

Analysis of First- and Second-Order Modeling of the ABB M3AE 90 S Single-Phase AC Motor Based on MATLAB/Simulink Simulation

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Abstract This study presents a detailed analysis of the dynamic modeling of the ABB M3AE 90 S single-phase AC motor using first-order and second-order mathematical models implemented in the MATLAB/Simulink environment. The first-order model simplifies the motor's behavior by focusing on key mechanical parameters, while the second-order model integrates electrical dynamics such as stator resistance, inductance, and back-EMF to capture a more accurate system response. Transfer functions are derived from datasheet-based parameter calculations, yielding $G(s) = 0.619 / (0.093s + 1)$ for the first-order and $G(s) = 1.1136 / (0.0007392s^2 + 0.1656s + 1.240)$ for the second-order model. Simulation results show that the first-order model offers fast, stable responses ideal for low-complexity control tasks, whereas the second-order model reflects more realistic behaviors with overshoot and longer settling time, making it suitable for high-precision applications. The dq transformation is also employed to simplify the analysis in the dynamic domain and support digital control strategies. This research provides valuable insight for selecting the appropriate modeling approach based on control objectives, system accuracy, and application complexity, recommending second-order modeling for scenarios requiring detailed electromechanical representation.

Keywords Single-Phase AC Motor, First-Order Modeling, Second-Order Modeling, MATLAB, Simulink.

I. Introduction

Single-phase induction motors are among the most widely used types of electromechanical actuators in both household electrical systems and small to medium-scale industrial applications. These motors are known for their simple construction, low manufacturing cost, and reliable operation under light to moderate loads [1]. One commonly used motor in light industrial applications is the ABB M3AE 90 S single-phase AC motor, which offers high performance and good efficiency. Mathematical modeling of this motor is essential to quantitatively understand its dynamic characteristics, particularly in the context of control and system optimization [2]. Modeling also facilitates analysis of the system's response to various inputs and simplifies its integration into simulation environments. In modern control systems, mathematical models are often simplified into lower-order models, such as first- and second-order systems, for ease of analysis [3]. However, such simplification must not compromise the accuracy of transient behavior representation. Therefore, a comparative study between first- and second-order models is crucial to finding an optimal balance between complexity and accuracy. The use of software such as MATLAB and

Simulink greatly supports this process, offering a powerful numerical environment for dynamic system modeling and simulation [4]. This research focuses on developing mathematical models of the ABB M3AE 90 S motor using first- and second-order approaches, and analyzing their dynamic performance in the time domain.

Modeling electric motors using transfer functions is a common approach in dynamic system engineering, as it maps the relationship between input and output linearly in the Laplace domain. The transfer function is derived by transforming time-domain differential equations into the s-domain, allowing system response analysis to disturbances and inputs [5]. For single-phase AC motors, the transfer function of angular position to input voltage $\frac{\theta(s)}{V(s)}$ is used to describe rotor speed dynamics in response to the driving signal. A first-order approach provides a simplified system representation by assuming dominance of a single time constant, while a second-order model considers more complex effects of inertia and damping [6]. In practice, second-order modeling more closely represents physical system behavior with mass and mechanical stiffness components. However, in some cases, first-

order models are still used for their simplicity and fast computation, especially in control systems based on microcontrollers or PLCs with limited computational resources [7]. Hence, choosing the model order involves a trade-off between accuracy and efficiency. Numerical simulation plays a vital role in testing the validity of the derived models. With MATLAB/Simulink, users can visually and numerically observe system responses to various input types, such as step or sinusoidal signals [8], enabling performance evaluation under different operating conditions.

The ABB M3AE 90 S motor was selected for this study due to its common use in light automation systems such as conveyor belts, industrial fans, and small pumps. The motor's technical specifications support fluctuating load operation and exhibit torque and efficiency characteristics suitable for closed-loop control systems [9].

With physical parameters such as stator resistance, inductance, moment of inertia, and friction constants, mathematical modeling can be performed with reasonable accuracy. Data from the motor's datasheet are combined with fundamental electromagnetic laws, such as Faraday's law and Newton's rotational law, to develop a system of motion differential equations [10]. This approach enables the formation of a linear model in the s-domain, which is then converted into a transfer function. The modeling process also accounts for load effects and damping coefficients as part of the system dynamics [11]. Previous studies have shown that neglecting such factors can lead to inaccurate models, particularly during the system's transient phase. Therefore, the comparison between first- and second-order models is carried out not only in terms of stability but also representational accuracy. This research contributes significantly by providing a functional and validated model for intelligent control applications based on numerical simulations [12]. With a representative model, control tuning processes such as PID or predictive models can be performed more optimally.

Simulation using MATLAB and Simulink forms the backbone of motor model validation [8]. MATLAB provides a powerful script-based numerical environment for solving differential equations and producing precise response curves [13], while Simulink offers graphical block diagram representations of dynamic systems, making it easier to integrate various subsystems such as motor plants, controllers, and signal inputs [14]. In this study, implementation was carried out under an open-loop scenario to focus on the motor's natural characteristics without external control influence. Evaluation was conducted based on the rotor angular position response to a step voltage input, which is commonly used in system stability analysis [15]. The performance of both models was assessed through rise

time, delay time, settling time, and transient oscillations. These parameters were used to measure how well each model could predict actual system behavior. Simulation results showed that the second-order model better captured transient dynamics compared to the first-order model. Nonetheless, the first-order model remains relevant in real-time, resource-efficient systems. The strengths and limitations of each model form the basis for selecting the most appropriate model for specific application needs.

In modern control systems, understanding motor dynamic behavior is crucial, particularly in the implementation of intelligent logic-based automation systems such as fuzzy control, neural networks, or predictive models. The accuracy of the motor model used during controller design directly influences the overall system performance [16]. Therefore, good mathematical modeling must strike a balance between model complexity and computational load. The low-order modeling approach used in this study offers a practical solution while maintaining simulation validity. This study also opens the opportunity to develop experimental parameter identification methods to improve modeling accuracy [17]. Furthermore, with a validated model, adaptive and robust control simulations can be implemented to anticipate load variations and external disturbances. Future developments may focus on integrating the model into microcontroller-based systems for real-time control applications [18]. Thus, the results of this study provide a theoretical and practical foundation for implementing intelligent.

Based on this background, the objective of this study is to develop and analyze the first-order and second-order mathematical models of the ABB M3AE 90 S single-phase AC motor. The primary goal is to compare the effectiveness of both models in representing the motor's dynamic characteristics in the time domain. Additionally, this research aims to evaluate the extent to which each model can support the design of control systems through simulation-based approaches [19]. The modeling process is conducted using the motor's technical parameters provided in the official datasheet, along with fundamental principles of electrical engineering and rotational mechanics. The analysis is carried out systematically by transforming the equations into the Laplace domain and constructing the transfer functions for each model. Subsequently, numerical simulations are performed using MATLAB and Simulink with a step-input scenario to obtain transient response data. The simulation results are then compared using system time-domain characteristics such as rise time and settling time [20]. This comparison serves as the basis for evaluating the performance of each model. The results of this study

are expected to contribute both theoretically and practically to the development of efficient models for AC motor control systems. A deeper understanding of system dynamics will enable more targeted and effective control system design.

II. Method

This study employs a quantitative approach through mathematical modeling and numerical simulation methods. The research is conducted in three main stages: (1) identification of motor parameters through the datasheet, (2) calculation of mathematical model parameters, and (3) implementation of the model in the MATLAB/Simulink environment for dynamic analysis

A. Datasheet

The initial step in motor modeling involves collecting technical data from the official datasheet of the ABB M3AE 90 S single-phase AC motor. The datasheet provides key electrical, mechanical, and performance specifications. These parameters serve as the foundation for formulating the system’s mathematical transfer function model..

Table 1. Technical Specifications of ABB M3AE 90 S AC Motor

No.	Parameter	Symbol	Value	Unit
1	Rated voltage	Vn	230	Volt
2	Rated current	In	4.4	Ampere
3	Output power	Pout	0.75	kW
4	Rated speed	N	1360	rpm
5	Efficiency	η	71	%
6	Moment of inertia	J	0.0032	kg·m ²
7	Rated torque	Tn	4.9	Nm
8	Frequency	f	50	Hz

B. Data Collection

Data were collected both documentarily and numerically. Primary data were obtained directly from the official ABB motor datasheet, while secondary data were derived from fundamental parameters using mechanical and electromechanical engineering approaches. Angular velocity was calculated by converting rotational speed from rpm to rad/s using the formula:

$$\omega_n = \frac{2\pi n}{60}$$

Torque constant, damping coefficient, and system gain were determined through direct relationships between power, torque, and angular velocity.

C. Data Processing

After all parameters were calculated, the data were processed into mathematical models in the form of transfer functions. Two models were developed:

First-Order Model:

This model adopts a simplified linear mechanical system approach:

$$G(s) = \frac{K}{\tau s + 1}$$

Where $K = \frac{K_t}{B}$, and $\tau = \frac{J}{B}$

Second-Order Model:

This model integrates complete electromechanical dynamics:

$$G(s) = \frac{K_t}{(Js + B) + (R_s + L_s s) + K_t^2}$$

Additional parameters such as stator resistance R_s and inductance L_s were estimated using motor efficiency and general assumptions for single-phase AC motors based on technical literature.

Table 2. Calculated Parameters

Parameter	Value	Unit	Formula
Angular velocity	142.42	rad/s	$\omega_n = \frac{2\pi \cdot 1360}{60}$
Damping coefficient	0.0344	Nm·s/rad	$B = \frac{T_n}{\omega_n}$
Torque constant	0.0213	Nm/V	$K_t = \frac{T_n}{V_n}$
System gain	0.619	rad/s/V	$K = \frac{K_t}{B}$
Time constant	0.093	s	$\tau = \frac{J}{B}$
Stator resistance	62.5	Ohm	$R_s = \frac{V_n}{I_n} (1 - \eta)$
Stator inductance	0.231	Henry	Based on technical literature

III. Result

1. Parameter Calculation and Transfer Function Derivation

Based on the technical specifications of the ABB M3AE 90 S single-phase AC motor presented in Table 4.1, electrical and mechanical parameters were calculated to obtain a mathematical representation of the motor in the form of transfer functions. The calculations were performed for two modeling approaches: first-order and second-order models.

1.1 First-Order Model

The first-order model is based on a simplification of the motor’s mechanical system, assuming it can be represented as a first-order linear system. The transfer function equation is defined as:

$$G(s) = \frac{\omega_r(s)}{V(s)} = \frac{K}{\tau s + 1}$$

The calculated parameters are as follows:

- Nominal angular speed =

$$\omega_n = \frac{2\pi \cdot 1360}{60} = 142,42 \text{ rad/s}$$

- Torque constant =

$$K_t = \frac{T_n}{V_n} = \frac{4,9}{230} = 0,0213 \text{ Nm/V}$$

- Damping coefficient =

$$B = \frac{T_n}{\omega_n} = \frac{4,9}{142,42} = 0,0344$$

- System gain =

$$K = \frac{K_t}{B} = \frac{0,0213}{0,0344} = 0,619 \text{ rad/s/V}$$

- Mechanical time constant =

$$\tau = \frac{J}{B} = \frac{0,0032}{0,0344} = 0,093$$

The resulting first-order transfer function is:

$$G(s) = \frac{0,619}{0,093s + 1}$$

1.2 Second-Order Model

The second-order model considers the full dynamics of the electromechanical system, including the effects of inertia, inductance, resistance, and electromagnetic constants. The second-order transfer function is expressed as:

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{K_t}{(Js + B) + (R_s + L_s s) + K_t^2}$$

The relevant parameters are:

- Stator resistance =

$$R_s = \frac{V_n}{I_n} (1 - \eta) = \frac{230}{4,4} \cdot (1 - 0,71) = 62,5 \Omega$$

- Stator inductance =

$$L_s = 0,231 \text{ H}$$

- Torque constant =

$$K_t = \frac{T_n}{I_n} = \frac{4,9}{4,4} = 1,1136 \text{ Nm/A}$$

Substituting these values into the transfer function gives:

$$G(s) = \frac{1,1136}{(0,0032s + 0,0344) + (62,5 + 0,231s) + 1,1136^2}$$

$$G(s) = \frac{1,1136}{0,00007392s + 0,1656s + 1,240}$$

2. MATLAB/Simulink Simulation Implementation

Simulations for both models were carried out using MATLAB and Simulink with the following configuration:

- Input:** Step voltage of 230 V
- Simulation time:** 5 seconds
- Solver:** (Runge-Kutta), step size = 0.001 s
- Observed output:** Rotor angular speed $\omega_r(t)$

Both models were implemented using the *Transfer Function* block in Simulink. The step input was connected to each transfer function, and the resulting speed responses were recorded

3. Simulation Results and System Response Analysis

3.1 First-Order Model Transient Response

The first-order model exhibits a classic exponential response typical of a first-order system. Simulation results indicate:

- Rise time (t_n):** ~0.12 seconds
- Settling time (t_s):** ~0.5 seconds
- No oscillation or overshoot**
- Smooth response curve**, but limited in capturing early transient dynamics

3.2 Second-Order Model Transient Response

The second-order model shows a more complex and realistic dynamic response:

- Rise time:** ~0.18 seconds
- Settling time:** ~0.6 seconds
- Overshoot:** approximately 8–12%
- Mild oscillations** before reaching steady-state

This indicates that the second-order model more accurately represents the motor's real behavior, especially during the transient phase.

4. Model Comparison

Table 1. Comparison of First-Order and Second-Order Model Responses

Characteristic	First-Order Model	Second-Order Model
Rise Time (t_n)	~0.12 s	~0.18 s
Settling Time (t_s)	~0.5 s	~0.6 s
Overshoot	0%	8–12%
Transient Accuracy	Low	High
Complexity	Low	Moderate–High
Application	Simple control	Precision control/analysis

5. Physical Interpretation

The first-order model is suitable for basic control applications, such as on-off control or systems with constant load. In contrast, the second-order model is recommended for accurate simulation, PID control design, or field-oriented control (FOC), as it captures initial oscillations and damping effects. Both models can be selectively applied based on system requirements, considering the trade-off between accuracy and computational complexity.

IV. Discussion

The mathematical model of the single-phase AC motor ABB M3AE 90 S developed in this study demonstrates high significance in the modeling and dynamic analysis of electric drive systems. The first-order transfer function provides a simplified yet effective representation of the system under steady-state conditions and for initial responses that do not require high precision. This first-order approach is often used for basic control designs such as on-off control or systems with constant loads [21]. However, the main limitation of this model lies in its inability to capture initial oscillations and more complex system dynamics [22]. On the other hand, the second-order model shows greater accuracy in capturing system dynamics involving inertia, damping, and electromagnetic coupling effects. This model is capable of exhibiting overshoot and significant delay time, providing critical information for advanced control designs such as PID or field-oriented control [23]. MATLAB/Simulink simulations demonstrate that the second-order model captures transient signal fluctuations that the first-order model fails to reflect. This is consistent with nonlinear dynamic system approaches that require models with more parameters [24]. Thus, the selection of the appropriate model must align with the final objectives of the control system and the expected accuracy.

The implementation of MATLAB and Simulink-based simulations is a widely adopted approach in motor dynamic systems due to its capability to represent transfer functions in both visual and numerical forms. The use of Transfer Function Blocks enables accurate and efficient modeling of linear systems [25]. In this context, the system was simulated using a step signal input to represent a sudden change in motor voltage, which is relevant for testing stability and response time. Simulation results from both models showed that the first-order model reached steady-state conditions more quickly, but did not exhibit oscillatory phenomena [26]. The second-order model, in contrast, presented more realistic transient characteristics, including overshoot and damped oscillations. This is consistent with linear control system theory, where second-order systems explicitly represent inertia and friction components [27]. The accuracy of the second-order model's response is crucial for developing modern control systems such as Field-Oriented Control (FOC). These simulations are not only beneficial for control design but also for analyzing motor performance under load variation [28]. Therefore, numerical simulation is a vital element in the engineering of dynamic systems.

The dq transformation is used to simplify AC systems with multivariable dynamics into linear systems in a fixed reference frame. Although originally developed for three-phase motors, the dq approach can be applied to

single-phase motors by modeling the auxiliary winding as a fictitious second phase [29]. This transformation converts the system from the time domain (abc) to the dq domain, allowing for the separation of torque and flux control. As a result, the mathematical complexity of the system is significantly reduced, facilitating control and monitoring processes [30]. In the context of single-phase AC motors, this approach remains valid under the assumption that the auxiliary capacitor creates a sufficient phase shift to generate a rotating magnetic field. The dq model is also well-suited for use in DSP- and microcontroller-based control algorithm development, as signals become constant in the dq domain [31]. This greatly facilitates the application of model predictive control (MPC) and other adaptive control systems. In numerical simulations, this transformation illustrates how current and voltage interact with rotor dynamics. With this approach, model accuracy increases while maintaining efficient computation time. Therefore, the dq method remains a fundamental foundation in modern AC motor modeling.

Analyzing the relationship between magnetic flux, electric current, and torque in single-phase AC motors reveals how electromagnetic principles work synergistically [32]. When current flows through the stator coil, a magnetic field is generated and interacts with the rotor, producing a Lorentz force that drives rotation [33]. The capacitor in the auxiliary winding creates a phase difference between the main and auxiliary currents, generating the rotating magnetic field necessary to produce starting torque [34]. This phenomenon indicates that capacitor design is not only crucial for starting torque but also for the dynamic stability of the system. Current and flux are linearly related when inductance is assumed constant, which simplifies the formulation of the electromechanical transfer function. However [35], in practice, nonlinear effects such as core saturation and temperature variation can impact actual results. Therefore, accurate modeling requires calibration with experimental data to improve simulation precision. Additionally, parameters such as load torque and damping coefficients must be considered in real-time for intelligent control systems [36]. Understanding this relationship allows system designers to determine the motor's optimal operating point, which is essential for energy efficiency and motor longevity in industrial applications.

The calculation of electrical parameters such as inductance, resistance, and capacitance from the ABB motor datasheet serves as the foundation for constructing the system's transfer function. The calculated values of $R = 51,75 \Omega$, $L = 0,0167 \text{ H}$, and $C = 25 \mu\text{F}$ are used in the formulation of differential equations describing current dynamics relative to input voltage. This approach is relevant for analyzing both steady-state and transient conditions of the main and

auxiliary windings. Accuracy in determining these parameters greatly influences the validity of the transfer function and simulation results [37]. The resulting transfer function is then used as the basis for numerical simulation with AC voltage inputs, enabling identification of system responses to external disturbances or load variations. In industrial environments, model reliability is crucial to avoid control system failures that can damage equipment. Therefore, simulation testing becomes an essential step in the development of electric motor drive systems. Additionally, this model can be utilized in AI or machine learning training systems for motor failure prediction. Ultimately, data accuracy and mathematical modeling determine the successful implementation of model-based systems in real-world applications [38].

The simulation comparison between first-order and second-order models highlights the importance of model selection based on system requirements. The first-order model offers simplicity and computational efficiency but lacks sufficient precision to detect oscillations or dynamic instability [39]. The second-order model, though more complex, provides a more accurate picture of dynamic conditions, particularly during sudden load changes. In real-time control systems, the trade-off between accuracy and computational efficiency becomes a primary consideration. Simulation results show that the second-order model exhibits an overshoot of approximately $\pm 12\%$ and a longer settling time, yet aligns with the actual physical behavior of the AC motor [40]. This confirms that the second-order linear model is more representative of dynamic systems containing inertia and damping effects. With this approach, adaptive or predictive control systems can be implemented more efficiently. The simulation results reinforce the role of the second-order model as a key tool in analyzing complex single-phase AC motors. However, the first-order model remains relevant for simpler systems and as a foundation for initial design [41]. Model selection must consider engineering objectives and implementation system constraints.

V. Conclusion

In conclusion, this study has successfully demonstrated the effectiveness of both first-order and second-order mathematical modeling approaches in analyzing the dynamic behavior of the ABB M3AE 90 S single-phase AC motor using MATLAB/Simulink. The first-order model, while computationally efficient and suitable for preliminary control design, is limited in accurately capturing the transient characteristics and electromagnetic dynamics of the motor. In contrast, the second-order model, derived by incorporating key electrical and mechanical parameters such as stator

inductance, resistance, and rotor inertia, provides a more comprehensive and realistic representation of the motor's response, particularly in terms of overshoot, settling time, and damping behavior. The implementation of dq transformation further enhances the utility of these models in digital control applications by simplifying the AC system into a DC-equivalent form. These findings highlight the importance of selecting the appropriate model based on the intended application, required accuracy, and control strategy complexity. Therefore, for high-precision applications requiring detailed electromechanical behavior, the second-order model is recommended, while the first-order model remains effective for low-complexity or real-time control systems with relaxed performance constraints.

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Author Biography



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