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Sensorless Control and Estimation Techniques for Electric Drives

Piyush Dhawan, Yogendra Chatarjee, Ankush Mishra, Gayatri Negi
Associate Professor, Assistant Professor
Department of Electrical and Electronics
Vidyaprabha College of Engineering, Nagpur, India
Email: *piyushdhawan5d@gmail.com, chatarjeeyogendrat08@yahoo.com,*
gayatri48nn@rediffmail.com

Abstract

Electric drives are widely used in industries, electric vehicles, robotics, and renewable energy systems. Traditionally, speed and position sensors such as encoders and resolvers are used for feedback control of motors. However, these sensors increase cost, reduce reliability, and create maintenance issues in harsh environments. Sensorless control techniques eliminate the need for physical sensors by estimating rotor position and speed using electrical signals. This paper presents a detailed review on various sensorless control and estimation methods applied to electric drives such as induction motor (IM), permanent magnet synchronous motor (PMSM), and brushless DC motor (BLDC). Techniques including back-EMF estimation, model reference adaptive system (MRAS), sliding mode observers, extended Kalman filter (EKF), high frequency signal injection, and artificial intelligence based estimators are discussed. Advantages, limitations, and application areas of each method are also analyzed. A comparative study is provided to help understanding the suitability of methods under different operating conditions.

Keywords: *Sensorless control, Electric drives, MRAS, EKF, Sliding mode observer, Back EMF, PMSM, Induction motor.*

INTRODUCTION

Electric drives require accurate information of rotor speed and position for proper control. Mechanical sensors provide this feedback but they increase system size and cost. In applications like electric vehicles, aerospace drives, and sealed industrial motors, placing sensors is difficult and sometimes not possible. Hence, sensorless control becomes an attractive solution.

Sensorless methods use terminal voltage and current signals to estimate the motor states. These techniques improves reliability and reduces wiring complexity. Also, sensorless drives perform better in high temperature, vibration and dusty environments where sensors may fail.
Initially sensorless techniques were developed for induction motors, later extended to PMSM and BLDC drives. With advancements in digital signal processors and control algorithms, estimation accuracy is greatly improved. This paper reviews major estimation techniques and compares their performance.

NEED FOR SENSORLESS CONTROL IN ELECTRIC DRIVES (ELABORATED)

In conventional electric drive systems, rotor speed and position are measured using mechanical sensors such as encoders, tachogenerators, Hall sensors, and resolvers. While these sensors provide accurate feedback, they introduce several practical issues related to cost, reliability, installation complexity, and maintenance. In many modern applications like electric vehicles, aerospace actuators, underwater drives, wind generators, and sealed industrial motors, placing such sensors is either difficult or undesirable. This leads to the growing importance of sensorless control techniques, where motor states are estimated using electrical signals instead of physical sensors.

The major reasons for adopting sensorless control in electric drives are explained below.

Reduction of Hardware Cost

Mechanical sensors significantly increase the overall cost of the drive system. High-resolution encoders and resolvers are expensive and require additional signal conditioning circuits, cables, connectors, and mounting accessories. In mass-produced systems such as home appliances, EV traction motors, and industrial pumps, eliminating these components reduces manufacturing cost noticeably.

Also, the cost is not only of the sensor itself but includes:

- Extra wiring and shielding
- Mounting arrangements and alignment

- Signal processing hardware
- Periodic calibration cost

Sensorless control removes all these components and thus makes the drive system more economical and attractive for commercial applications.

Increased System Reliability

Sensors are often the weakest part of an electric drive system. They are prone to failure due to:

- Mechanical vibrations
- Dust and moisture
- High temperature exposure
- Misalignment during installation
- Cable damage and loose connections

When a sensor fails, the entire drive system may stop working even though the motor and inverter are healthy. By removing mechanical sensors, the overall reliability of the drive improves significantly. Sensorless drives are therefore preferred in critical applications where continuous operation is required, such as process industries and electric transportation.

Compact Drive Structure

Modern electric drive applications demand compactness and light weight, especially in electric vehicles, drones, robotics, and aerospace systems. Sensors increase the physical size of the motor assembly and require additional space for installation.

In sensorless drives:

- No encoder housing is required
- No extra wiring harness
- Reduced mechanical coupling arrangement

This leads to a more compact and integrated motor-drive system which is easier to install and handle.

Less Maintenance Requirement

Mechanical sensors require periodic maintenance and alignment. Encoders may lose calibration over time, resolvers need checking of connections, and Hall sensors can drift due to temperature changes.

Maintenance activities include:

- Cleaning dust and debris
- Checking cable integrity
- Recalibration
- Replacement after wear

Sensorless drives eliminate these maintenance tasks, making them suitable for remote, inaccessible, or sealed installations such as wind turbines, submersible pumps, and hazardous industrial zones.

Better Performance in Harsh Environments

In many industrial and automotive environments, conditions are not favorable for delicate sensors. Factors such as:

- High ambient temperature
- Oil, dust, and moisture
- Mechanical shock and vibration
- Electromagnetic interference

can degrade sensor performance. Sensorless control depends only on electrical measurements (voltage and current), which can be reliably measured using robust electronic sensors placed inside protected control units. Hence, sensorless drives are more suitable for harsh working environments.

Suitability for High-Speed and High-Temperature Operation

At very high speeds, mechanical sensors may suffer from:

- Mechanical wear
- Signal distortion
- Mounting limitations

Similarly, at high temperatures, sensor materials may degrade, affecting accuracy. Sensorless methods do not have these mechanical limitations since estimation is done through algorithms in digital controllers. This makes them ideal for high-speed spindles, EV traction motors, and turbo-compressors.

Table 1: Comparison of Sensor Based and Sensorless Drives

Parameter	**Sensor Based Drive**	**Sensorless Drive**
Cost	High due to sensors	Lower
Reliability	Sensor failure possible	More reliable
Maintenance	Frequent	Less
Wiring complexity	High	Low
Suitability in harsh env.	Poor	Good
System size	Larger	Compact

MATHEMATICAL MODEL OF ELECTRIC DRIVES (ELABORATED)

Accurate sensorless control of electric drives is not possible without a proper mathematical model of the motor. The estimation algorithms such as MRAS, SMO, EKF, and observers are all based on motor equations that relate measurable electrical quantities (stator voltage and current) with unmeasurable mechanical quantities (rotor speed, position, and flux).

These models are generally expressed in different reference frames to simplify analysis:

- abc (three phase stationary frame)
- α–β (two phase stationary frame – Clarke transformation)
- dq (two phase rotating frame – Park transformation)

By transforming three-phase quantities into two orthogonal components, the motor equations become easier to handle and suitable for digital implementation.

Reference Frame Transformations

Clarke Transformation (abc → αβ)

This converts three-phase variables into two-phase stationary orthogonal components.

iα=iaiβ=13(ia+2ib)\begin{aligned} i_\alpha &= i_a \\ i_\beta &= \frac{1}{\sqrt{3}}(i_a + 2i_b) \end{aligned}iαiβ=ia=31(ia+2ib)

This representation is helpful because it reduces the system to two axes.

Park Transformation (αβ → dq)

This rotates the stationary frame into a rotating frame aligned with rotor flux.

id=iαcos⁡θ+iβsin⁡θiq=−iαsin⁡θ+iβcos⁡θ\begin{aligned} i_d &= i_\alpha \cos\theta + i_\beta \sin\theta \\ i_q &= -i_\alpha \sin\theta + i_\beta \cos\theta \end{aligned}idiq=iαcosθ+iβsinθ=−iαsinθ+iβcosθ

Where **θ** is the rotor electrical position. In sensorless control, this angle is unknown and must be estimated.

Mathematical Model of PMSM

In the dq rotating reference frame, the stator voltage equations of PMSM are written as:

Vd=Rsid+dλddt−ωrλqV_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_qVd=Rsid+dtdλd−ωrλq Vq=Rsiq+dλqdt+ωrλdV_q = R_s i_q + \frac{d\lambda_q}{dt} + \omega_r \lambda_dVq=Rsiq+dtdλq+ωrλd

Where:

- Vd,VqV_d, V_qVd,Vq = dq axis stator voltages
- id,iqi_d, i_qid,iq = dq axis currents
- RsR_sRs = stator resistance
- λd,λq\lambda_d, \lambda_qλd,λq = flux linkages
- ωr\omega_rωr = electrical rotor speed

Flux linkages are given by:

λd=Ldid+λm\lambda_d = L_d i_d + \lambda_mλd=Ldid+λm λq=Lqiq\lambda_q = L_q i_qλq=Lqiq

Here, LdL_dLd and LqL_qLq are inductances and λm\lambda_mλm is flux due to permanent magnet.

The electromagnetic torque equation is:
Te=32P[λmiq+(Ld−Lq)idiq]T_e = \frac{3}{2} P \left[\lambda_m i_q + (L_d - L_q)i_d i_q \right]Te=23P[λmiq+(Ld−Lq)idiq]
Using these equations, if stator voltages and currents are known, the rotor position θ\thetaθ and speed ωr\omega_rωr can be estimated.

Mathematical Model of Induction Motor (IM)

For induction motor, the model is more complex due to rotor currents. In dq frame, stator voltage equations are:
Vds=Rsids+dλdsdt−ωsλqsV_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs}Vds=Rsids+dtdλds−ωsλqs Vqs=Rsiqs+dλqsdt+ωsλdsV_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds}Vqs=Rsiqs+dtdλqs+ωsλds

Rotor equations (short-circuited rotor):
0=Rridr+dλdrdt−(ωs−ωr)λqr0 = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_s - \omega_r)\lambda_{qr}0=Rridr+dtdλdr−(ωs−ωr)λqr 0=Rriqr+dλqrdt+(ωs−ωr)λdr0 = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (\omega_s - \omega_r)\lambda_{dr}0=Rriqr+dtdλqr+(ωs−ωr)λdr

Where:

- RrR_rRr = rotor resistance
- ωs\omega_sωs = synchronous speed
- ωr\omega_rωr = rotor speed

Flux linkages:
λds=Lsids+Lmidr\lambda_{ds} = L_s i_{ds} + L_m i_{dr}λds=Lsids+Lmidr λdr=Lridr+Lmids\lambda_{dr} = L_r i_{dr} + L_m i_{ds}λdr=Lridr+Lmids
Sensorless methods estimate rotor flux λr\lambda_rλr first, and from that rotor speed is derived.

State Space Representation

For observer design, motor equations are written in state-space form:
x˙=Ax+Bu\dot{x} = Ax + Bux˙=Ax+Bu y=Cxy = Cxy=Cx

Where state vector xxx may include:

- Stator currents
- Rotor flux
- Rotor speed

Observers like EKF and SMO use this form to estimate unknown states.

Importance of Accurate Parameters

The mathematical model depends on parameters such as:

- Stator resistance RsR_sRs
- Rotor resistance RrR_rRr
- Inductances Ld,Lq,LmL_d, L_q, L_mLd,Lq,Lm

These parameters change with temperature and saturation. Any mismatch affects estimation accuracy, which is a major challenge in sensorless control.

Role of Mathematical Model in Estimation

Using the above equations, the controller:

- Measures stator voltages and currents
- Uses motor model to estimate flux linkages
- Derives rotor position and speed from flux angle
- Updates control signals accordingly

Thus, the mathematical model acts as the backbone for all sensorless estimation algorithms.

Back EMF Based Estimation

Back EMF method is simplest and widely used in BLDC and PMSM drives. Rotor position is derived from zero crossing of back EMF.

Advantages

- Simple implementation
- Low computational requirement
- Good for medium and high speeds

Limitations

- Not effective at low speed
- Noise sensitive
- Requires filtering

This method is popular in BLDC motor for fan, pump and EV applications.

MODEL REFERENCE ADAPTIVE SYSTEM (MRAS)

MRAS is popular for induction motor sensorless control. It uses two models:

- Reference model independent of speed
- Adjustable model dependent on speed

The difference between outputs of two models is used to adapt speed.

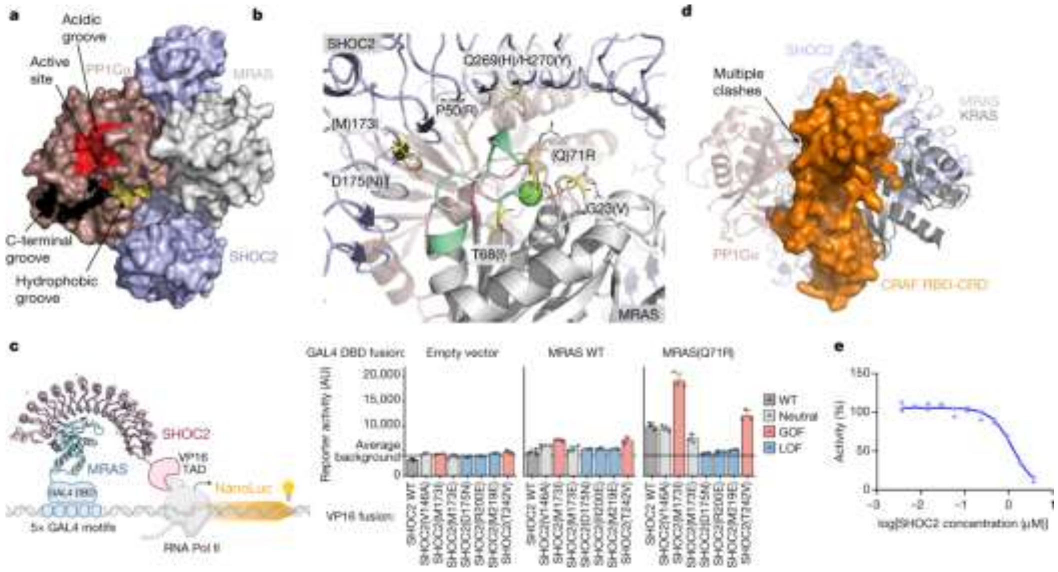

Figure 1: MRAS Structure

Advantages

- Good dynamic response
- Suitable for wide speed range
- Less parameter sensitivity

Disadvantages

- Complex tuning

- Sensitive to parameter variation

SLIDING MODE OBSERVER (SMO)

SMO uses nonlinear control theory and switching functions to estimate back EMF and rotor position.

Features

- Robust against disturbances
- Accurate at low speed
- Fast convergence

However, chattering effect is major issue and requires filtering techniques.

EXTENDED KALMAN FILTER (EKF)

EKF is stochastic observer which estimates states using prediction and correction steps.

Benefits

- High estimation accuracy
- Works in noisy environment
- Suitable for PMSM drives

Drawbacks

- Heavy computation
- Requires precise model
- Difficult implementation in low cost controller

HIGH FREQUENCY SIGNAL INJECTION METHOD

This method is useful for low and zero speed operation. High frequency voltage signal is injected into stator and rotor saliency is used for position detection.

Application

- Interior PMSM drives
- Servo drives
- Robotics

But it increases switching losses and acoustic noise.

ARTIFICIAL INTELLIGENCE BASED ESTIMATORS

Recently, AI techniques like Neural Network, Fuzzy Logic, and Machine Learning are used.

Characteristics

- Learns nonlinear motor behaviour
- Reduces dependency on exact mathematical model
- Good under parameter variation

Still, training complexity and real time implementation issues exist.

COMPARATIVE ANALYSIS OF TECHNIQUES

Table 2: Comparison of Sensorless Estimation Methods

Method	Motor Type	Low Speed	High Speed	Complexity	Accuracy
Back EMF	BLDC/PMSM	Poor	Good	Low	Medium
MRAS	IM	Good	Good	Medium	Good
SMO	PMSM/IM	Good	Good	Medium	Good
EKF	PMSM	Excellent	Excellent	High	Very High
HF Injection	PMSM	Excellent	Moderate	High	High
AI Based	All	Good	Good	High	High

APPLICATIONS OF SENSORLESS ELECTRIC DRIVES

- Electric Vehicles
- Industrial Automation
- Robotics and CNC machines
- Renewable energy systems
- Aerospace actuators
- Household appliances

Sensorless drives are very suitable where maintenance is difficult.

CHALLENGES IN SENSORLESS CONTROL

Despite many advantages, few challenges are present:

- Parameter sensitivity (resistance, inductance changes)

- Noise in measurement signals
- Difficulty at zero speed for some methods
- Requirement of high speed processors
- Stability issues during transients

Researchers are continuously working to overcome these problems.

FUTURE TRENDS

Future research is moving towards:

- AI and deep learning based observers
- Sensorless control for multi-phase motors
- Integration with IoT monitoring
- FPGA and DSP based fast estimation
- Hybrid estimation techniques combining two methods

CONCLUSION

Sensorless control techniques have become essential part of modern electric drives. Various estimation methods such as back EMF, MRAS, SMO, EKF, high frequency injection and AI based observers provide reliable rotor position and speed estimation without mechanical sensors. Each technique has its own advantages and limitations depending on motor type and operating condition. With advancement in computation power and intelligent algorithms, sensorless drives are becoming more accurate and widely adopted in EVs, robotics and industrial systems. Still some problems like parameter variation and low speed operation needs improvement. Overall, sensorless technology will play major role in future electric drive systems.

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