation (robustness) versus tuning for effective real-time usage [11].
- Unscented Kalman Filter (UKF): In some highly nonlinear systems, UKF can be used instead of EKF. Recent works with comparative studies only conclude that in some sensor less PMSM configurations the UKF provides better estimation performance due to its ability to manage nonlinear transformations [12].
- The Model Reference Adaptive System (MRAS try to use observers since they are easy to implement and flexible. They are especially suitable for low and medium speed PMSM applications. Recently, hybrid [13] and cascade MRAS [14] structures are put forward in order to enhance the estimation quality and dynamic response.
- Sliding Mode Observer (SMO): The SMO is used for its strong robustness to variations in parameters and external disturbances. If we do not design for them properly, these can become disastrous chattering effects. In order to overcome this limitation, many enhanced versions of SMO were proposed including adaptive-gain SMO [14], super twisting algorithms and fuzzy-assisted SMO structures.
- Linear Observers (Luenberger Observers): The Luenberger-type observers have been in great use among PMSM drive systems due to their relatively simple architecture. Most recent works, however, aim at improving their performance either by incorporating them with adaptive estimation schemes or other observer methods [15].

- Load Torque Observers (LTOs): Dedicated observers have been developed in the last few years to allow load torque estimation directly from monitored electric signals and motor models. In these applications, such observers are normally enhanced through EKF, SMO, or adaptive observer form to enhance disturbance rejection and stability in electric vehicle and high-performance drive [16].

2.2. Nonlinear Observers and Disturbance Observer

In order to enhance the performance of estimation under varying operation, nonlinear observers and disturbance observers have also been extensively studied. High-Gain Observers (HGO) and Disturbance Observers (DOB) for estimating fast system dynamics, compensating for unknown disturbance. Some PMSM sensorless control approaches include disturbance observers along with further estimation algorithms, such as SLIP or EKF, to be more robust. The existing adaptive disturbance observers focus on estimating the time-varying load torque in PMSM drive systems [17], achieving good results in terms of stability and dynamic performance.

2.3 AI-Driven and Hybrid Observers

Over the last few years, AI (artificial intelligence) and data guided schemes have been leveraged to improve observer performance in presence of an uncertain operating context. The neural network (NN)-based observer, fuzzy logic observer, and hybrid estimation frameworks integrating conventional observers with intelligent learning models are among these approaches.

There are several proposed methods that are hybrid, like EKF-NN (Extended Kalman Filter- Neural Networks based) and also MRAS-Fuzzy observers to manage uncertainties in model and also nonmodelled dynamics of system. This approach to implementation makes the observer adaptive in the sense that the observer learns about system dynamics and improves estimates in real time. Nevertheless, recent contributions indicate that the load torque estimation accuracy into PMSM systems from different and uncertain conditions can be enhanced by means of neural network or fuzzy logic architectures [18].

2.4 Observer Tuning via Metaheuristic Optimization

In PMSM drive systems, tuning observer and controller parameters have become a hot research topic recently, which are focused on metaheuristic optimization algorithms. Algorithms like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Differential Evolution (DE), and Grey Wolf Optimizer (GWO) have been extensively adapted to optimize observer gains, Kalman filter covariance matrices (Q and R), as well as controller parameters in specialized control schemes, including FOC and MPC.

The specific optimization methods yield superior results in solving nonlinear and high-dimensional optimization problems that are hard to deal with using traditional tuning approaches. Many studies on PMSM control systems have demonstrated that the addition of metaheuristic optimization techniques into observer-based schemes results in better estimation accuracy, more robust control, and increased stability [19].

TABLE.1. Summary of Recent Observer-based Torque Estimation Techniques for PMSM Drives and their key results and limitations.

Ref.	year	Observer (Type)	Method	Application	Key contribution	Limitation
[20]	2020	SMO (1st and 2nd order)	Voltage Source Inverter (VSI) error compensation with feed-forward torque	Sensor less PMSM control	Comparative analysis of SMO variants; feed-forward torque compensator improves transient response	Chattering effect may still appear under severe disturbances
[21]	2020	LTO (Linear Regression + LTI Filters)	Stator flux observer with constant TL estimation	Sensor less PMSM control	Improves robustness under parameter variations and external load disturbances	Assumes relatively constant load torque during operation
[22]	2021	SMO	Improved SMO with back-EMF filtering and torque compensation	Sensor less speed and position estimation for PMSM drives	Minimize chattering, guess more accurately in dynamic conditions	Increased computational complexity from the filtering stages
[23]	2021	EKF, SMO and MRAS (Comparative review)	Design methods + tuning strategies for high-frequency estimation	Sensor less PMSM systems under nonideal conditions	Offers comparative analysis on the robustness of observers and tuning techniques	Mainly simulation-based work without experimental validation
[24]	2021	Predictive Control Based Load Torque Compensation	Model Predictive Direct Speed Control (MPDSC) which cost-function optimization and MTPA tracking	PMSM drive subjected to dynamic load	Tied into predictive control for enhanced dynamic response with minimum ripple of the speed	High computation overload and complex implementation
[25]	2022	MRAS with switched Proportional-Integral (PI) control	MRAS with switched PI control and fuzzy logic disturbance compensation	Sensor less PMSM control with estimator tracking of stator resistance	Improves both resistance estimation and dynamic performance through the switching of adaptive PIs	Performance may compromise under fast parameter variations
[27]	2023	Second-order generalized integrator for flux estimation	Sensor less PMSM control with harmonic disturbance	Sensor less PMSM control under DC bias and harmonic interference	Improves rotor position estimation accuracy under DC bias and harmonic interference	Sensitive to parameter tuning of SOGI
[28]	2023	EKF + LTO	Extended Kalman Filter with embedded load torque observer	PMSM drives under dynamic mechanical load	Provides embedded estimation of load torque in EKF for ripple speed estimation High	computational complexity of Kalman filtering
[29]	2024	GPI Observer + Kalman Filter	EMF estimation using GPI observer with Kalman noise suppression	Sensor less PMSM control under disturbance	Achieves robust EMF tracking without PLL or LPF	Requires accurate model parameters
[30]	2024	Improved Sliding Mode Observer (ISMO)	Fuzzy logic control with DSOGI-FLL	Sensor less PMSM control	Accurate load torque tracking and improved disturbance rejection	Increased controller complexity

[31]	2025	Adaptive SMO + LTO	Super-twisting SMO with adaptive gain	Sensor less PMSM control for EV drives	Improves torque stability and fault diagnosis capability	Implementation complexity in real-time systems
[32]	2025	Various (MPC / SMC / AI-based control)	Integration of advanced control with Multiphysics simulation tools	PMSM in EVs and renewable systems	Highlights shift toward AI-assisted predictive control frameworks	Lacks detailed observer implementation

Table 1 summarizes the most relevant works of observer-based torque estimators. The survey of literature demonstrates the strides already taken in improving estimation accuracy/robustness via new observers and optimization-based algorithms. Nonetheless, there are still some limitations in the available studies. A variety of observer designs focus on electromagnetic torque or speed estimation, but the literature on accurate load torque estimation over highly dynamic operating conditions is relatively sparse. Second, many methods are validated largely through simulation without the testing of experimental or real-world implementations. Third, the design of hybrid observer-based estimation frameworks integrated with metaheuristic optimization techniques remains challenging from a systematic perspective, thereby limiting their performance comparison. Discussion on these limitations motivates a thorough study of observer-based torque estimation methods and optimization approaches for PMSM systems. So, the purpose of this review is to present a structured classification of available observers, discuss recent advances on load torque estimation, and provide future research lines for PMSM observer-based control systems.

3. SYSTEM DESCRIPTION OF ELECTROMAGNETIC AND LOAD TORQUE ESTIMATION CONTROL SYSTEM

3.1. PMSM in dq Reference Frame Modelling.

PMSM is normally represented in the rotating direct–quadrature (dq) reference frame to simplify the control and analysis. The electrical equations are given as follows:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (1)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e (L_d i_d + \lambda_f) \quad (2)$$

Where v_d , v_q are the stator voltages, i_d , i_q are the stator currents, L_d , L_q are the inductances, R_s is the stator resistance, ω_e is the electrical angular speed, and λ_f is the flux linkage from the permanent magnets. These equations form the basis for torque control and observer design.

3.2 Torque Estimation via Observer Design

Proper torque estimation is necessary in Sensorless PMSM control. In current research, neural network based observers and sliding mode observers have been suggested to estimate electromagnetic torque in the absence of mechanical sensors. The example was the case where a better Elman Neural Network observer was demonstrated to be more precise and more robust to parameter changes [34]. The stator measurements and currents are processed by the observer to rebuild rotor position and speed which are then converted to calculate torque, through:

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

Where p , is the number of pole pairs. Besides the electromagnetic torque, the load torque T_L is also necessary to be taken into account and has a substantial influence on the motor performance when operating at variable loads. The PMSM mechanical model with load torque is given by:

$$T_e - T_L = J \frac{d\omega}{dt} + B\omega \quad (4)$$

Shuffling provides the dynamics of speed:

$$\dot{\omega} = \frac{K_t}{J} u - \frac{B}{J} \omega - \frac{T_L}{J} \quad (5)$$

Due to the fact that TL cannot be measured directly, the design of a Load Torque Observer (LTO) is possible. The long load torque sensor brings in the approximated values of the state variables [28]:

$$\hat{\omega} = \frac{K_t}{J} u - \frac{B}{J} \hat{\omega} - \frac{\hat{T}_L}{J} \quad (6)$$

where $\hat{\omega}$ is the estimated angular velocity and \hat{T}_L is the estimated torque load. Through constant adaptation of \hat{T}_L the observer basically re-constructs external disturbances and also provides strong performance of PMSM in different load conditions. Such estimation of both electromagnetic torque and load torque enhances the overall reliability of PMSM drives, especially in the situations when the load can vary considerably such as in electric vehicle and robotics drives.

3.3. Optimal Control Strategies (FOC & MPC) Integration.

Calculation of both electromagnetic torque T_e and load torque T_L is an important input to superior control mechanisms like field-oriented control (FOC) and model predictive control (MPC). With FOC, flux-producing and torque producing components are separated, which allows the independent control of i_d and i_q with PI controllers. T_L estimation enables the controller to counter external load disturbances, so that it improves stability in changing mechanical conditions. In MPC, the future evolution of the system is optimized by minimizing a cost functional, which takes into account not only torque error and electrical constraints (currents, voltages), but also load torque variations due to estimated load. This increases resilience to variations in loads and increases disturbance rejection [35].

In recent works combining MPC and FOC with load torque observers, better dynamic response, less torque ripple and increased reliability of drives in electric vehicles using PMCs and robotics have been demonstrated [36].

3.4. Block Diagram Description

The control structure of a Permanent Magnet Synchronous Motor (PMSM) drive with a load torque observer is shown in the block diagram in Figure 1. The system has two major control loops: a speed control and a current control loop. The speed controller generates a reference current based on the difference between the reference speed (ω^*) and the measured motor speed (ω). to create a current reference that produces torque. The current controller processes this signal and the controller manages the stator currents so that the required electromagnetic torque is attained. The d/q transformation block is used to transform the three phase stator currents (i_{abc}) into the components of the rotating reference frame so that torque and flux can be decoupled and controlled [8].

A value of the estimated T_e is given to the motor model and T_L is the external mechanical perturbation over motor shaft. This external disturbance can be re-constructed by the TLOs based on electrical quantities being measured (voltages and currents) thus allowing better compensation and stability in a variable load condition [26], [27]. PMSM drive improves the robustness and dynamic performance of the drive when feedback of the estimated torque and speed is considered [15]. This observer-based control system can guarantee correct torque control and disturbance/noise rejection, that is crucial in high-performance electric vehicles and robotics.

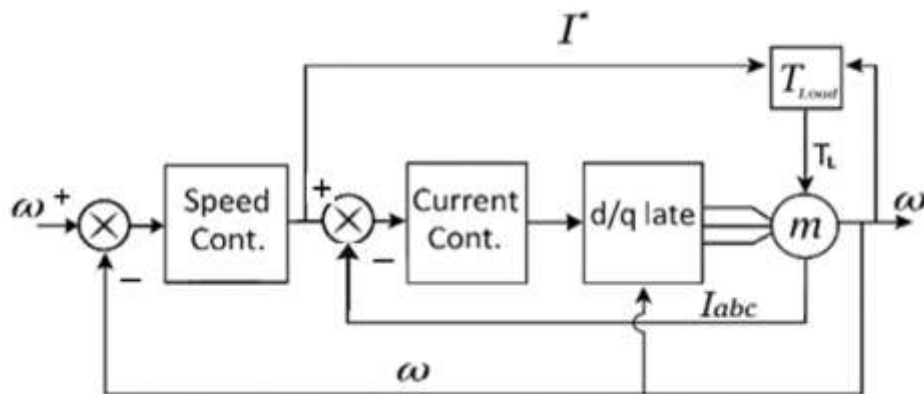


Fig .1. PMSM Control System with Load Torque Observation [8].

A. Observer Types

Observers are mathematical models that attempt to approximate immeasurable states of a system as a function of measurable variables and the mathematical model of the plant. Important in PMSM are Observers which can replace costly and non-durable sensors (e.g., encoders or torque transducers) and can still provide viable estimation of rotor position, velocity, electromagnetic torque T_e . and, most recently, load torque T_L . A Various observer structures have been constructed over the years, beginning with classical model-based approaches and progressing into adaptive and intelligent schemes. By adding load torque observers, the estimation task is not restricted to states on the inside of the machine but also to the external mechanical disturbances. This allows greater resilience to instantaneous changes in load and better performance of PMSM drives in practice (e.g., electric vehicles, robotics) by supplying current and voltage to an observer (e.g., EKF, SMO, MRAS) to produce estimated states (speed, electromagnetic torque [10]. [18]., load torque and rotor position). to produce estimated states (speed, electromagnetic torque T_e , load torque T_L and rotor position). The estimated load torque is denoted as T_{Lse} (Estimated Load Torque), where T_{Lse} represents the load torque estimated by the load torque observer, as shown in Figure 2.

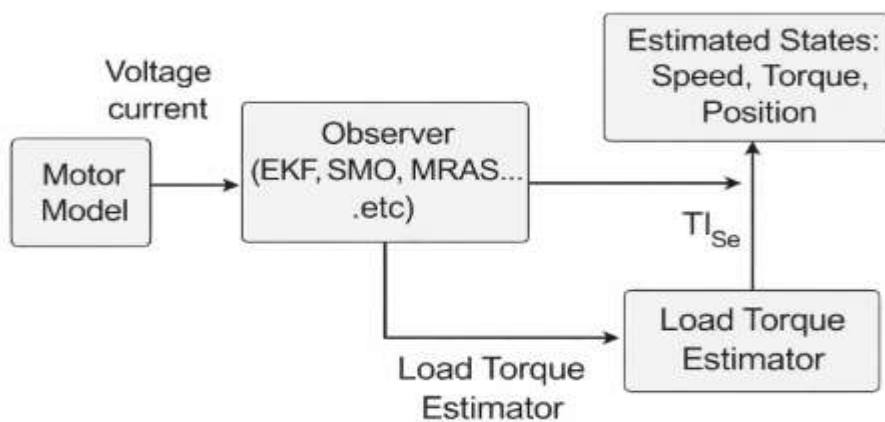


Figure.2. Load Torque Observer [18].

Table 2 provides a summary of the key observer types employed in PMSM drives, their principal advantages and limitations, and points out some recent attempts to add load torque estimation to these models [37].

TABLE.2. Summary of Major Observer Types

Observer type	Key advantages	Limitations
Extended Kalman Filter(EKF) filter [38]	Supports nonlinearity and measurement noise; extensively tested in PMSM drives.	Efficient with respect to parameter mismatch; costly to compute.
Unscented Kalman Filter (UKF) filter [39]	Improved results with large nonlinearity; no Jacobian evaluation.	Higher computational cost
MRAS [40]	Simple structure; adaptive in low/mediocre range of speed.	Poor accuracy when very slow; is related to reference model quality.
SMO [36]	Insensitive to disturbances and variations in parameters; rapid convergence.	Noise filtering requirement; chattering effect
Luenberger Observer [41]	Minimal design and minimal computational requirements	Sensitive to parameter mismatch; weaker
High-Gain Observer (HGO) [26]	Rapid convergence of state estimates	Enhances noise; susceptible to measurement errors
Disturbance Observer (DOB) [42]	Balances model uncertainty and exogenous shocks	Needs correct nominal model
Adaptive / Nonlinear Observers [43]	Self-tuning, which works with parameter variation	Design analysis, analysis of stability required.
Neural Network Observers [44]	Acquire unmodeled dynamics; adaptive.	Training data is needed, generalization problem.
Fuzzy Logic Observers [45]	Process nonlinearities through linguistic rules	Design of fuzzy rules is dependent on performance.
Hybrid Observers (e.g., EKF+NN, MRAS+Fuzzy) [23]	Integrate the advantages of models and AI.	More complexities; difficulties in implementation
Load Torque Observer (LTO) [21], [46], [47].	Estimates torque due to external load and enhances disturbance rejection and stability under varying load conditions.	Relies on correct mechanical parameters (inertia, friction); it can be inaccurate when there is much noise in measurements.

B. Control Strategies

Control strategies define how the currents and voltages of PMSM are controlled to achieve the desired torque and speed. The conventional PI- based Field-Oriented Control (FOC) is still popular due to its simplicity and effectiveness. However, such sophisticated tools like Model Predictive Control (MPC) have also become the focus of attention because of their speedy dynamic reaction and the fact that they can manage various constraints [48]. These control strategies are improved with the addition of load torque estimation TL. The estimated TL - acts as a disturbance signal that can be compensated in real time making it possible to have FOC to ensure strict flux-torque decoupling, and MPC to incorporate load torque effects in its predictive cost model. Consequently, the PMSM drive possesses a better robustness to the external variations in loads and decreasing performance under existing dynamic operating conditions.

Practically, the accuracy of state estimation may be compromised by environmental noise, e.g., measurement noise, or mechanical vibration outside the experiment. Thus, strong observer designs are used to counteract these effects and provide good load torque estimates.

Figure .3. shows the control structure of PMSM drives in the form of block diagram. A controller is then connected to one of the reference signals (speed or torque), and could use techniques including FOC, MPC, PI or DTC to produce voltage commands. The commands are inputted to the inverter that drives the Permanent Magnet Synchronous Motor (PMSM). In the extended scheme, not only the estimates of the rotor position and electromagnetic torque are given by the observer, but also the estimated load torque, which is used by the controller as part of disturbance rejection. This closed loop control system brings more precise and consistent motor operation at variable load conditions [35]. The most important control strategies in the PMSM are summarized in Table 3 with the most recent extensions that combine load torque observers.

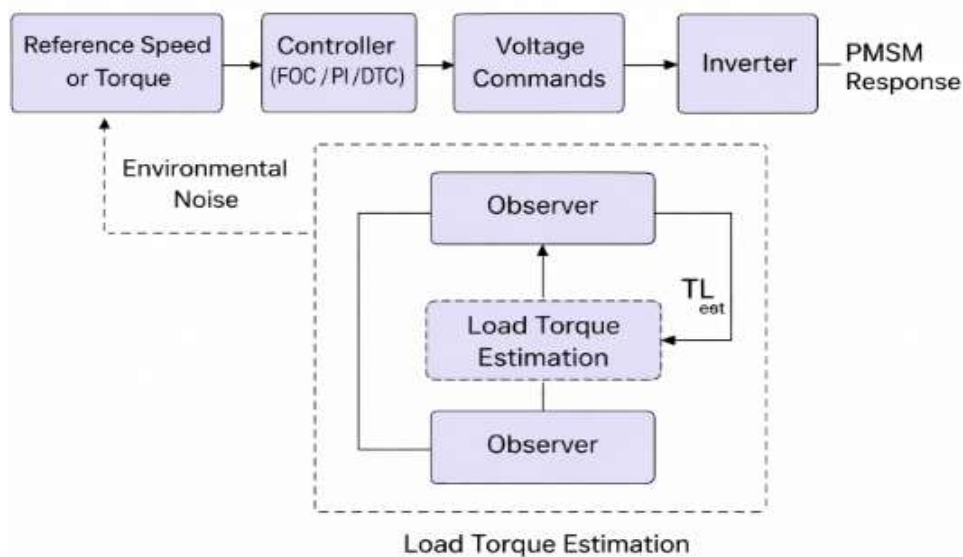


Figure .3. the control structure of PMSM drives[35].

TABLE.3. Summary of Control Strategies

Control type	Key advantages	Limitations
PI-based Field-Oriented Control (FOC) [49]	Casual, well-established, strong in steady state.	Tuned; not optimal in nonlinearities.
Model Predictive Control (MPC) [50]	Quick reaction; copes with limitations; suitable with temporary.	Demands a lot of computing; parameter sensitive.
Direct Torque Control (DTC) [51]	Very fast torque response	Variable switching frequency/torque/flux ripple.
Intelligent Controllers / Hybrid (FOC+AI, MPC+NN) [52]	Enhances robustness and accuracy using intelligent or hybrid control techniques.	Complexity; requirements optimization of parameters.
Load Torque Observer (LTO) FOC / MPC [53]	Balances external load upsets; enhances robustness, stability and accuracy with variable load conditions.	Computational complexity: Depends on correct estimation of TL.

C. Optimization Algorithms

Metaheuristic optimization algorithms, based on natural or evolutionary mechanisms are widely used to automatically optimize controller and observer parameters that typically would then have to be developed through trial and error [54].

The introduction of load torque observers (LTOs) has added an incremental purpose to optimization algorithms: optimization of the gains in electromagnetic torque observers, as well as optimization of the parameters of the load torque estimation models. This causes a better rejection against disturbance and robustness of the system under variable load conditions. Figure.4. is a block diagram that shows how optimization algorithms may be incorporated into PMSM control systems, Particle Swarm Optimization (PSO), Genetic Algorithm (GA) or Gray Wolf Optimizer (GWO) are some of the methods used to optimize observer parameters (e.g., covariance matrices in Kalman filters, SMO gains), controller gains and the LTO adaptation laws, The flexibility and accuracy of the whole system are enhanced by automating the process of tuning [55].

The outcome is an improved performance in terms of speed tracking, torque response and resistance to both parameter variations and external load disturbances. Notably, the accuracy of the torque estimation can be reduced by environmental factors like noise in measurements and mechanical vibrations. In response, noise data is then injected into the optimization process to enable the algorithms to change system parameters in the direction of enhanced robustness. This combination leads to a higher performance level based on the speed tracking performance, torque response, and resistance to the change of both parameters and external disturbances.

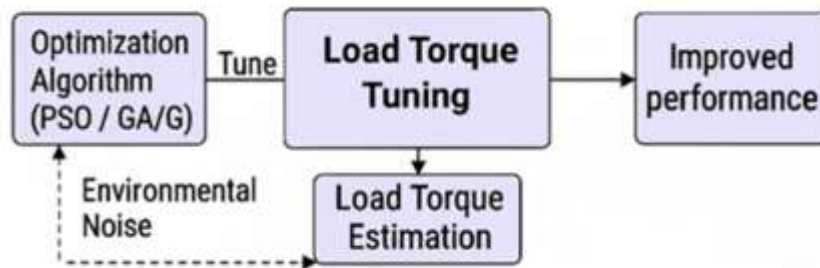


Fig.4. Optimization Diagram Incorporating Load Torque Tuning [55].

Table .4. provides a summary of the principal metaheuristic algorithms and the role they play in tuning not only classical observers and controllers, but also load torque observers.

Table .4. Summary of Optimization Algorithms

Optimization Algorithm	KEY ADVANTAGES	Limitations
Genetic Algorithm(GA) [56]	Global optimization capability; simple implementation	Slowness of convergence; danger of premature convergence
Particle Swarm Optimization (PSO) [57]	Fast convergence; suitable for continuous tuning	Can get trapped in local minima.
Grey Wolf Optimizer (GWO) [58]	Balanced exploration/exploitation; fewer parameters.	Less tested in hardware compared to GA/PSO
Differential Evolution (DE) [59]	Good at handling nonlinear problems	May require many generations to converge

Hybrid Metaheuristics (e.g., PSO+GA, GWO+DE) [60]	Better robustness; find multi-objective tuning	Complexity; computational overhead
Metaheuristic Tuning for Load Torque Observer (LTO) [61]	Increases the strength of the load disturbances; enhances the dynamic stability of the variable load conditions.	Conditional upon correct observer structure; expands the search space and computation cost.

4. METHODOLOGY OF THE RESEARCH

The load torque estimation of PMSMs and optimal control can be approached both through experimental implementation using hardware premises, as well as through simulation with the help of software environments as illustrated in Figure 5. The choice of methodology varies between the bullet points above and depends on research goals, available lab facilities, and when real-time validation is needed under dynamic loading conditions [28].

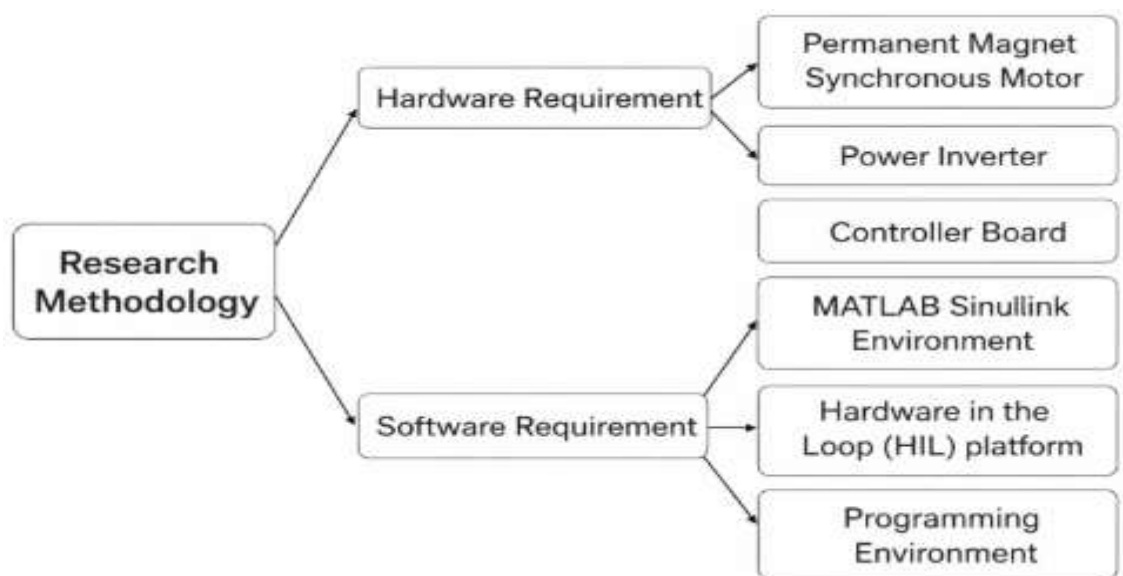


Figure 5. Research methodology for PMSM load torque estimation and control implementation

A. Hardware Requirements

To experimentally validate the devised load torque observer (LTO) and optimization algorithms, a hardware-dedicated test bench is needed. The essential components include:

- PMSM (Permanent Magnet Synchronous Motor)

High torque, high speed rated surface-mounted or inside PMSM was optimized based on the provided application areas for electric vehicles or industrial drive systems [62].

Power Inverter (Voltage Source Inverter, VSI):

Three-phase voltage source inverter (VSI) or current source converter [23:10] capable of generating modulated voltage signals. Reliable switching during torque transients has been proven via integrated gate drivers and protection circuitry in today's inverter modules.

- **Controller Board:**

Digital Signal Processors (DSPs), Field Programmable Gate Arrays (FPGAs) or microcontroller units (MCUs), e.g. STM32s implement load torque observers and real-time control algorithms. They also research and provide the ultra-processing power for the online torque estimation [63].

- **Current and Voltage Sensors:**

Real-time feedback needed to sense stator currents & voltages, typically with use of Hall-effect or shunt-based sensors. These measurements are primarily used in estimating rotor position, rotor speed and electromagnetic torque over a wide operating load [64].

- **Data Acquisition & Communication Interfaces**

Data channels CAN, UART or Ethernet provides the opportunity of monitoring the internal states, in-use datalogging as well as the configuration of the external observer parameters during online evaluation tests (i.e., experiments in response to load torque perturbations).

- **Experimental Validation Platforms:**

Significant advancements have also engaged differentiated LTO layouts to validate through PMSM experiment set-ups based on DSP or FPGA controllers using advanced LTO architectures such as Extended Kalman Filters (EKF), Sliding Mode Observers (SMO) and neural-network-based observers. Especially for these platforms, since they are less sensitive to variations of load torque and parameters [65].

B. Simulation Requirements

At such hardware use case, simulation-based approach provides the engineers with the most viable vehicle, where they can assess the performance of their load torque estimation algorithm and load torque control approach. They allow for flexible testing of observer and controller designs over a range of load scenarios, allowing iterative development [65].

- **MATLAB/Simulink Environment:**

Commonly used simulators for control strategies simulation (PI based FOC, MPC, DTC-MATLAB Simulink), load torque observer designing EKF, MRAS, and SMO, and PMSM dynamic modelling are [48]. These include an early-stage validation review and works [35] which supports parameter tuning, stability analysis, and performance evaluation under diverse load torque profiles using Simulink.

- **Hardware-in-the-Loop (HIL) Platforms:**

Now, the observer and the control algorithms can be executed in near-real-time on a large-scale system using advanced real-time simulation platforms such as OPAL-RT and dSPACE. The proposed solutions stand in between pure simulation and HW implementation and allow fast evaluation of the accuracy of load torque estimation and the disturbance rejection ability in real-time [66].

- **Programming Environments (C++, Python):**

C++ or Python based offline programming can, obviously, be done using our theory based load torque estimation algorithms and control strategies and may be implemented not only on DSP or FPGA based platforms. They allow one to be flexible in creating algorithms to test and assess the computational performance.

• Recent Research Trends:

Recent papers show some knowledge about computations and robustness as well as the expected precision related to observer architecture design [8], [9], mostly based on MATLAB/Simulink-based simulations performed in HIL setups. It is also essential to integrate torque observer investigations through various mechanical and electrical working ranges before deploying within physical prototypes [67].

5. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The trend of integration of metaheuristic optimization algorithms is thoroughly examined as this work aims at cataloguing modern observer-based methodologies to estimate T_e and T_L in PMSM drives. In applications that are influenced by parametric uncertainties and quick load fluctuations, a precise estimation of these torques is critical to realizing dependable Sensor less motion control. In PMSM drive systems, observer-based estimation techniques are used to estimate electromagnetic torque, load torque, rotor speed, and rotor position without mechanical sensors, which are expensive and sensitive to harsh operating conditions. The use of LTOs further increases the robustness of the system as they provide an estimation of external disturbances in real-time, resulting in a highly reliable and low-maintenance solution. This study presented a few recent developments of metaheuristic optimization algorithms such as GA, PSO, and GWO that have provided better performance for observer-controller systems using systematic and efficient parameter tuning. The same DMETQ-feeding optimization techniques could be employed in conjunction with electromagnetic torque and load torque observers to enhance their performance (faster dynamics, improved robustness) in PMSM drive applications. This review also finds key limitations in the current literature. Most studies depend mainly on simulation validation. Few present experimental verifications on real-time hardware. Additionally, hybridizations of single metaheuristics have received little attention. These hybrids can exhibit improved resilience and adaptability. More research should create an optimization framework of hybrid nature. They should integrate advantages of various metaheuristic algorithms, particularly when ensuring simultaneous tuning of the EM and the load torque observers. In real-time hardware in loop practices, and in experimental validations, more effort needs to be concentrated. This will allow to evaluate the practical applicability in all kind of operating conditions. Finally, the combination of efficient senseless control strategies and load torque estimation for EV drive-train systems is very well suitable for further research as efficiency, robustness against load disturbances, and low costs are all main demands of modern transportation technologies. This review provides strong evidence that PMSM control under metaheuristic optimization techniques in integration with load torque observers are well positioned. This kind of integration goes beyond research and development levels, but brings tremendous potential for groundbreaking, robust, and high-performance practical implementations in advanced PMSM drive applications.

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