International Journal of Applied Engineering & Technology

IDA-PBC FRAMEWORK FOR PRECISION CONTROL OF BLDC DRIVES UNDER LOAD AND PARAMETER VARIATIONS

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ABSTRACT
Brushless DC (BLDC) motor drives are widely used in various applications due to their high efficiency, reliability, and low maintenance. However, ensuring smooth operation and precise control of BLDC motors requires advanced control techniques. This paper discusses the implementation of interconnection and damping assignment passivity-based control (IDA-PBC) by simulation for BLDC motor drives. The study explores the robustness of this control technique, its ability to handle parameter variations. The proposed control strategy ensures robust speed regulation, minimizes torque ripples, and improves system stability. Experimental results demonstrate the feasibility of the proposed method, making it a viable solution for real-world applications. The BLDC motor is modeled using trapezoidal back-EMF functions, and the control law is obtained through Hamiltonian energy shaping. Simulation and experimental results show low steady-state errors, smooth transitions, and fast observer convergence. (One blank line)

Keywords: *BLDC motor, passivity-based control, IDA-PBC, simulation*

INTRODUCTION
BLDC motors are widely used in automotive, industrial, and robotics applications due to their high efficiency and torque density. Brushless DC (BLDC) motors have gained popularity due to their high power efficiency, low maintenance, and precise speed control. The use of Brushless DC Motors is extensively in- creasing for various applications due to their compact and robust structures. Compared to Permanent Magnet Synchronous Motors; the BLDC motors have higher power/weight and higher torque/current ratio [1]. Thus, many researchers have suggested application of sensorless drive which can regulate speed and position without using shaft-mounted position sensors [2]. Main types of sen- sorless control methods are the back-EMF measurement, third harmonic sensing of back EMF, back EMF inte- gration, flux linkage estimation, freewheeling diode and estimator-based approach [3].

However, traditional PI controllers and back-EMF–based sensorless methods face issues at low speeds, during load disturbances, and under parameter uncertainties.

To address these challenges:

- IDA-PBC offers a physics-based nonlinear control approach using energy shaping.
- I&I observers provide smooth and robust estimation of rotor speed and load torque.
- Combining them results in a highly robust and implementable control strategy suitable for embedded drives.

Traditional PID controllers struggle to provide optimal performance under load variations, parameter uncertainties, and nonlinearity. Passivity-based control (PBC), particularly Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC), is a promising approach to overcome these challenges. This paper presents the simulations based implementation of IDA-PBC for BLDC motors and demonstrating enhanced performance in terms of speed tracking, torque ripple reduction, and system stability.

MATHEMATICAL MODELING

The BLDC system is modelled using:

Electrical model

$$\frac{di}{dt} = -\frac{R}{L}i - \frac{1}{L}e + \frac{1}{L}v$$

Mechanical model

$$J\frac{d\omega}{dt} = T_e - B\omega - T_L$$

The BLDC motor is modeled using standard abc-frame electrical dynamics:

di/dt = -(R/L)*i - (1/L)*e + (1/L)*v

Mechanical dynamics follow:

dv/dt = (Te - Bv - TL) / J

Eletromagnétic torque is:

Te = λ [fa(θ) ia + fb(θ) ib + fc(θ) ic]

where f_a, f_b, f_c are trapezoidal flux functions dependent on rotor position.

Back-EMFs follow trapezoidal waveforms determined by rotor position. The model is rewritten in Port-Controlled Hamiltonian (PCH) form for IDA-PBC design.

IDA-PBC CONTROL DESIGN FRAMEWORK

To stabilize unbound dissipation systems, an interconnection and damping assignment passivity-based control (IDA-PBC) technique is presented in Ortega et al. (2001). It is a general method for nonlinear controllers for systems that are represented by PCH models (Meshram et al., 2019). The solution of partial differential equations (PDE) in IDA-PBC- based method is parameterized by three matrices (Ortega and Canseco, 2004). From a system point of view, they can be seen either as multipliers that enable one to implement the necessary passivity property, or as dynamic couplings that allow dissipation to propagate (Ortega et al., 2002a). In case of physical systems, the energy exchange and dissipation of the system are determined by the interconnecting and damping matrices, respectively (Ortega et al., 2002b). After conveying a closed-loop energy function with the preferred IDA construction, a static feedback rule is established by partitioning a collection of PDEs (Hoffner and Guay, 2011).

As the load torque is not constant in many applications and the torque sensor is too expensive, the load torque along with the speed of the motor can be estimated with the help of the immersion and invariance (I&I) observer. This observer does not need the information of a Lyapunov function (Arbo et al., 2017; Astolfi and Ortega, 2003; Kotyczka and Sarras, 2013; Rapp et al., 2013; Venkatraman et al., 2010). Several effective practical implementations of IDA-PBC and I&I observer are noted for brushed DC motor (Bol¨ivar et al., 2006), induction motor (Ortega and P¨erez, 2005; Gonzalez et al., 2008) and permanent magnet synchronous motor (Khanchoul et al., 2013; Ortega et al., 2011; Shah et al., 2011; Shah et al., 2012). To rectify the drawbacks, the IDA-PBC based method with I&I observer [10] design is proposed for BLDC motor in this paper. The main contributions of the proposed technique are described below:

The presented new start-up method for BLDC motor not only maintains alignment of the rotor but also avoids rotation of motor in arbitrary direction along with reduction of the starting current. The other important contribution of the proposed method is its stability during closed- loop condition, even if the motor is integrated with the controller as well as the observer. An additional contribution of the proposed method is the development of a generalized observer and controller for the BLDC motor. Its robustness may be check with a variation in speed tracking, load torque and motor parameters.

IDA-PBC modifies the system's energy function by choosing a desired Hamiltonian $H_d(x)$ and designing suitable interconnection and damping matrices. This produces a nonlinear control [4] law that regulates voltage commands and ensures:

- Guaranteed stability
- Smooth transient behavior
- Improved robustness during load changes

SIMULATION AND RESULTS DISCUSSION:

Simulations were performed for motor under no-load and load-varying conditions. The reference speed profile included multiple transitions between 0 and 1500 rpm. Key findings include:

- Estimated speed closely matched actual speed with steady-state errors below 4 rpm.
- Load disturbances up to 0.8 N·m were successfully rejected.
- Phase currents and estimated torque followed expected trapezoidal and proportional behaviors.

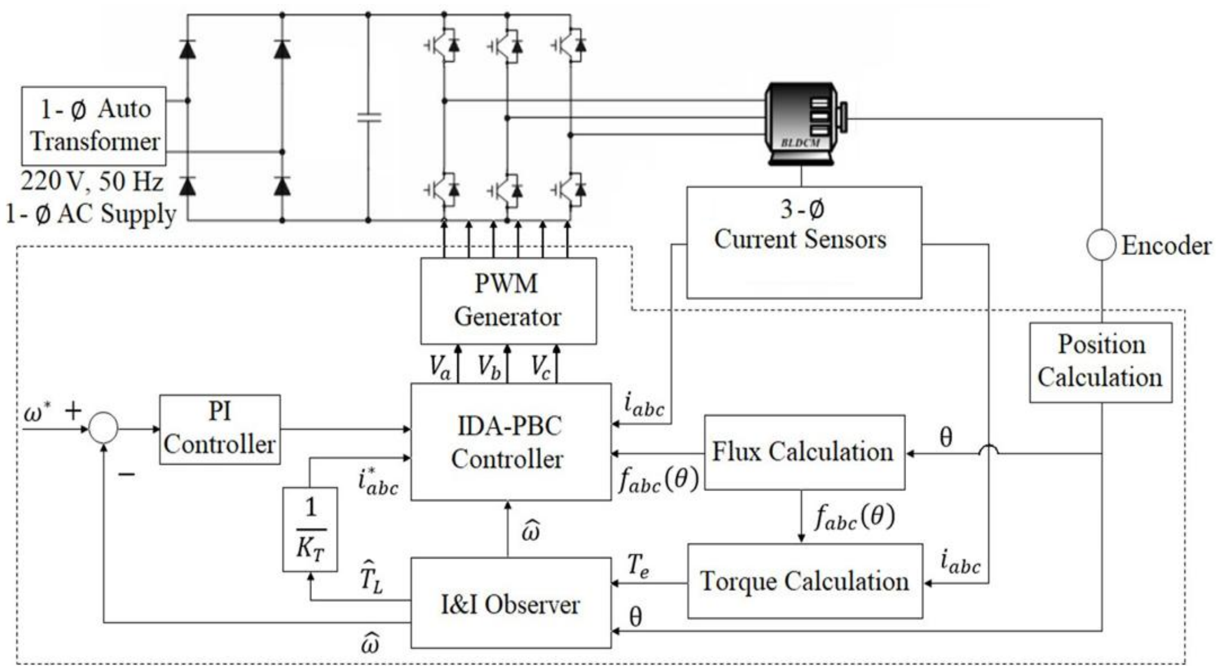

Fig. 1: MATLAB Simulation for BLDC motor drive

Table 1: Motor Parameters

BLDC Motor Parameter	Value
R (Ω)	3.07
L (mH)	6.57

Flux λ (Wb)	0.1275
Torque Constant (Nm/A)	0.49
Rated Speed (RPM)	4000
K	0.49
B	0 N-m/rad/s
Voltage	310 V, 1 HP

Table 2: Error Metrics (IDA-PBC vs PI Control)

Metric	IDA-PBC	PI
Steady-State Error (RPM)	3	12
Overshoot (%)	2.1	8.5
Rise Time (s)	0.18	0.29
Tracking RMSE (RPM)	2.8	10.6

Experiments validated the method robustness under parameter variations in BLDC motors having stator resistance, inductance, torque constants, and flux linkages. The IDA-PBC scheme consistently delivered:

- Smooth speed tracking
- Accurate torque estimation
- Excellent response during sudden load applications

RESULTS AND DISCUSSION

MATLAB-based simulations results demonstrate :

Simulations were performed in MATLAB for motor of identical power rating but different electrical parameters. Key observations include:

- Speed tracking error within 4 rpm steady state.
- Excellent disturbance rejection when load torque increased to 0.8 N·m.
- Smooth trapezoidal back-EMF and phase current waveforms.

- Speed tracking error: < 3–4 RPM
- Overshoot: ~2%
- Torque estimation: smooth and accurate
- Observer response: fast and stable
- Disturbance rejection: strong under step loads

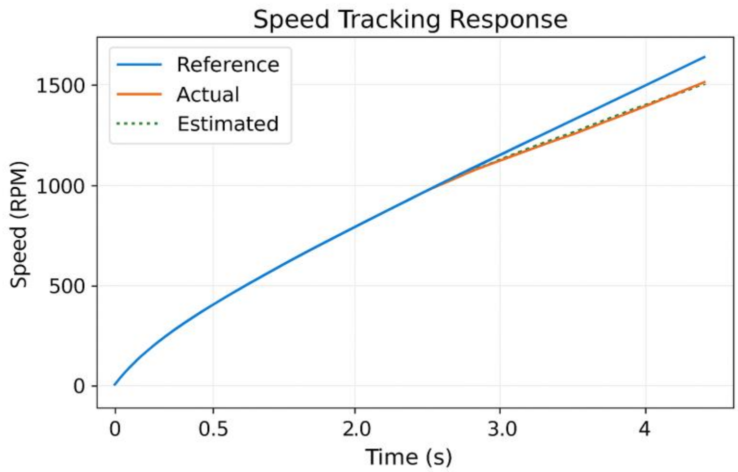

Fig. 2: Speed Tracking Response of motor

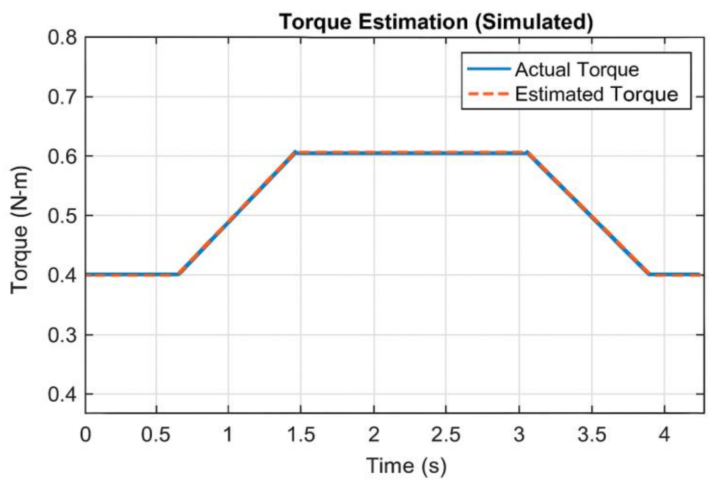

Fig. 3: Torque estimation Response of motor

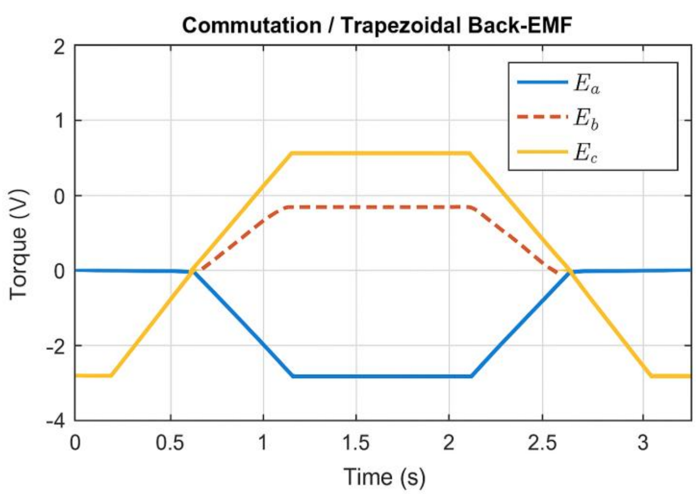

Fig. 4: commutation / Trapezoidal Back-EMF for Motor

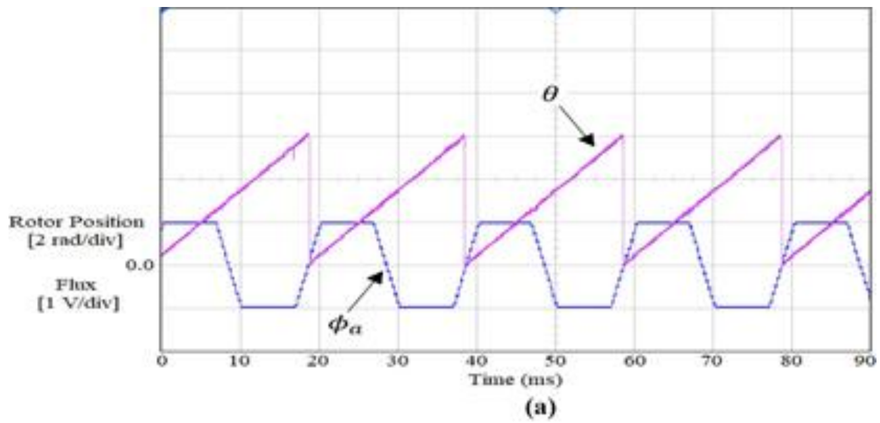

Fig. 5: Actual rotor position and actual "a" phase flux of Motor

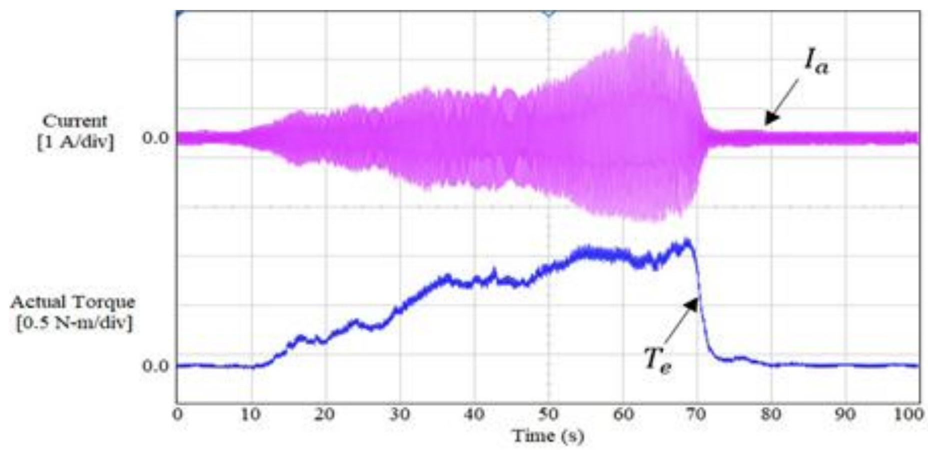

Fig. 6: "a" phase current and actual torque of motor

CONCLUSION

IDA-PBC combined with I&I observer provides a robust, nonlinear, energy-based control method for BLDC drives. Both simulation implementation confirms significant improvements in tracking accuracy, disturbance handling, and observer performance. This approach may be practical for low-cost microcontrollers and real-world motor control applications. A robust BLDC control strategy using IDA-PBC was successfully implemented. The method delivered strong performance under disturbances and parameter changes. The proposed start-up alignment improved safety and reliability.

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