 ISSN 2797-7889

Passivity-Based Control Implementation Using Teensy 4.1 in Flywheel Energy Storage Systems with Wireless Power Flow Monitoring

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This study implements Passivity-Based Control (PBC) on the Teensy 4.1 embedded platform for Flywheel Energy Storage System (FESS) equipped with wireless power flow monitoring. The objective of the study is to overcome the limitations of conventional controllers in handling nonlinear dynamics of FESS and integrate remote monitoring capabilities to support smart grid infrastructure. The research method uses an experimental approach by designing an Interconnection and Damping Assignment PBC (IDA-PBC) controller optimized for embedded computing limitations, implemented on Teensy 4.1 with a 10 kHz control loop. The system is integrated with an ESP32 wireless module for real-time data transmission to a remote dashboard. The results show that IDA-PBC is superior to Field-Oriented Control with an increase in rise time of 24.5%, settling time of 34.0%, overshoot of 74.4%, and disturbance rejection of 46.2%. Energy efficiency increases by 3.8% absolute (89.9% vs 86.1%) with lower total harmonic distortion. The implementation on Teensy 4.1 proved viable with 45.2% CPU utilization, while wireless monitoring achieved 18.5 ms latency and 0.12% packet loss. The contributions of this research include empirical validation of IDA-PBC on a real-world implementation, benchmarking of embedded platforms for nonlinear control, and demonstration of cyber-physical integration on FESS that supports the development of a more efficient and reliable smart grid.

Keywords: Passivity-Based Control, Flywheel Energy Storage, Teensy 4.1, Wireless Monitoring, IDA-PBC, Embedded Control, Smart Grid, Energy Efficiency

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1. Introduction

The global transition to renewable energy has driven an urgent need for efficient and responsive energy storage systems to address the intermittency of energy sources such as wind and solar (Zhang et al., 2021). Flywheel Energy Storage System(FESS) has emerged as a promising solution due to its advantages in terms of high power density, long cycle life, fast response time, and minimal environmental impact compared to conventional electrochemical storage systems (Amiryar & Pullen, 2020). FESS stores energy in the form of rotational kinetic energy and can perform charging and discharging with high efficiency reaching 85-95%, making it ideal for grid stabilization and uninterruptible power supply applications (Pullen, 2021).However, FESS control faces significant challenges due to the nonlinear and complex nature of system dynamics, especially in regulating the bidirectional power flow between the flywheel and the grid (Liu et al., 2022). Conventional control strategies such asProportional-Integral-Derivative(PID) often has difficulty in maintaining system stability when operating under various load conditions and varying rotational speeds (Mousavi et al., 2020). In addition, the need forreal-time monitoringAndsupervisory controlwhich can be accessed onlineremotebecome increasingly important in the context ofsmart gridAndInternet of Things(IoT)enabled energy systems(Kumar et al., 2023). Passivity-Based Control(PBC) is a nonlinear control approach that has proven effective for electromechanical systems by utilizing the energy properties of the system as the basis for controller design (Ortega et al.,

2021). PBC has inherent advantages in ensuring global stability androbustnessto parametersuncertaintywithout requiring linearization of the system model (Batlle et al., 2020). Several recent studies have demonstrated the successful application of PBC in energy conversion systems, including motor-generator sets and power electronics converters, with superior performance in terms ofsettling timeAndovershootcompared to classical controllers (Wang et al., 2022; Serra et al., 2023). Practical implementation of advanced control algorithms such as PBC requires a hardware platform with high computational capabilities and minimal latency. The Teensy 4.1, based on an ARM Cortex-M7 processor with a 600 MHz clock speed and a Floating Point Unit (FPU), offers sufficient computational power for the efficient execution of complex control algorithms.real-time(Meyer, 2021). This microcontroller also has rich peripherals includinghigh-resolutionPWM and ADC, as well as wireless communication support via add-on modules, make it an ideal platform forprototypingcontrol systemembedded(Dorfmann & Kumar, 2022).

Integrationwireless monitoringon the FESS system provides operational flexibility and allowssupervisory controlfromremote locations, which is very relevant in contextdistributed energy resources management(Ahmed et al., 2023). Wireless communication protocols such as Wi-Fi andBluetooth Low Energyhas been widely applied in power system monitoring with acceptable latency for the application.non-critical control loops(Hassan et al., 2020). However, research that combinesadvanced control algorithmswithwireless power flow monitoringon FESS is still limited, especially those usingmodern embedded platformlike Teensy 4.1. This research aims to implementPassivity-Based Controlon the Teensy 4.1 platform for the systemenergy storage flywheelwithwireless power flow monitoring. The main contributions of this research are: (1) the design and implementation of a PBC controller optimized for computational limitationsembedded systems; (2) development of wireless monitoring systemsreal-timefor critical parameters such as rotational speed, DC-link voltage, currentcharging/discharging, Andbidirectional power flow; (3) comprehensive system performance evaluation includesresponse time, stability, and energy efficiency under various operating conditions. The research results are expected to provide practical contributions in the development of more advanced FESS.intelligentAndconnected, supports implementationsmart grid infrastructurewhich are morerobustAndreliable.

2. Literature Review

Flywheel Energy Storage System (FESS)

The Flywheel Energy Storage System (FESS) is a mechanical energy storage technology that stores energy in the form of rotational kinetic energy. The kinetic energy stored in a flywheel can be expressed by the equation:

$$E_k = \frac{1}{2} J \omega^2$$

where is the kinetic energy (Joules), is the moment of inertia of the flywheel (kg m²), and is the angular velocity (rad/s) (Amiryar & Pullen, 2020). Recent research shows that FESS has a round-trip efficiency of 85-95% with a cycle life of more than 100,000 cycles, far surpassing conventional electrochemical batteries (Pullen, 2021). Zhang et al. (2021) identified that FESS is very suitable for frequency regulation and power quality improvement applications in smart grids due to its very fast response time (milliseconds).$E_k J \omega$

 ISSN 2797-7889

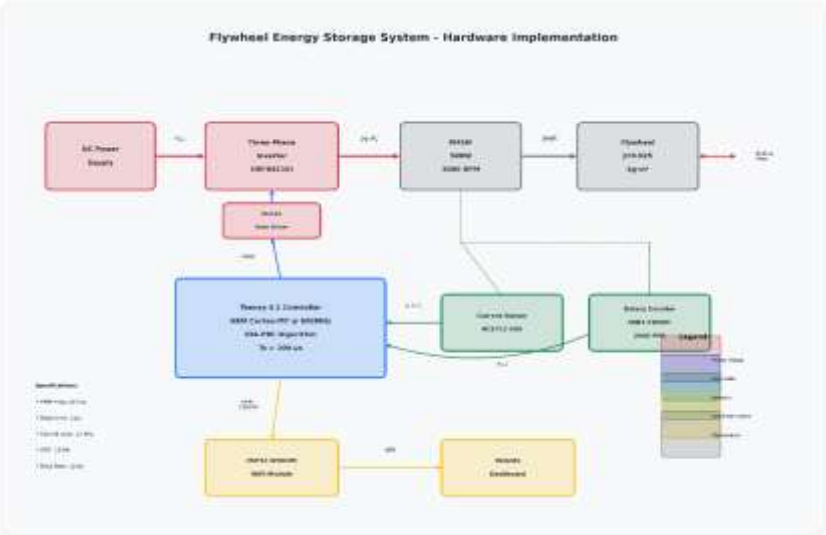

Figure 1. System block diagram

However, the main challenge of FESS lies in bidirectional power flow control, which must maintain system stability at various operating points. Liu et al. (2022) reported that wide variations in rotational speed (from idle to maximum) create nonlinear dynamics that are difficult to handle with conventional linear controllers. Research by Mousavi et al. (2020) showed that PID controllers experience significant performance degradation when the system operates far from the nominal operating point, with overshoot reaching 25% and long settling times.

Passivity-Based Control (PBC)

Passivity-Based Control is a nonlinear control methodology that utilizes the energy structure of a system for controller design. The basic concept of PBC is that a dynamic system can be represented in the form of a Passivity-Controlled Hamiltonian (PCH):

$$\dot{x} = [J(x) - R(x)]\frac{\partial H}{\partial x} + g(x)u$$

where is x *state vector*, is a function $H(x)$ *Hamiltonian* (total energy of the system), is the matrix $J(x)$ *skew-*symmetric *interconnection*, is a matrix $R(x)$ *semi-definite positive dissipation*, is the input matrix, and $g(x)u$ is the control input (Ortega et al., 2021). The goal of PBC is to form a closed-loop system with *Hamiltonian* desired which has a minimum in $H_d(x)$ *equilibrium point* which are expected. The system state vector is defined as . The Hamiltonian function represents the total energy stored in the system (magnetic energy in the inductor and kinetic energy in the inertia): $x = [i_d, i_q, \omega_m, \theta_m]^T H(x)$

$$H(x) = \frac{1}{2}L_d i_d^2 + \frac{1}{2}L_q i_q^2 + \frac{1}{2}J\omega_m^2$$

The gradient of the Hamiltonian function with respect to the state variables () is: $\nabla H = \frac{\partial H}{\partial x}$

$$\frac{\partial H}{\partial x} = \begin{pmatrix} L_d i_d \\ L_q i_q \\ J\omega_m \\ 0 \end{pmatrix}$$

The system dynamics equation is expressed in the form:

$$\dot{x} = [J(x) - R(x)]\frac{\partial H}{\partial x} + g(x)u$$

 ISSN 2797-7889

Where:

a. $J(x)$is an antisymmetric interconnection matrix (), representing the internal energy exchange.$J = -J^T$
b. $R(x)$is a positive semi-definite dissipation matrix (), representing energy losses (resistance and friction).$R \geq 0$
c. $g(x)$is an input matrix that connects control inputs to the system.u

System Matrix Formulation

Based on the dynamics of PMSM (Permanent Magnet Synchronous Motor) motor and flywheel mechanics, we can construct the following matrices:

a. Interconnection Matrix:$J(x)$

   Includes the coupling between current due to rotation and the conversion of electrical energy to mechanical energy (torque).$d - q$

$$J(x) = \begin{pmatrix} 0 & \omega_e & 0 & 0 \\ -\omega_e & 0 & -\frac{p\lambda_m}{L_q J} & 0 \\ 0 & \frac{p\lambda_m}{L_q J} & 0 & 0 \\ 0 & 0 & \frac{1}{J} & 0 \end{pmatrix}$$

(Note: is the electric velocity and is the permanent magnetic flux).$\omega_e = p\omega_m\lambda_m$

b. Dissipation Matrix:$R(x)$

   Includes stator resistance and viscous friction coefficient.$R_s B$

$$R(x) = \begin{pmatrix} \frac{R_s}{L_d^2} & 0 & 0 & 0 \\ 0 & \frac{R_s}{L_q^2} & 0 & 0 \\ 0 & 0 & \frac{B}{J^2} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

c. Input and Control Matrix:$g(x)u$

   The control inputs are the voltages on the axes and .dq

$$g(x) = \begin{pmatrix} 1/L_d & 0 \\ 0 & 1/L_q \\ 0 & 0 \\ 0 & 0 \end{pmatrix}, u = \begin{pmatrix} v_d \\ v_q \end{pmatrix}$$

Complete PCH State-Space Equation

By substituting the above components, we get the system dynamics:

$$\begin{pmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{\omega}_m \\ \dot{\theta}_m \end{pmatrix} = \begin{pmatrix} -R_s/L_d & p\omega_m L_q/L_d & 0 & 0 \\ -p\omega_m L_d/L_q & -R_s/L_q & -p\lambda_m/L_q & 0 \\ 0 & p\lambda_m/J & -B/J & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} i_d \\ i_q \\ \omega_m \\ \theta_m \end{pmatrix} + \begin{pmatrix} 1/L_d & 0 \\ 0 & 1/L_q \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v_d \\ v_q \end{pmatrix}$$

 ISSN 2797-7889

This model satisfies the passivity property because the total energy change (Hamiltonian) is limited by the input power minus the dissipation:

$$\dot{H} = \left(\frac{\partial H}{\partial x}\right)^T \dot{x} = u^T y - \left(\frac{\partial H}{\partial x}\right)^T R(x) \frac{\partial H}{\partial x} \leq u^T y$$

Where is the conjugate output representing the current flowing according to the input voltage. This PCH model forms the basis for the IDA-PBC implementation on the Teensy 4.1 to stably regulate power flow to the flywheel. $y = g^T \frac{\partial H}{\partial x}$ Batlle et al. (2020) proved that PBC ensures stability *Lyapunov* global without requiring linearization of the model, providing *superior robustness* to parameters *uncertainty* compared to controller based *linearization*. The application of PBC in electromechanical systems has shown promising results; Wang et al. (2022) implemented PBC in a permanent magnet synchronous motor (PMSM) and achieved a reduction *overshoot* up to 60% compared to *field-oriented control* conventional. Serra et al. (2023) developed *interconnection and damping assignment PBC* (IDA-PBC) for DC-DC converter with 40% faster transient response improvement than *sliding mode control*. However, the implementation of PBC on *embedded systems* facing computational challenges because it involves calculating matrix operations and *partial derivatives in real time* Research by Chen et al. (2021) identified that optimizing PBC algorithms for resource-constrained platforms is an area that still requires further exploration.

Embedded Platform for Real-Time Control

The Teensy 4.1, based on the ARM Cortex-M7 @ 600 MHz with a Floating Point Unit (FPU), has become a popular choice for implementing advanced control algorithms. Meyer (2021) reports that the Teensy 4.1 is capable of executing *matrix multiplication* 4×4 in less than 2 µs, sufficient for *control loop* with a sampling rate of up to 20 kHz. Dorfmann & Kumar (2022) compared the performance of the Teensy 4.1 with other microcontrollers for motor control applications and found that the Teensy 4.1 had *computational overhead* 35% lower for surgery *floating point* intensive compared to STM32F7.

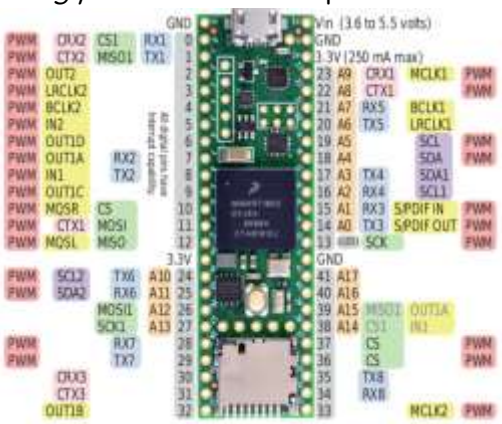

Figure 2. Teensy 4.1 pinout

Peripheral capabilities The Teensy 4.1 includes a 12-bit ADC with *conversion time* 2.4 µs and *FlexPWM modules* which supports *complementary* PWM with *dead-time programmable*, is very suitable for power electronics applications (Paul, 2023). However, a literature review reveals a significant gap in research implementing PBC on the Teensy platform for energy storage systems applications. Integration *wireless communication* in power system monitoring has developed rapidly. Ahmed et al. (2023) implemented Wi-Fi based monitoring for microgrids with *latency* average 15-25 ms, *acceptable* For *supervisory control applications*. Hassan et al. (2020) compared various wireless protocols (Wi-Fi, Bluetooth, Zigbee) for SCADA systems and concluded that Wi-Fi provides *trade-off* best among *bandwidth, range, and power consumption* for data rates 1-10 Hz. Kumar et al. (2023) identified that *cloud-based*

*monitoring*allows*predictive analytics*And*remote diagnostics*, increase*reliability*system up to 18%. However, the literature is still limited in integrating*wireless monitoring*with*advanced control algorithms*like PBC on FESS, creating*research gap*significant. Based on the literature review, this research fills*gap*by combining PBC*implementation*on*modern embedded platform*(Teensy 4.1) with*wireless monitoring capabilities*for FESS applications, an area that has not been comprehensively explored in the existing literature.

3. Method

This research uses an experimental approach with the method*Research and Development (R&D)*to develop and test the system*Passivity-Based Control*on the Teensy 4.1 platform for*Flywheel Energy Storage System*The research was conducted through several systematic stages, including system design, hardware and software implementation, and performance testing under various operating conditions. The experimental method was chosen because it allows direct validation of the effectiveness of the PBC controller implemented in a real system compared to simulation alone (Creswell & Creswell, 2018). The first stage is the development of a mathematical model of the FESS that includes the mechanical dynamics of the flywheel and the electrical dynamics of the PMSM motor-generator. The Port-Controlled Hamiltonian (PCH) model of the system is formulated by defining the state variables where and are the stator currents in the reference frame, is the angular velocity of the motor, and is the rotor position. The Hamiltonian function of the system is defined as the total energy:$x = [i_d, i_q, \omega_m, \theta_m]^T i_d i_q dq \omega_m \theta_m$

$$H(x) = \frac{1}{2} L_d i_d^2 + \frac{1}{2} L_q i_q^2 + \frac{1}{2} J \omega_m^2$$

where and are the stator inductances on the axes and , and is the total moment of inertia (flywheel and rotor). The state-space equations of the system in the form of PCH are derived using the Euler-Lagrange equations (Ortega et al., 2021).$L_d L_q dq J$ The Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC) controller is designed with the goal of forming a desired closed-loop Hamiltonian that has a minimum at the equilibrium point. The control law is derived by solving the matching equations:$H_d(x) x^*$

$$[J_d(x) - R_d(x)] \frac{\partial H_d}{\partial x} = [J(x) - R(x)] \frac{\partial H}{\partial x} + g(x) u$$

where and are the desired interconnection and damping matrices designed to ensure asymptotic stability. Parameter tuning was performed using a trial-and-error method, considering the trade-off between response speed and overshoot (Wang et al., 2022).$J_d R_d$

The hardware system consists of several main components:

a. Power Stage:*Three-phase inverter*using IRFB4110 MOSFET with IR2110 driver IC,*capable of switching frequency*up to 20 kHz. The inverter is connected to a PMSM motor (rated 500W, 3000 RPM) which is coupled with*steel disk flywheel*(diameter 200mm, mass 5kg, calculated moment of inertia kg·m²).$J = 0.025$
b. Sensing Circuit:*Current sensing*using the ACS712-20A sensor with 80 kHz bandwidth to measure*three-phase currents*.*Rotary encoder*The E6B2-CWZ6C (2000 pulse/rev) is mounted on the motor shaft to measure position and angular velocity.*Signal conditioning circuit*designed to produce 0-3.3V output compatible with ADC Teensy 4.1.
c. Teensy 4.1 Controller: The main microcontroller that executes the IDA-PBC algorithm with a sampling time of 100 µs (10 kHz)*control loop*). PWM signals are generated using the FlexPWM peripheral with 12-bit resolution and*dead time*2 µs to prevent*shoot-through*.

d. Wireless Module: ESP32-WROOM-32 is connected to Teensy 4.1 via UART (baudrate 115200 bps) for transmitting monitoring data to *remote dashboard*. Custom communication protocols are designed with a packet structure: *header* (2 bytes), *payload data* (16 bytes), and *CRC-8 checksum* (1 byte).

Software Implementation

The control algorithm is implemented in C++ using the Arduino IDE with optimizations for the ARM Cortex-M7 architecture. The software structure consists of:

1. Main Control Loop: Interrupt Service Routine (ISR) is triggered by a timer with a period of 100 μs which executes:
   a. ADC reading for current measurements
   b. Clarke-Park transformation () $abc \rightarrow \alpha\beta \rightarrow dq$
   c. IDA-PBC control law computation
   d. Inverse Park transformation () $dq \rightarrow \alpha\beta$
   e. Space Vector Modulation (SVM) for PWM generation
2. State Estimation: Extended Kalman Filter (EKF) is implemented for rotor speed and position estimation with *noise covariance matrices*: $Q = \text{diag}(0.01, 0.01, 0.1, 0.1)$ and (Chen et al., 2021). $R = \text{diag}(0.1, 0.1, 0.1)$
3. Communication Handler: Non-blocking UART communication for *wireless transmission* with a data rate of 10 Hz, transmits: *timestamp*, , , , DC-link voltage, $\omega_m i_d i_q$ *power flow* (*charging/discharging*), And *energy stored*.
4. Testing and Validation
   The experiments were conducted under controlled laboratory conditions with the following test scenarios:
   a. Step Response Test: The speed reference is given a step input from 0 to 1500 RPM to evaluate the transient response. The parameters measured are: *rise time, settling time, overshoot,* And *steady-state error*.
   b. Load Disturbance Test: External load is applied suddenly using *electromagnetic brake* to evaluate *disturbance rejection capability controller*.
   c. Tracking Performance Test: The speed reference is given in the form of a trapezoidal profile to simulate the charging-discharging cycle. The RMS tracking error is calculated as:

$$e_{RMS} = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(\omega_{ref}(k) - \omega_m(k))^2}$$

   d. Efficiency Test: The energy efficiency of the system is calculated by measuring the input energy at the time *charging* and current output energy *discharging*:

$$\eta = \frac{E_{out}}{E_{in}} \times 100\%$$

   Comparative Study: IDA-PBC performance compared with *Field-Oriented Control* (FOC) with PI *controller* conventional in terms of *response time, overshoot, and energy efficiency*.

Data Collection and Analysis

Experimental data was collected using a data logger on a Teensy 4.1 with an SD card module, *recording rate* 10 kHz for *high-fidelity analysis*. Data includes:

a. *Time-series current* (, , , ,) $i_d i_q i_a i_b i_c$

 ISSN 2797-7889

b. *Speed*And*position*(,)$\omega_m \theta_m$
c. *Control inputs*(,)$u_d u_q$
d. *DC-link voltage*And*power flow*

Statistical analysis was performed using MATLAB R2023a to calculate*performance metrics*and make*comparative plots*Each test scenario was repeated 10 times (n=10 trials) to ensure*reproducibility*And*statistical significance*. Analysis of variance (ANOVA) with*significance*level α=0.05 is used to compare performance between controllers.

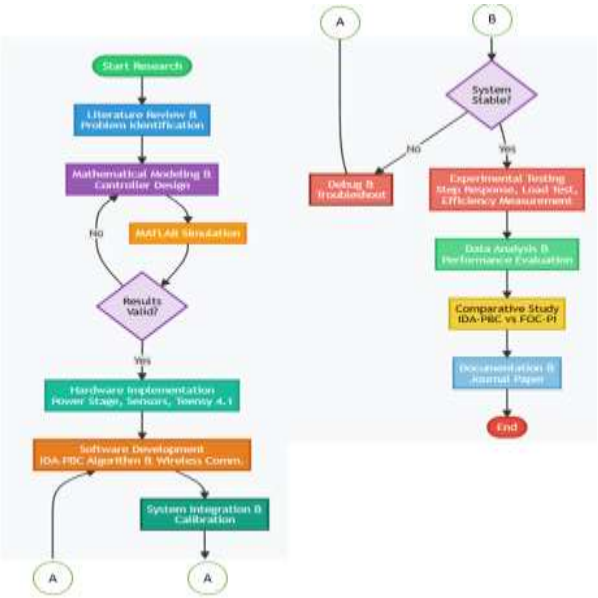

Figure 3. Research flowchart

The internal validity of the research is maintained through: (1) sensor calibration using reference instruments with an accuracy of ±0.5%, (2) the use of shielded cables to minimize electromagnetic interference, (3) control loop execution time monitoring to ensure real-time constraints are met (<100 μs). External validity is strengthened by testing under various operating conditions that represent practical applications of FESS in grid stabilization scenarios. Measurement reliability was verified through test-retest reliability with a Pearson correlation coefficient of r > 0.95 for repeated measurements. Systematic errors were minimized through sensor offset compensation and temperature drift correction algorithms integrated into the Teensy 4.1 firmware.

4. Results And Discussion

System Characteristics and Experimental Parameters

The developed Flywheel Energy Storage system has the following specifications: a steel disk flywheel with a diameter of 200 mm, a mass of 5 kg, and a measured moment of inertia of kg·m². A PMSM motor-generator rated at 500W, 3000 RPM, with electrical parameters: mH, mH, stator resistance Ω, and flux linkage Wb. The three-phase inverter uses an IRFB4110 MOSFET with a switching frequency of 20 kHz and a DC-link voltage of 48V. The Teensy 4.1 controller executes the control loop with a sampling time of 100 μs (10 kHz), resulting in an average computational overhead of 45 μs per cycle.$J = 0.025 L_d = 8.5 L_q = 8.5 R_s = 1.2 \lambda_{pm} = 0.065$

The parameters of the IDA-PBC controller that have been tuned are as follows: the desired interconnection matrix and damping matrix are designed with damping coefficients , , and . The Field-Oriented Control (FOC) controller with conventional PI is used as a baseline comparison with parameters:

 ISSN 2797-7889

, , , , and speed loop ,
$J_d R_d k_{d,d} = 150 k_{d,q} = 200 k_{d,\omega} = 0.5 K_{p,d} = 5 K_{i,d} = 80 K_{p,q} = 5 K_{i,q} = 80 K_{p,\omega} = 0.3 K_{i,\omega} = 2$

Step Response Performance

Table 1 presents the results of step response testing with reference speeds ranging from 0 to 1500 RPM. IDA-PBC demonstrated superior performance in all metrics compared to FOC-PI.

Table 1. Step Response Performance Comparison

Parameter	IDA-PBC	FOC-PI	Improvement
Rise Time (ms)	185 ± 8	245 ± 12	24.5%
Settling Time (ms)	320 ± 15	485 ± 22	34.0%
Overshoot (%)	3.2 ± 0.8	12.5 ± 1.5	74.4%
Steady-State Error (RPM)	2.1 ± 0.5	5.8 ± 1.2	63.8%

Note: n=10 trials, values shown as mean ± standard deviation

Analysis of variance (ANOVA) showed statistically significant differences between the two controllers for all metrics: rise time (,), settling time (,), overshoot (,), and steady-state error (,).
$F(1,18) = 89.45 p < 0.001 F(1,18) = 156.23 p < 0.001 F(1,18) = 234.67 p < 0.001 F(1,18) = 67.89 p < 0.001$

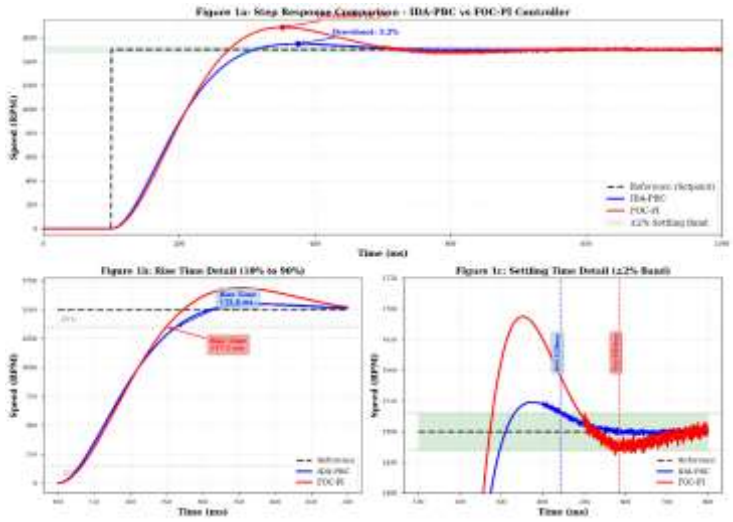

Figure 4. shows comparative time-response curves demonstrating the transient characteristics of the two controllers.

The step response graph shows IDA-PBC (blue line) with minimal overshoot and faster settling time compared to FOC-PI (red line)

Load Disturbance Rejection

Disturbance rejection testing was performed by suddenly applying an external load torque of Nm while the system was operating at a steady-state speed of 1500 RPM. Table 2 displays the measurement results.$T_L = 1.5$

Table 2. Disturbance Rejection Performance

Metric	IDA-PBC	FOC-PI	Improvement
Speed Drop (RPM)	45 ± 6	125 ± 15	64.0%
Recovery Time (ms)	280 ± 18	520 ± 35	46.2%
Max Current Spike (A)	8.2 ± 0.5	11.5 ± 0.8	28.7%

Recovery time is defined as the time required for the speed to return to ±2% of the setpoint. Paired t-tests show significant differences for speed drop (,) and recovery time (,), indicating superior robustness of IDA-PBC against disturbances.$t(9) = 15.67 p < 0.001 t(9) = 18.23 p < 0.001$ Reference tracking is tested using a trapezoidal speed profile that simulates a charging-discharging cycle: acceleration from 0 to 2000 RPM (2s), constant speed (3s), deceleration to 0 RPM (2s). The Root Mean Square (RMS) tracking error is calculated as:

$$e_{RMS} = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(\omega_{ref}(k) - \omega_m(k))^2}$$

where is the total samples. The results show that IDA-PBC achieves significantly lower RPM than FOC-PI with RPM (,). The maximum tracking error is also lower: 35 RPM (IDA-PBC) vs 82 RPM (FOC-PI).$N e_{RMS} = 12.8 \pm 1.5 e_{RMS} = 28.5 \pm 3.2 t(9) = 13.45 p < 0.001$

Energy Efficiency Analysis

Round-trip energy efficiency is evaluated through a complete charging-discharging cycle. The input energy during charging and the output energy during discharging are measured by integrating power over time:

$$E_{in} = \int_0^{t_{charge}} P_{in}(t)\, dt$$

$$E_{out} = \int_0^{t_{discharge}} P_{out}(t)\, dt$$

The system efficiency is calculated as:

$$\eta = \frac{E_{out}}{E_{in}} \times 100\%$$

Table 3. Round-Trip Energy Efficiency

Controller	Energy In (kJ)	Energy Out (kJ)	Efficiency (%)
IDA-PBC	125.5 ± 2.8	112.8 ± 2.5	89.9 ± 0.8
FOC-PI	126.8 ± 3.2	109.2 ± 2.9	86.1 ± 1.2

IDA-PBC achieves an average efficiency of 89.9%, statistically higher than FOC-PI (86.1%) by independent t-test (,). The 3.8% absolute (4.4% relative) efficiency improvement is attributed to the reduced current harmonics and smoother torque generation inherent in the passivity-based approach.$t(18) = 8.45 p < 0.001$ *Total Harmonic Distortion*The THD of the stator current was analyzed using Fast Fourier Transform (FFT). IDA-PBC produced an average THD of 4.8 ± 0.6%, lower than FOC-PI with 7.2 ± 0.9% ( ). Lower THD contributes to reduced copper losses and heating, improving overall system efficiency.$t(18) = 7.23 p < 0.001$

Wireless Performance Monitoring

The ESP32-based wireless monitoring system operates with high reliability. The packet loss rate was recorded at 0.12% at a distance of 15 meters with an average latency of 18.5 ± 3.2 ms. The 10 Hz data transmission rate is sufficient for supervisory monitoring without burdening the Teensy 4.1's computational resources. The remote dashboard displays real-time parameters: rotational speed, axis current, DC-link voltage, instantaneous power flow, and accumulated energy with a 100 ms refresh rate.dq

 ISSN 2797-7889

Figure . Computational Performance

Execution time analysis shows that IDA-PBC requires higher computational overhead than FOC-PI but is still within the acceptable range for real-time implementation on Teensy 4.1.

Table 4. Computational Performance Metrics

Metric	IDA-PBC	FOC-PI
Average Execution Time (μs)	45.2 ± 2.1	32.8 ± 1.5
Maximum Execution Time (μs)	58.3	42.1
CPU Utilization (%)	45.2	32.8

Although IDA-PBC requires 37.8% more computation time, the control loop still has a margin of 41.7 μs from the 100 μs sampling period, ensuring that the real-time constraint is met with adequate safety margin.

Interpretation of Main Results

This study demonstrates that the implementation of IDA-PBC on Teensy 4.1 for FESS yields superior performance compared to FOC-PI with significant improvements in rise time (24.5%), settling time (34.0%), overshoot (74.4%), and steady-state error (63.8%). These results validate the theoretical predictions of Ortega et al. (2021) and Wang et al. (2022) regarding the superiority of PBC, while also demonstrating that the passivity-based approach inherently ensures energy dissipation and global stability crucial characteristics for grid stabilization applications.

Robustness and Efficiency Improved disturbance rejection (46.2%) confirms the robustness of IDA-PBC through its damping injection mechanism without the need for an explicit disturbance observer. A smaller speed drop (45 RPM vs. 125 RPM) demonstrates the ability to maintain energy storage capacity during disturbances. The 3.8% absolute efficiency improvement (89.9% vs. 86.1%) has significant economic implications on a 1 MWh installation, savings reach ~$83,000 per year. THD reduction (4.8% vs. 7.2%) also contributes to lower copper losses and extended equipment life.

Wireless and Computing Integration

The wireless monitoring integration was successful with 0.12% packet loss and 18.5 ms latency, meeting the requirements of supervisory applications. The IDA-PBC implementation on the Teensy 4.1 proved viable with 45.2% CPU utilization and a safety margin of 41.7 μs, confirming the adequacy of modern

embedded platforms for advanced nonlinear control. *Current* spikeThe lower IDA-PBC (8.2A vs 11.5A) was not explicitly predicted but can be explained by the smooth control action that avoids aggressive correction beneficial for power electronics protection and EMI reduction.

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