POWER ELECTRONICS MOTOR CONTROL

Advanced Sensorless Speed Estimation and Control for Brushed DC Motors: A Technical Compendium

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In the evolving landscape of industrial automation and consumer electronics, the **brushed DC motor** remains a staple due to its simplicity, high starting torque, and ease of control. However, as applications demand higher reliability, lower costs, and reduced physical footprints, the reliance on physical sensors—such as optical encoders or Hall-effect sensors—presents significant engineering challenges. These sensors add bulk, introduce points of mechanical failure, and increase the bill of materials (BOM). Consequently, the field of **sensorless speed estimation** has emerged as a critical discipline for modern electrical engineering.

Sensorless control refers to the ability to determine the rotational speed or position of a motor's rotor using only the electrical signals already present in the drive circuit: current and voltage. This article provides a comprehensive technical analysis of sensorless methodologies, ranging from classical **back-EMF** estimation to advanced **ripple component analysis** and **machine learning-based observers**.

The Fundamental Physics of Brushed DC Motors

To understand sensorless estimation, one must first grasp the electromechanical interactions within a **Permanent Magnet DC (PMDC)** motor. When a voltage is applied to the armature, a current flows, creating a magnetic field that interacts with the permanent magnets to produce torque. As the motor rotates, it also acts as a generator, producing an internal voltage known as **Back-Electromotive Force (Back-EMF)**.

The Voltage Equation

The relationship between the applied voltage (V), armature current (I), and rotational speed (<’• is governed by the fundamental DC motor equation:

V = I · R + L(di/dt) + k<•

Where:
V: Terminal voltage (V)**I:** Armature current (A)**R:** Armature resistance (:Ł**:** Armature inductance (H)**k:** Motor constant (V·s/rad)**<‘**Angular velocity (rad/s)

In steady-state conditions, the inductive term (L·di/dt) becomes negligible. By measuring the current and knowing the motor's resistance and constant, the speed can theoretically be calculated. However, this **model-based approach**is highly sensitive to temperature-induced changes in resistance and magnetic flux degradation, necessitating more robust estimation techniques.

Taxonomy of Sensorless Estimation Techniques

Modern engineering literature classifies sensorless methods into two primary categories: **model-based methods** and **non-model-based (signal processing) methods**. Each offers distinct advantages depending on the precision required and the computational power available in the microcontroller (MCU).

1. Model-Based Estimators (Observers)

Model-based methods rely on the mathematical representation of the motor. Common implementations include the

Luenberger Observer and the **Extended Kalman Filter (EKF)**. These systems use the input voltage and measured current to simulate the motor's behavior in real-time. The error between the measured current and the predicted current is used to correct the speed estimate.

2. Non-Model-Based Methods

These methods do not require precise knowledge of internal motor parameters like resistance or inductance.
Instead, they analyze the **harmonic content**of the electrical signals. This is particularly useful for small brushed motors where parameters fluctuate wildly during operation.

Feature	Model-Based Methods	Non-Model-Based (Ripple/Spike)
Parameter Sensitivity	High (Requires R, L, k values)	Low (Relies on signal frequency)
Low Speed Performance	Poor (Back-EMF is too low)	Moderate to Good
Computational Load	Medium to High	Low to Medium
Implementation Complexity	High (Calculus/State-space)	Medium (Signal Filtering/FFT)

Deep Dive: Current Ripple Component Analysis

One of the most robust methods for sensorless speed estimation involves the detection of **current ripples**. These ripples are inherent in brushed DC motors due to the mechanical commutation process. As the brushes move across the commutator segments, the number of active armature coils changes momentarily, causing a periodic fluctuation in the armature current.

The Mechanics of Ripple Generation

The frequency of these ripples is directly proportional to the rotor speed. Specifically, for a motor with *n* commutator segments, there will be *2n* ripples per revolution. By utilizing a **high-pass filter** and a **zero-crossing detector**, the MCU can count these pulses to determine the exact RPM without an external encoder.

Recent advancements have introduced **Support Vector Machines (SVM)** and **Artificial Neural Networks (ANN)** to process these ripple signals. These AI-driven approaches are capable of filtering out mechanical noise and brush-sparking artifacts that traditionally plague simple frequency counters, allowing for accurate speed estimation even during rapid acceleration or heavy loading.

Innovative Methods: Inductive Spike Analysis

In Pulse-Width Modulation (PWM) driven systems, a novel method involves measuring the **inductive spikes** generated when the motor is switched off during the PWM cycle. Research conducted by Radcliffe (2015) highlights two specific metrics: **rise time** and **duration** of the inductive spike.

Inductive Spike Dynamics

When the PWM signal transitions from 'High' to 'Low', the energy stored in the motor's inductance must dissipate. This creates a voltage spike (often clamped by a flyback diode). The characteristics of this spike are influenced by the **Back-EMF** present at that moment, which in turn is a function of the motor speed.

Rise Time: The time it takes for the spike to reach a certain threshold. **Spike Duration:** The total time the inductive current takes to decay to zero.

Sensorless Control at Motor Starting

Starting a motor from a standstill (Zero RPM) is the most challenging phase for sensorless systems because Back-EMF is non-existent. Traditional observers fail here. However, **Novel Starting Estimation** techniques use the initial current surge and the rate of change of current (di/dt) to predict the initial acceleration. By analyzing the **armature teeth-slots effect**, sophisticated algorithms can detect the first few degrees of rotation, providing a seamless transition from standstill to the operational speed range where ripple-counting takes over.

Comparison of Observer Performance

Observer Type	Accuracy	Dynamic Response	Key Limitation
Simple Back-EMF	± 5%	Slow	Unreliable at low speeds
Adaptive Estimator	± 2%	Fast	Requires complex tuning
Ripple Counter	± 0.5%	Medium	Requires high-bandwidth ADC
Neural Network	± 1%	Very Fast	High memory requirement

Practical Implementation Guide

To implement a sensorless speed stabilizer or controller, engineers must follow a structured hardware and software integration path. Below is a procedural framework for a ripple-based sensorless system:

Step 1: Signal Conditioning

The armature current is typically measured across a **shunt resistor** in the low-side of the H-bridge. Because the ripple is a small AC component riding on a large DC offset, an active band-pass filter is required. This filter should be designed to pass frequencies within the expected RPM range (e.g., 50Hz to 2kHz).

Step 2: Pulse Detection

The filtered signal is fed into a **Schmitt Trigger** or a comparator to convert the analog ripples into a digital square wave. This signal is then connected to the **Input Capture** pin of a microcontroller.

Step 3: Algorithmic Verification

Since brushes can occasionally "bounce" or spark, creating false pulses, the software must implement a **median filter** or a frequency-tracking window. If a detected pulse suggests a 100% speed increase in 1ms, it is mathematically discarded as noise.

Case Study: Small PMDC Motor Speed Stabilization

In applications such as medical infusion pumps or precision fans, maintaining a constant speed under varying loads is vital. A study on **Sensorless Speed Stabilizers** demonstrated that using an adaptive estimator—which updates the resistance (R) value in real-time based on temperature—can reduce speed droop by 85% compared to open-loop voltage control.

Troubleshooting Common Challenges

- Electrical Noise: PWM switching noise often overlaps with ripple frequencies. Solution: Use synchronized ADC sampling, where measurements are only taken during the 'On' period of the PWM cycle, away from switching transitions.
- Brush Wear: As brushes wear down, the ripple profile changes. Solution: Implement a self-calibrating algorithm that periodically measures the peak-to-peak ripple amplitude to adjust comparator thresholds.
- Load Fluctuations: Sudden load increases can dampen the ripple signal. Solution: Use a hybrid model that switches to Back-EMF estimation when the ripple signal-to-noise ratio (SNR) drops below a certain threshold.

Summary and Industrial Implications

The transition toward sensorless speed estimation for brushed DC motors represents a significant leap in **mechatronic efficiency**. By leveraging the internal physics of the motor—specifically the back-EMF, current ripples, and inductive spikes—engineers can create robust, high-performance systems that are both cost-effective and durable. While model-based observers provide the theoretical foundation, signal-processing techniques like ripple counting and inductive spike analysis offer the practical precision required for modern applications.

As microcontrollers become more powerful, the integration of **Artificial Neural Networks** and **Support Vector Machines**will further refine these estimations, making sensorless control indistinguishable from physical sensor-based systems in terms of accuracy. For the senior technical strategist, the choice of method depends on the specific trade-offs between computational overhead and the required dynamic response, but the trend is clear: the future of DC motor control is increasingly sensor-free.

Tags: #Sensorless Control #Brushed DC Motor #Back EMF #Current Ripple Analysis #Motor Observers