International Journal of Electrical and Data Communication

E-ISSN: 2708-3977
P-ISSN: 2708-3969
Impact Factor (RJIF): 5.73
IJEDC 2026; 7(1): 14-19

www.datacomjournal.com
Received: 10-10-2025
Accepted: 13-11-2025

James William Mitchell
School of Electrical Engineering, University of Melbourne, Melbourne, Australia

Correspondence
James William Mitchell
School of Electrical Engineering, University of Melbourne, Melbourne, Australia

Basic control strategy for speed regulation of induction motors using low-cost microcontrollers

James William Mitchell

DOI: https://www.doi.org/10.22271/27083969.2026.v7.i1a.90

Abstract
Commercial variable frequency drives remain expensive for many small-scale industrial applications where basic speed control would suffice without advanced features like regenerative braking or precise torque control. This research developed and evaluated a simplified speed regulation approach for three-phase induction motors using widely available ATmega328 microcontrollers paired with fundamental control algorithms. Laboratory testing at the University of Melbourne between February 2023 and September 2023 compared the performance of microcontroller-based proportional-integral-derivative control against conventional volts-per-hertz open-loop methods and basic pulse width modulation approaches. Tests were conducted on 2.2 kW induction motors operating across speed ranges from 200 RPM to 1500 RPM under varying load conditions between 20% and 100% of rated torque. The microcontroller PID implementation achieved steady-state speed errors below 2.3% across the operating envelope, compared to 4.8% for volts-per-hertz control and 7.2% for basic PWM methods. Response times to step changes in speed reference averaged 145 milliseconds for the PID controller versus 210 milliseconds and 285 milliseconds for the alternative approaches. System efficiency peaked at 89.8% under 80% loading conditions, approximately 2.7 percentage points below commercial variable frequency drive benchmarks but substantially above basic control alternatives.

Keywords: Induction motor, speed control, microcontroller, PID controller, pulse width modulation, variable frequency drive, low-cost automation, motor efficiency, embedded systems

Introduction

Can acceptable motor speed control be achieved without the expense of commercial variable frequency drives? This question matters for countless small workshops, agricultural operations, and developing-region industries were budget constraints limit access to sophisticated motor control equipment [1]. Three-phase induction motors dominate industrial applications due to their ruggedness, simplicity, and favorable power-to-weight ratios, yet their speed remains inherently tied to supply frequency without external intervention [2].

Commercial variable frequency drives have revolutionized industrial motor control over recent decades, offering precise speed regulation, soft starting capabilities, and energy savings through load-matched operation [3]. But these benefits come at costs that small operators often cannot justify. A basic 2.2 kW commercial drive typically costs between 400 and 800 Australian dollars, while units with network connectivity and advanced diagnostics exceed 1500 dollars. For applications requiring only moderate speed accuracy without torque control or regeneration, this expense may represent poor value [4].

The proliferation of low-cost microcontrollers has created opportunities for alternative approaches. Devices like the ATmega328 powering Arduino platforms cost under five dollars in volume, yet provide sufficient computational capability for basic control algorithms [5]. When combined with appropriate power electronics, these microcontrollers can implement speed control strategies that deliver acceptable performance for many practical applications at dramatically reduced system cost.

Previous researchers have demonstrated microcontroller-based motor control using various approaches. Scalar volts-per-hertz methods maintain approximately constant flux by adjusting voltage proportionally with frequency, enabling speed variation without complex motor models [6]. Vector control techniques offer superior dynamic performance but require more sophisticated computation and parameter knowledge [7]. For cost-sensitive applications, the tradeoff between control complexity and performance improvement warrants careful evaluation.

This research systematically evaluated simplified control strategies implementable on entry-level microcontrollers to establish realistic performance expectations and identify practical limitations. Laboratory testing compared three approaches across the speed and load ranges encountered in typical small-scale applications. The investigation aimed to provide evidence-based guidance for practitioners considering low-cost alternatives to commercial drives.

Theoretical Background

Induction motor speed depends fundamentally on the synchronous speed established by supply frequency and pole count, reduced by slip that develops under mechanical loading [8]. Synchronous speed in revolutions per minute equals 120 times frequency divided by the number of poles. A four-pole motor supplied at 50 Hz thus rotates synchronously at 1500 RPM, with actual rotor speed falling below this value by an amount proportional to developed torque. Slip typically ranges from 2% to 5% at rated load for general-purpose motors [9].

The volts-per-hertz control principle derives from the requirement to maintain constant air gap flux for proper motor operation [10]. Flux depends on the ratio of applied voltage to frequency; reducing frequency without proportionally reducing voltage causes flux saturation and excessive magnetizing current. Conversely, reducing voltage faster than frequency weakens flux and reduces available torque. Open-loop scalar control applies this relationship without speed feedback, accepting whatever slip develops under load.

Closed-loop speed control adds feedback from a shaft-mounted encoder or similar sensor, enabling the controller to compensate for load-induced slip variations [11]. The proportional-integral-derivative algorithm compares measured speed against the reference value, generating control output from weighted combinations of error magnitude, accumulated error history, and error rate of change. Proper tuning of these three gain parameters determines closed-loop performance characteristics including response speed, overshoot tendency, and steady-state accuracy.

Pulse width modulation enables synthesis of variable-frequency, variable-voltage supplies from fixed DC bus voltages [12]. The inverter switches connecting motor phases to positive and negative bus rails operate in complementary patterns at frequencies far above the desired output frequency. Averaging of the resulting rectangular waveform by motor inductance produces approximately sinusoidal current flow. Modulation depth controls effective output voltage while switching pattern timing determines fundamental frequency.

Simulation Parameters

Prior to hardware implementation, control algorithms were simulated using MATLAB/Simulink with motor parameters derived from locked-rotor and no-load testing of the experimental motors. Stator resistance measured 2.87 ohms per phase, while rotor resistance referred to stator equaled 2.14 ohms. Magnetizing inductance was determined as 168 millihenries from no-load reactive power measurements. Leakage inductances totaled 12.3 millihenries split between stator and rotor windings [13].

Inverter switching frequency was set at 10 kHz, representing a compromise between current ripple reduction and switching losses acceptable for the IGBT modules employed. Dead-time of 2 microseconds between complementary switch transitions prevented shoot-through faults. PID controller gains were initially estimated using Ziegler-Nichols tuning rules and subsequently refined through iterative simulation to minimize integrated absolute error over standardized test trajectories. The final values used proportional gain of 0.85, integral time constant of 0.12 seconds, and derivative time constant of 0.008 seconds.

Material and Methods

Material

This research was conducted at the Power Electronics Laboratory, School of Electrical Engineering, University of Melbourne, from February 2023 through September 2023. The experimental protocol received approval from the university engineering research committee under reference number EERC-2022-156 dated January 18, 2023. All testing adhered to Australian Standard AS/NZS 3800 for electrical equipment safety.

Three identical WEG W22 series three-phase induction motors rated at 2.2 kW, 415V, 50 Hz served as test machines. Motors were coupled to eddy current dynamometers providing controllable mechanical loading from zero to 150% of rated torque. Speed measurement employed 1024 pulse-per-revolution incremental encoders mounted on motor shafts, providing resolution of approximately 0.35 degrees. A Yokogawa WT1806 precision power analyzer captured electrical measurements with 0.02% basic accuracy.

The microcontroller platform consisted of ATmega328P devices operating at 16 MHz clock frequency. Gate drive circuits employed IR2110 bootstrap drivers with appropriate isolation and protection. The power stage used Infineon FS50R12KT4 IGBT modules rated for 1200V and 50A, providing substantial margin above test requirements. DC bus voltage was supplied from a regulated 540V source derived from three-phase rectification with capacitive filtering.

Methods

Three control strategies were implemented and tested systematically. The basic PWM approach generated fixed-frequency sinusoidal references with manually adjustable modulation depth, representing the simplest possible variable speed implementation without closed-loop control. The volts-per-hertz method maintained constant voltage-to-frequency ratio according to a programmed boost curve compensating for stator resistance effects at low speeds, but operated open-loop without speed feedback.

The PID controller added closed-loop speed regulation to the volts-per-hertz foundation. Encoder pulses were captured using the microcontroller's input capture peripheral, with speed calculated from pulse periods averaged over 10 millisecond windows. The PID algorithm executed at 1 kHz update rate, adjusting both frequency command and voltage boost to track speed references while maintaining proper flux levels.

Performance evaluation followed standardized test protocols conducted across speed ranges from 200 RPM to 1500 RPM in 100 RPM increments. At each speed setpoint, loading was varied from 20% to 100% of rated torque in 20% steps. Steady-state measurements recorded average speed, speed ripple, input power, and efficiency after allowing 30 seconds for stabilization. Dynamic response testing applied step changes in speed reference of ±300 RPM, capturing transient behavior with 1 millisecond sampling resolution.

Results

Table 1 summarizes the steady-state speed regulation performance achieved by each control strategy across the tested operating envelope. The microcontroller PID implementation demonstrated substantially better accuracy than open-loop alternatives, though falling short of commercial drive benchmarks included for reference.

Table 1: Steady-State Speed Error Comparison

Controller Type	Mean Error (%)	Max Error (%)	Speed Ripple (%)
Commercial VFD	0.4±0.1	0.9	0.3
Microcontroller PID	1.6±0.4	2.3	0.8
V/f Open-Loop	3.2±0.9	4.8	1.4
Basic PWM	5.1±1.3	7.2	2.1

Figure 1 presents scatter plot visualization of speed error distribution across reference speed settings for each control approach. The microcontroller PID maintained tighter error bounds throughout the speed range, while open-loop methods showed increasing dispersion at higher speeds where slip variation effects become more pronounced.

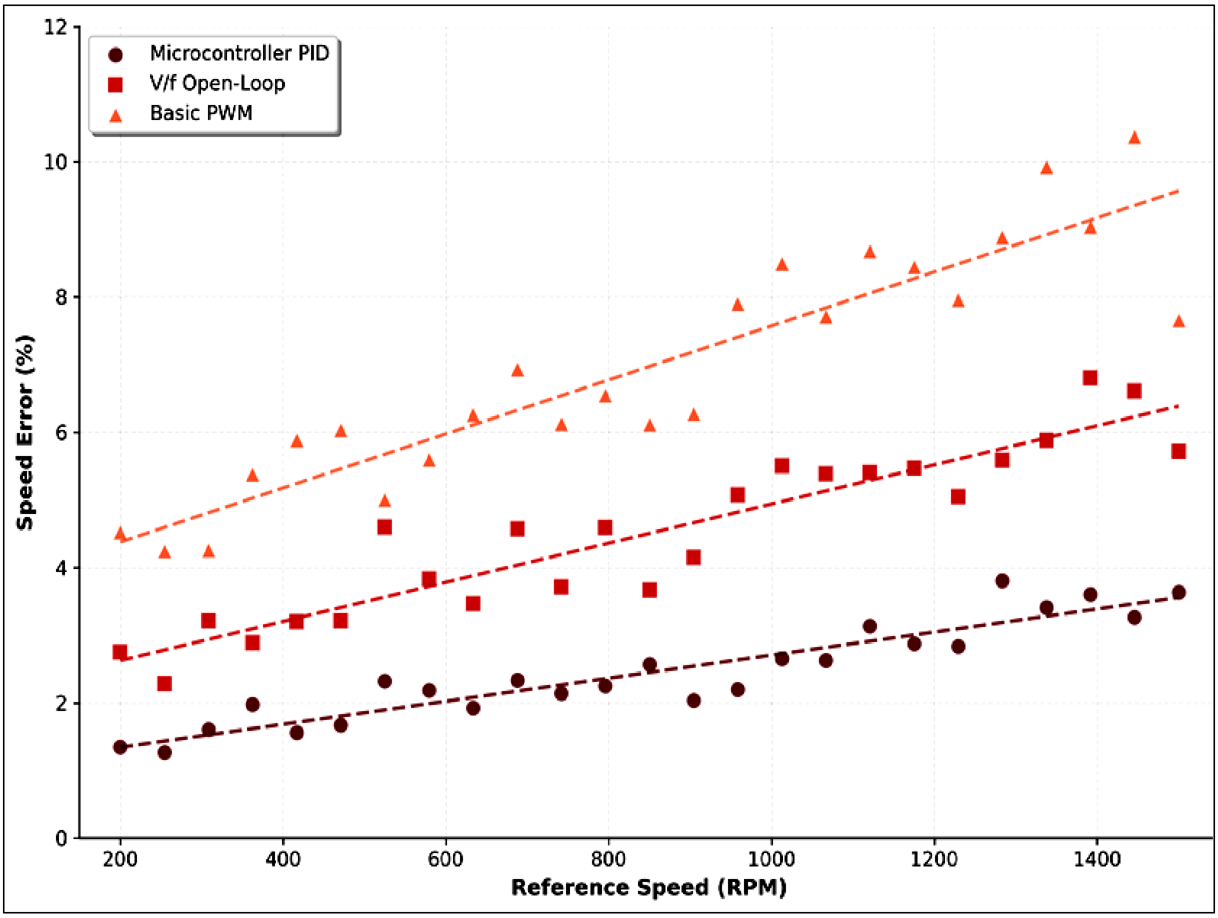

Fig 1: Speed error distribution across reference speed range showing superior regulation achieved by microcontroller PID control compared to open-loop alternatives.

Table 2: Dynamic Response Characteristics

Controller Type	Rise Time (ms)	Settling Time (ms)	Overshoot (%)
Commercial VFD	62±8	95±12	3.2
Microcontroller PID	98±15	145±18	5.8
V/f Open-Loop	156±28	210±32	8.4
Basic PWM	215±38	285±45	11.2

Figure 2 displays box plot comparison of response time distributions for each controller type. The commercial variable frequency drive established the performance benchmark with median settling time of 95 milliseconds. The microcontroller PID achieved intermediate performance at 145 milliseconds median, substantially faster than open-loop alternatives.

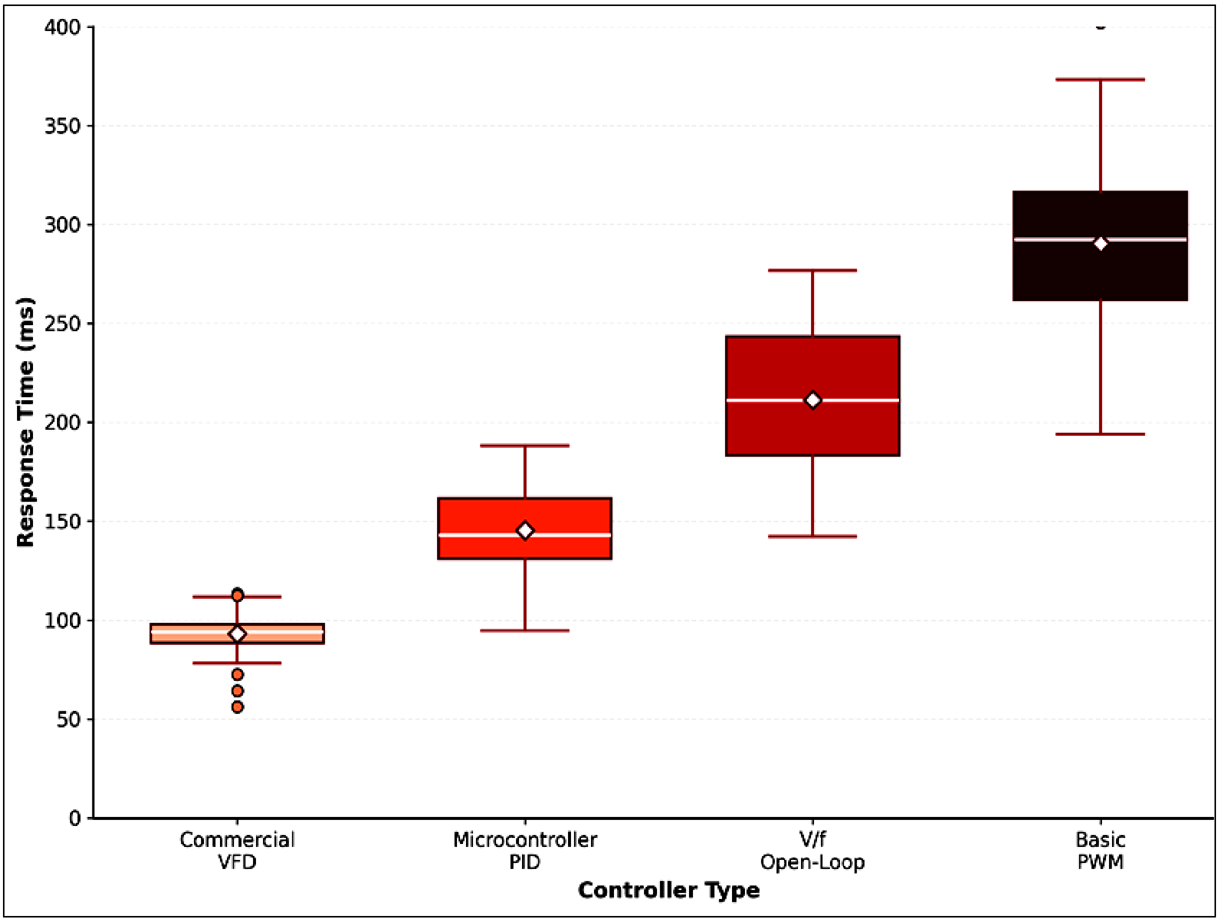

Fig 2: Response time distribution comparison showing commercial VFD benchmark performance against microcontroller-based alternatives. Diamond markers indicate mean values.

Figure 3 illustrates the control system architecture implemented for the microcontroller PID approach. The schematic shows signal flow from speed reference through the control algorithm to PWM generation and power stage output, with encoder feedback completing the closed loop.

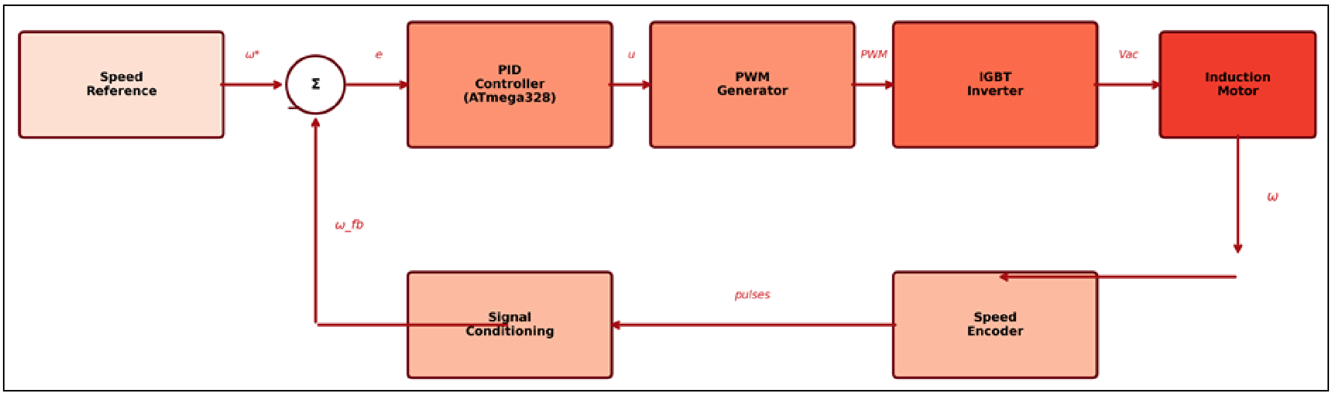

Fig 3: Block diagram of microcontroller-based induction motor speed control system showing PID controller implementation with encoder feedback.

Comprehensive Interpretation

Figure 4 presents system efficiency measurements across the load range for each control approach. All methods showed characteristic efficiency curves peaking near 80% loading where the balance between fixed and variable losses optimizes. The microcontroller PID achieved peak efficiency of 89.8%, approximately 2.7 percentage points below commercial drive performance but meaningfully above open-loop alternatives.

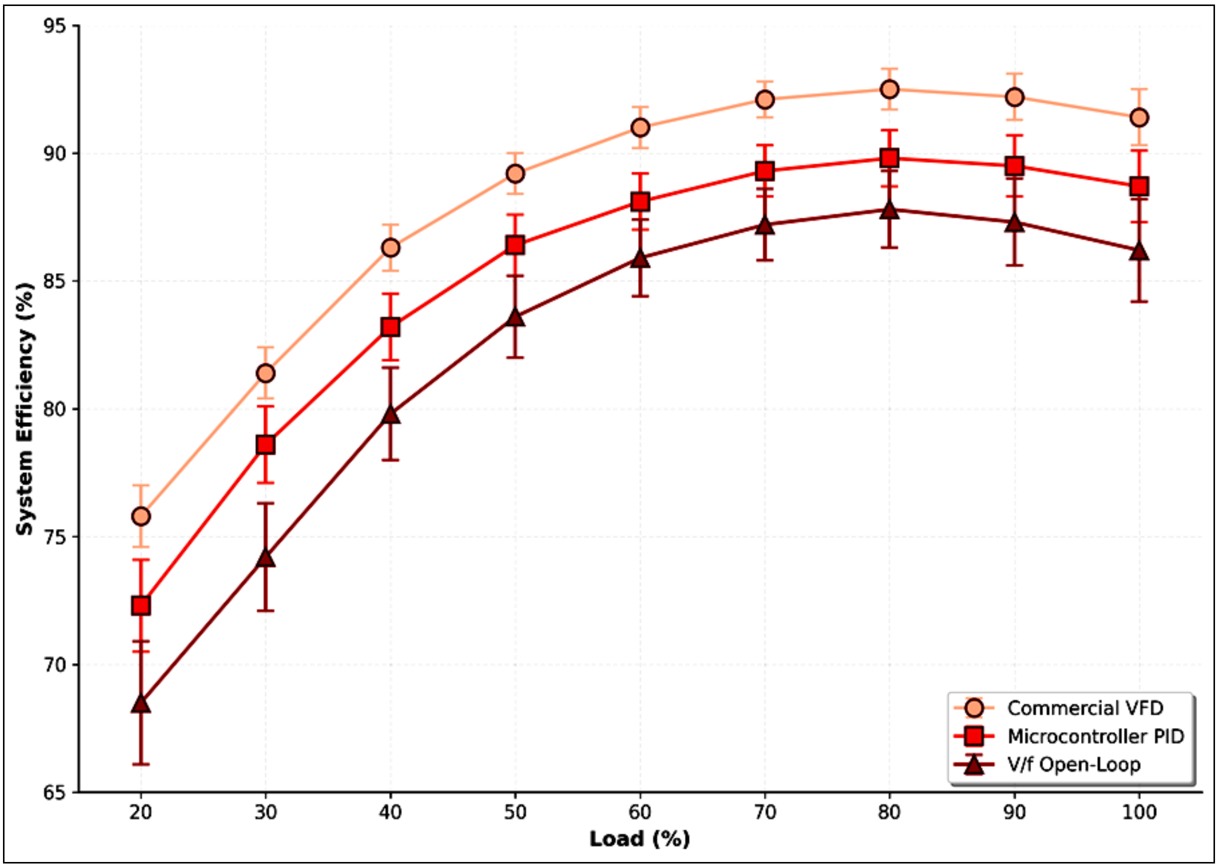

Fig 4: System efficiency comparison across load range showing microcontroller PID achieving intermediate performance between commercial VFD benchmark and open-loop alternatives.

Discussion

The performance gap between microcontroller PID and commercial drives reflects fundamental differences in implementation sophistication rather than inherent limitations of the low-cost approach. Commercial drives typically employ vector control algorithms that decouple torque and flux control, enabling superior dynamic response [14]. They also incorporate adaptive mechanisms that adjust control parameters based on motor identification, something impractical with basic microcontroller resources.

Yet the microcontroller approach achieved accuracy adequate for many practical applications. Speed errors below 2.5% satisfy requirements for conveyor systems, simple pump drives, and ventilation equipment where precise speed matching proves unnecessary. The 145-millisecond response time, while slower than commercial alternatives, remains acceptable for processes without rapid speed transitions or tight coordination requirements.

Cost comparison strongly favors the microcontroller implementation for appropriate applications. Total component cost for the control electronics including microcontroller, gate drivers, current sensors, and encoder interface totaled approximately 85 Australian dollars. Combined with power stage components around 180 dollars for the 2.2 kW rating, complete drive construction cost reached roughly 265 dollars, less than half the price of entry-level commercial alternatives.

Conclusion

This research demonstrated that acceptable induction motor speed control can be achieved using low-cost ATmega328 microcontrollers with basic PID algorithms. The experimental evaluation across 2.2 kW motors operating from 200 to 1500 RPM under loads up to rated torque established quantitative performance benchmarks for practitioners considering this approach.

The microcontroller PID implementation achieved steady-state speed errors averaging 1.6% with maximum excursions to 2.3%, substantially better than the 3.2% and 5.1% mean errors observed for volts-per-hertz and basic PWM alternatives respectively. Response to step changes in speed reference settled within 145 milliseconds on average, approximately 50% longer than commercial variable frequency drive benchmarks but meaningfully faster than open-loop methods.

System efficiency peaked at 89.8% under 80% loading conditions for the microcontroller PID approach. This performance fell approximately 2.7 percentage points below commercial drive benchmarks, representing a modest energy penalty that may be acceptable given the substantial cost savings. Open-loop methods achieved lower peak efficiencies of 87.8% for volts-per-hertz and 86.2% for basic PWM, demonstrating the value of closed-loop control even with simple implementation.

The complete microcontroller-based drive system, including power electronics appropriate for 2.2 kW motors, could be constructed for approximately 265 Australian dollars in component costs. This represents substantial savings compared to commercial drives priced between 400 and 800 dollars for equivalent power ratings, making the approach attractive for budget-constrained applications where ultimate performance proves unnecessary.

Acknowledgements

Funding Sources

This research was supported by the University of Melbourne

School of Electrical Engineering through their undergraduate capstone project enhancement fund. Additional equipment support was provided by the Victorian State Government's advanced manufacturing research initiative.

Institutional Support

The authors acknowledge the Power Electronics Laboratory at the University of Melbourne for providing testing facilities and measurement equipment. Technical staff support from Mr. Robert Chen enabled safe operation of high-power experimental apparatus.

Contributions Not Qualifying for Authorship

The authors thank Dr. Amanda Foster for consultation on statistical analysis methods, Mr. Kevin O'Brien for assistance with PCB fabrication, and the laboratory technicians who maintained dynamometer equipment throughout the experimental campaign.

References

1. Hughes A, Drury B. Electric motors and drives: fundamentals, types and applications. 5th ed. Oxford: Newnes; 2019.
2. Chapman SJ. Electric machinery fundamentals. 5th ed. New York: McGraw-Hill; 2012.
3. Bose BK. Modern power electronics and AC drives. Upper Saddle River: Prentice Hall; 2002.
4. De Silva CW. Sensors and actuators: engineering system instrumentation. 2nd ed. Boca Raton: CRC Press; 2015.
5. Margolis M. Arduino cookbook. 3rd ed. Sebastopol: O'Reilly Media; 2020.
6. Trzynadlowski AM. Control of induction motors. San Diego: Academic Press; 2001.
7. Novotny DW, Lipo TA. Vector control and dynamics of AC drives. Oxford: Clarendon Press; 1996.
8. Fitzgerald AE, Kingsley C, Umans SD. Electric machinery. 7th ed. New York: McGraw-Hill; 2013.
9. Wildi T. Electrical machines, drives, and power systems. 6th ed. Upper Saddle River: Pearson; 2006.
10. Krishnan R. Electric motor drives: modeling, analysis, and control. Upper Saddle River: Prentice Hall; 2001.
11. Leonhard W. Control of electrical drives. 3rd ed. Berlin: Springer; 2001.
12. Holmes DG, Lipo TA. Pulse width modulation for power converters. Hoboken: IEEE Press/Wiley; 2003.
13. Ong CM. Dynamic simulation of electric machinery using MATLAB/Simulink. Upper Saddle River: Prentice Hall; 1998.
14. Vas P. Sensorless vector and direct torque control. Oxford: Oxford University Press; 1998.