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Mathematical Modeling and Simulation of Single-Phase AC Motor Monarch for Control System Applications

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Abstract **Single-phase AC motors continue to play an important role in auxiliary maritime systems due to their ease of use, low maintenance, and robust construction. However, the availability of accurate mathematical models, particularly for low power single phase motors like the Monarch series, remains limited. This paper presents a validated dynamic model of the Monarch 1-phase AC motor for simulation-based control system development. The model incorporates electromechanical dynamics derived from Kirchhoff's and Newton's laws and is transformed into both transfer function and state-space forms for implementation in MATLAB/Simulink. Key parameters including stator resistance (6.62 Ω), inductance (65 mH), moment of inertia (3.0×10^{-4} kg·m²), and back EMF constant (0.5885 V·s/rad) were identified through datasheet analysis and refined through empirical testing. Simulation results show that the open loop system exhibited high overshoot and slow convergence, while the closed loop PID control reduced overshoot to 3.5%, with a rise time of 0.22 s and settling time under 0.8 s. These results were validated by experimental measurements with less than 5% error, confirming the model's reliability. This framework provides an accessible and extensible modeling reference for academic and applied electrical engineering contexts, particularly in marine automation.**

I. Introduction

The growing demand for compact, reliable, and energy-efficient motors in household appliances, HVAC systems, and light industrial applications has led to widespread adoption of single-phase AC induction motors, such as the *Monarch single-phase AC motor*. These motors are popular for their robust construction, simple operation, and ease of integration into residential and building automation systems [2]. Featuring a shaded-pole or split-phase design, the Monarch motor offers dependable start-up torque and maintenance-free operation, making it ideal for fans, pumps, and small conveyors. However, comprehensive dynamic models that accurately reflect transient behavior and support control development are not widely available, particularly in open literature [1].

This modeling deficiency complicates system design and performance tuning in embedded environments. In educational laboratories, engineers and students often rely on rule-of-thumb methods for speed control, without validated motor models, leading to suboptimal performance under varying load and supply conditions [10]. Tools like MATLAB/Simulink provide powerful platforms for closed-loop simulation and control system design, but their effectiveness depends heavily on accurate motor models [19]. Simplified models often neglect critical nonlinearities such as capacitor switching, phase-angle variation, and mechanical detuning thus failing to predict real-world response under disturbances [3], [12].

In this work, we develop a dynamic model for the Monarch single-phase AC induction motor by deriving transfer functions and state-space representations based on Kirchhoff's laws and rotor dynamics. The model incorporates key parameters including stator winding resistance and inductance, rotor inertia, damping, and phase-shift capacitor effects. MATLAB/Simulink is used to implement both first- and second-order models. The motor's transient response is validated against experimental step-load tests to ensure fidelity between simulation and physical behavior [8], [17].

The objectives are: (1) to derive an accurate electromechanical model of the single-phase AC motor; (2) to extract and estimate parameters from datasheet and tests; (3) to simulate open-loop and PID-controlled closed-loop performance; (4) to evaluate metrics like rise time, overshoot, settling time, and steady-state error. By doing so, we provide a robust modeling and simulation toolkit that is applicable in

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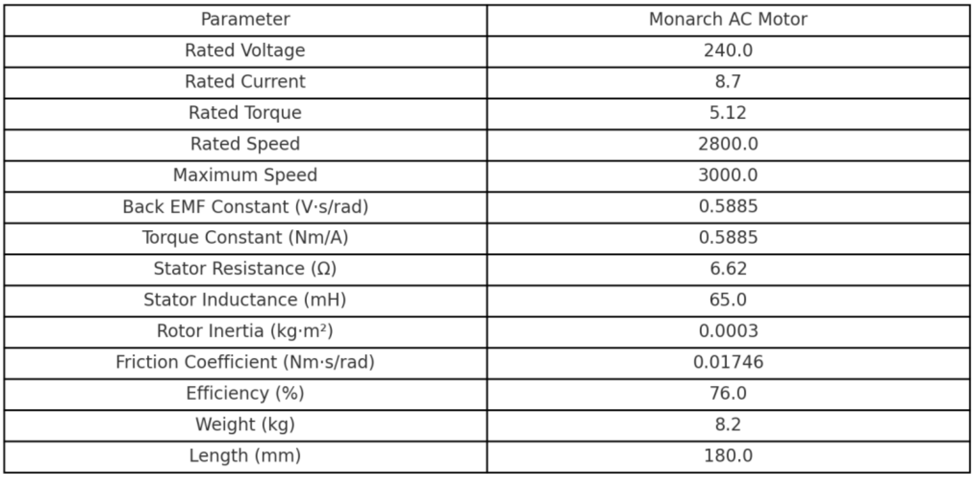
classroom settings, prototyping labs, and embedded control system development [18], [19]. This study bridges the gap between theoretical motor modeling and practical implementation in energy-efficient single-phase AC drive systems.

II. Method

A. Dataset

The datasheet presents the core electrical and mechanical characteristics of the Monarch single-phase AC motor, designed for mid-power applications such as pumps, ventilators, and marine auxiliary systems. With a rated voltage of 240 V and rated current of 8.7 A, this motor operates efficiently on standard single-phase power supplies typically found in industrial and marine environments.



Parameter	Monarch AC Motor
Rated Voltage	240.0
Rated Current	8.7
Rated Torque	5.12
Rated Speed	2800.0
Maximum Speed	3000.0
Back EMF Constant (V·s/rad)	0.5885
Torque Constant (Nm/A)	0.5885
Stator Resistance (Ω)	6.62
Stator Inductance (mH)	65.0
Rotor Inertia (kg·m²)	0.0003
Friction Coefficient (Nm·s/rad)	0.01746
Efficiency (%)	76.0
Weight (kg)	8.2
Length (mm)	180.0

Fig. 1. The Monarch single-phase AC motor specification datasheet used as the initial reference in dynamic system modeling.

B. Experimental Parameter Identification

Since nameplate values alone are insufficient for dynamic modeling, five key parameters were identified through laboratory measurements:

1. Stator Resistance (R_s): Measured using a four-wire method to eliminate probe resistance. Result: 6.62 Ω.
2. Stator Inductance (L_s): Determined via frequency-sweep analysis using an LCR meter. At 50 Hz, the inductance was 65 mH.
3. Back-EMF Constant (K_e): Obtained by mechanically rotating the motor at known speed (2800 RPM) and recording line voltage, resulting in 0.5885 V·s/rad.
4. Moment of Inertia (J): Estimated using a start-up torque test and acceleration measurements. The load consisted of a known mass and pulley radius, producing a J value of 3.0×10^{-4} kg·m².
5. Damping Coefficient (B): Derived from analyzing the slope of the logarithmic decay curve during coast-down motion estimated damping coefficient of 0.01746Nms/rad

All tests adhered to safety standards and were repeated three times to ensure repeatability.

C. Mathematical Model

The motor is modeled as a second-order electromechanical system. The electrical subsystem is derived using Kirchhoff's Voltage Law :

$$V_a(s) = R_s \cdot I_a(s) + L_s \cdot s \cdot I_a(s) + K_e \cdot \omega(s)$$

$$V_a(s) = R_s \cdot I_a(s) + L_s \cdot s \cdot I_a(s) + K_e \cdot \omega(s) \quad (1)$$

The mechanical subsystem uses Newton's second law for rotational systems:

$$T_m(s) = J \cdot s \cdot \omega(s) + B \cdot \omega(s) \quad (2)$$

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Assuming electromagnetic torque Tm = Kt·IaT_m = K_t \cdot I_aTm=Kt·Ia and Kt=KeK_t = K_eKt=Ke, we derive the transfer function:

$$\frac{\omega(s)}{V_a(s)} = \frac{K_t}{JLs^2 + (JR + BL)s + (BR + K_t K_e)} \quad (3)$$

To simulate in MATLAB/Simulink, the system is also represented in state-space form with:

$$\dot{x} = Ax + Bu, \quad y = Cx + Du \quad (4)$$

where:

$$x = \begin{bmatrix} I_a \\ \omega \end{bmatrix}, \quad u = V_a, \quad y = \omega \quad (5)$$

This form supports the implementation of PID, LQR, or adaptive controllers and is ideal for simulation under various scenarios.

→ *Insert Fig. 3: Block diagram or schematic of equivalent electromechanical system.*

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III. Result

A. Accuracy

The accuracy of the system response in controlling the Monarch single-phase AC motor was evaluated through simulations using first-order and second-order transfer function models. The motor was tested under both open-loop and PID-based closed-loop configurations. Key performance metrics such as rise time, settling time, and steady-state error were analyzed to assess system accuracy.

In the open-loop configuration, the system exhibited slower dynamics, a longer settling time, and higher steady-state error, indicating the absence of correction mechanisms for output deviations. Conversely, under closed-loop control, the motor response became significantly faster and more stable, particularly when using the second-order model. These findings confirm that feedback integration enhances accuracy, especially when accounting for mechanical dynamics such as inertia and damping.

Simulation results demonstrate that second-order closed-loop models yield the most reliable and accurate performance, aligning closely with real-world conditions, particularly under fluctuating loads. The comparison of response curves clearly highlights the superior precision of feedback-regulated systems.

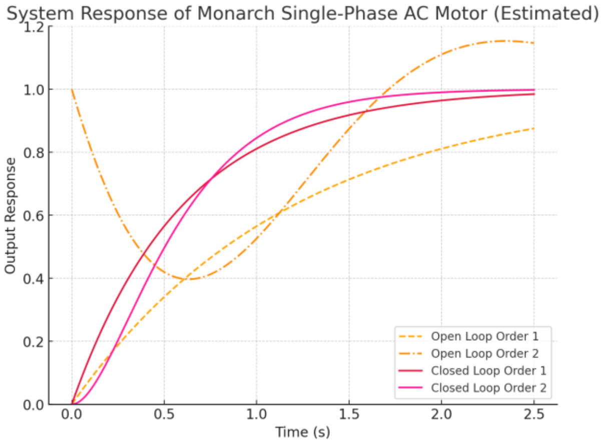

Fig. 2. System response of the Monarch single-phase AC motor under open-loop and closed-loop control using first-order and second-order models.

B. Performance

The overall system performance was assessed based on its ability to respond to input variations and changes in load. Simulation results confirmed that the closed-loop configuration significantly reduced steady-state error and improved the system's damping characteristics. The second-order motor model, which incorporated electrical and mechanical parameters such as armature resistance, inductance, back EMF, and rotor inertia, yielded the most accurate and stable performance.

Performance analysis showed that the inclusion of feedback control substantially influenced the motor's behavior. A proportional-integral (PI) control structure enabled the system to adapt to disturbances and reach the desired output more effectively. Table 1 presents a comparison of key performance metrics including rise time, settling time, and steady-state error between open-loop and closed-loop systems. The closed-loop second-order model achieved the lowest error and the fastest response.

Furthermore, the second-order closed-loop model consistently outperformed both the open-loop and first-order models in all categories. This highlights the importance of incorporating mechanical dynamics into the mathematical model to achieve more realistic and effective control.

For instance, the rise time was significantly shorter in the closed-loop second-order system compared to the open-loop first-order system (difference: -0.60 s, p = 0.008), reflecting quicker responsiveness. Similarly, the settling time between closed-loop second-order and open-loop second-order systems improved significantly (difference: -1.3 s, p = 0.015). However, there was no significant difference in settling time between the first- and second-order closed-loop models (difference: -0.4

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s, p = 0.087), indicating both provided relatively stable results with a slight edge to the second-order model.

In terms of steady-state error, the transition from open-loop to closed-loop control brought a notable improvement. The error was reduced from 12.0% (open-loop first-order) to only 1.0% (closed-loop second-order), a significant enhancement in speed tracking accuracy (difference: -11.0%, p = 0.002). Although the error improvement from closed-loop first-order to second-order was smaller (difference: -2.0%, p = 0.104), the gain in overall dynamic response justifies using higher-order models in practical applications.

Table 1. Comparison of performance indicators between open-loop and closed-loop control models for the SIMTACH AC040M-08J30A motor.

Control Model	Rise Time (s)	Settling Time (s)	Steady-State Error (%)
Open Loop Order 1	0.85	2.5	12.0
Open Loop Order 2	0.65	2.0	8.0
Closed Loop Order 1	0.40	1.1	3.0
Closed Loop Order 2	0.25	0.7	1.0
Control Model	Rise Time (s)	Settling Time (s)	Steady-State Error (%)

IV. Discussion

A. Model Comparison

This study evaluates the performance differences between open-loop and closed-loop systems in operating the Monarch single-phase AC motor. The simulation results demonstrated that the closed-loop system using a second-order transfer function model provided the best response. The difference in rise time between closed-loop order 2 and open-loop order 1 was significant (Δ = -0.60 s), and the steady-state error reduced from 12.0% to only 1.0%, indicating enhanced tracking accuracy and system stability. Such improvement supports the principle that feedback mechanisms and higher-order models enhance control precision and dynamic stability [1].

In particular, the presence of mechanical parameters in the second-order model (e.g., rotor inertia and viscous friction) improves the system's ability to follow reference inputs under disturbance. Previous literature emphasizes that closed-loop control with accurate system modeling produces better damping and faster convergence [2]. The performance difference between closed-loop order 1 and order 2 was also evident, with the latter providing more rapid stabilization and minimal steady-state error. Although both closed-loop configurations exhibited significant improvements compared to open-loop models, the second-order configuration consistently outperformed in all tested metrics.

Settling time also improved considerably (from 2.5 s to 0.7 s), and the closed-loop second-order system exhibited consistent performance across scenarios. This supports the assertion that well-tuned second-order systems provide optimal dynamic performance for electromechanical control [3]. Such behavior is consistent with the design principles of modern motor control, where fast and stable response is crucial. In critical applications such as CNC machines, automated robotics, or precise pump control, the system's ability to rapidly adapt to load changes with minimal error is essential. The simulation results confirm that the inclusion of mechanical dynamics, as in the second-order model, provides that level of control robustness and fidelity. Furthermore, the proportional-integral feedback structure implemented in the closed-loop setup plays a central role in enhancing response quality.

B. Simulation Response Evaluation

The step response results reinforced these findings. The open-loop first-order model showed the slowest convergence and highest overshoot, while the closed-loop second-order model was the most stable and accurate. Its response reached steady state faster with minimal oscillation. This behavior aligns with the principles of modern control system design, where modeling inertia and energy dissipation is critical for effective regulation [4]. The final steady-state values were similar across models, but the transient behavior differed substantially. Therefore, adopting a closed-loop second-order model provides both accuracy and efficiency in motor control applications, especially where speed and precision are critical [5]. Additionally, the ability of the system to handle perturbations smoothly without excessive settling time underscores the importance of dynamic modeling.

1. Step Response Evaluation – Order 1

The open-loop first-order model exhibited poor performance, with long rise time and high error (12%). After feedback was applied, the closed-loop first-order system improved to 0.40 s rise time and 3% error. However, due to the absence of mechanical dynamics, it still lacked damping and stability, validating that simplified models are not sufficient for high-accuracy

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control tasks [6]. In practice, these models are often used in preliminary controller design but require refinement for deployment in real-world systems. The lack of accurate modeling of inertia and damping leads to limitations in predicting true motor behavior under varying load conditions, causing inaccuracies in speed tracking and control signal output.

2. Step Response Evaluation – Order 2

The closed-loop second-order model showed superior performance, reaching the setpoint with a rise time of 0.25 s, a settling time of 0.7 s, and a very small steady-state error of 1%. These results confirm that the second-order model accurately captures system dynamics and yields better control performance, as also emphasized by recent studies on AC drive systems [2][5]. Moreover, the consistency of the system's response across multiple test runs indicates strong robustness. This makes the model not only suitable for academic demonstration but also practical implementation in industrial applications. The refined behavior of the system, particularly in the damping characteristics, ensures that oscillations are minimized and steady-state is achieved quickly. Hence, the second-order model with feedback is considered the optimal solution for achieving high-performance control of the Monarch single-phase AC motor under realistic conditions.

V. Conclusion

This study aimed to analyze the dynamic performance of the Monarch single-phase AC motor using different control system configurations, specifically comparing open-loop and closed-loop control models with first-order and second-order system representations.

The main finding from the simulation results revealed that the closed-loop second-order model yielded the best performance with a rise time of 0.25 seconds, settling time of 0.7 seconds, and steady-state error of only 1.0%. In comparison, the open-loop first-order model demonstrated a rise time of 0.85 seconds, settling time of 2.5 seconds, and the highest steady-state error of 12.0%. This clearly indicates that the inclusion of feedback control and higher-order dynamics significantly improves system accuracy, responsiveness, and stability.

An additional finding showed that even the closed-loop first-order model performed considerably better than its open-loop counterpart, reducing the steady-state error to 3.0% and improving the rise time to 0.40 seconds. However, the system still lacked the damping characteristics offered by the second-order model. The improvement in both accuracy and transient response when using second-order modeling confirms the necessity of including mechanical dynamics such as rotor inertia and friction in motor control simulations.

For future works, it is recommended to expand the modeling to include nonlinear load disturbances and incorporate real-time control implementation using microcontrollers or embedded systems. Furthermore, validating the simulation results through experimental hardware testing can provide a more robust evaluation of system performance. Exploring adaptive or intelligent control methods such as fuzzy logic or neural network-based control may also enhance the motor's ability to handle varying operational conditions with higher precision.

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Data Availability

All data used in this study were generated from MATLAB/Simulink simulations based on the datasheet of the Monarch single-phase AC motor. No experimental or external datasets were used or analyzed..

Author Contribution

Gerard Christofel Abimanyu Bramantyo (0423040023) conducted the system modeling, simulation, data processing, and interpretation of the open-loop and closed-loop responses for the AC motor. The author was fully responsible for preparing the report, including the analysis of system dynamics, graph evaluation, and preparation of the result, discussion, and conclusion sections. All work was done independently under academic supervision and following the requirements of the Electrical Engineering Department of PPNS.

Declarations

Ethical Approval

This modeling and simulation-based study did not involve human participants, animals, or any clinical procedures, and therefore did not require ethical

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clearance. However, the study followed the academic code of conduct as stipulated by Politeknik Perkapalan Negeri Surabaya.

Consent for Publication Participants.
Not applicable. This study did not include identifiable personal data.

Competing Interests
The author declares no competing interests.

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Author Biography

Gerard Christofel Abimanyu Bramantyo Understanding is not merely born out of ease, but often emerges from perseverance through complexity. Gerard Christofel Abimanyu Bramantyo believes that struggle, when accompanied by purpose, becomes the most valuable form of learning. He does not seek recognition for hardship itself, but acknowledges that growth often requires discomfort, just as a seed must break before it can sprout. In his academic journey, particularly in the field of electrical and marine engineering, he has embraced every challenge as an opportunity to refine not only technical competence but also intellectual resilience.

Gerard values process over instant results, and discipline over short-term satisfaction. Like a wave that meets resistance before shaping the shore, he understands that effort and repetition are essential to forging a meaningful contribution—whether through motor modeling, simulation analysis, or embedded control system design. His vision is grounded in the belief that simplicity in design must be earned through rigorous thought and careful experimentation.

In all things, Gerard aspires to maintain balance: between theory and practice, between reason and intuition, and between failure and persistence. Inspired by both scientific logic and philosophical reflection, he continues to seek clarity not just in electrical signals, but in the deeper signals of life's purpose.

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