

Article

Magnetic Field Simulation and Torque-Speed Performance of a Single-Phase Squirrel-Cage Induction Motor: An FEM and Experimental Approach

Jhonny Barzola ^{*,†}  and Jonathan Chandi [†]

Facultad de Ingeniería en Ciencias Aplicadas (FICA), Universidad Técnica del Norte (UTN), Carrera de Electricidad (CIELE), Ibarra 100150, Ecuador; jfchandig@utn.edu.ec

* Correspondence: jjbarzola@utn.edu.ec; Tel.: +593-9-92417971

[†] These authors contributed equally to this work.

Abstract: This study presents a detailed investigation of the torque-speed characteristics of a WEG single-phase squirrel-cage induction motor (SPSCIM) of (1/2 hp), 110/220 V at 60 Hz. The primary objective was to derive the motor's equivalent circuit and validate its performance curves through finite element analysis (FEA), simulation using MATLAB[®]/Simulink[®], and experimental testing. Finite element simulations were conducted using the software FEMM (Finite Element Method Magnetics) to model the magnetic flux distribution within the motor's stator and rotor. These simulations, based on the motor's dimensions and nameplate data, provided essential insights into the electromagnetic behavior, including flux density and saturation effects, which are crucial for accurate torque-speed curve predictions. For experimental validation, tests were performed under open-circuit and locked-rotor conditions through a universal machine as a load emulator. The torque-speed characteristics were determined using the Suhr method and the classical approach, with the resulting curves compared to experimental measurements. Voltage and current were measured using AC PZEM-004T and DC PZEM-017 meters, while rotor speed was monitored with a Hall effect sensor (A3144). The results revealed strong agreement between the FEM simulations, Suhr method, and experimental data, demonstrating the reliability and accuracy of the combined simulation and analytical methods for modeling the motor's performance. The estimations using classical and Suhr methods, Simulink simulations, and FEMM yielded low error percentages, mostly below 2%. However, in the FEMM simulation, rotor resistance showed a higher error of around 20% due to unavailable data on the exact number of windings turns, a modifiable parameter that can be corrected through further adjustments in the simulation. The torque-speed curves obtained at different voltage levels showed an excellent correlation, confirming the effectiveness of the proposed approach in characterizing the motor's operational behavior.

Keywords: induction motor; single phase; finite elements; experimental validation



Academic Editors: Hongli Gao and Zhichao You

Received: 31 March 2025

Revised: 24 April 2025

Accepted: 27 April 2025

Published: 5 June 2025

Citation: Barzola, J.; Chandi, J. Magnetic Field Simulation and Torque-Speed Performance of a Single-Phase Squirrel-Cage Induction Motor: An FEM and Experimental Approach. *Machines* **2025**, *13*, 492. <https://doi.org/10.3390/machines13060492>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Single-phase squirrel-cage induction motors (SPSCIM) are fundamental components in industrial and, primarily, domestic applications. However, as the demand for energy efficiency increases, it is essential to enhance their performance in terms of both operation and design. Two key research areas are optimal motor design and parameter determination, as these define the motor's behavior and characteristic curves. One approach to evaluating the electromagnetic design characteristics of an electric motor is the finite element method

(FEM), which allows for quantifying the magnetic field, electromagnetic losses, and torque under different load conditions, as seen in [1]. Previous studies have demonstrated that unbalanced operation in a three-phase motor negatively impacts losses and efficiency, highlighting the need to investigate its effects on vibrations and structural forces. Additionally, winding optimization, along with parameter adjustments, is employed to maximize efficiency. Reference [2] states that low-power single-phase squirrel-cage induction motors (SPSCIMs) in the 0.5–1.5 kW range account for approximately 10% of the total energy consumption of AC motors. Their study analyzes the impact of the main winding's magnetic flux in the interpolar space and the resistive–inductive ratio. These investigations are valuable for proposing new designs, such as the one presented in [3], which focuses on a 45 W SPSCIM for ceiling fans aimed at improving efficiency. The study employs finite element analysis (FEA) to achieve efficiency improvements of up to 57% or a power consumption of 35 W while maintaining the same fan dimensions—values comparable to those of BLDC fans. One strategy used in this type of study is the determination of equivalent circuit parameters based on various approaches that utilize catalog data to evaluate manufacturers' design strategies. This allows for analyzing variations in winding resistance across different brands, such as LS, WEG, ABB, and SIEMENS, as observed in [4]. The transition from IE2 to IE3 efficiency classes reflects specific manufacturer strategies to meet efficiency requirements, either by reducing series resistance or increasing parallel resistance.

To accurately estimate motor parameters, optimization techniques are employed, such as the approach used in [5] for three-phase induction motors, which achieves a lower error margin (1–3%) compared to manufacturer estimates. This method first optimizes the stator parameters, followed by the rotor parameters, using the least squares method and manufacturer data, resulting in a more accurate model.

A similar study focuses on parameter estimation for NEMA A and B single-cage induction motors, utilizing manufacturer data and nonlinear equations dependent on slip, solved through a least squares-based algorithm [6]. This method has been validated on more than 300 motors, consistently aligning with manufacturer specifications. Another strategy involves parameter estimation based on operational load data, with a focus on modeling and fault diagnosis in electrical systems [7]. This study highlights the limitations of traditional IEEE techniques, which rely on offline testing and those experimental validations are sensitive to environmental conditions. Additionally, the research employs particle swarm optimization (PSO) and H-G diagrams as part of the study.

An alternative approach utilizes phase-to-phase variable-frequency testing under standstill conditions, where the response data is incorporated into an error function to estimate the parameters of single-cage and double-cage induction motors [8]. The single-cage model fails to accurately fit frequencies above a few tenths of a Hertz, whereas the double-cage model achieves a good fit within the 0–150 Hz range. These models were validated by comparing them with two additional tests: a steady-state torque and current test at various speeds, and a dynamic free acceleration test. Another study proposes the use of a hybrid water cycle algorithm for parameter estimation, leveraging both literature-based and experimental data from a 4 kW three-phase motor for single-cage and double-cage models. The results demonstrate that the algorithm achieves higher accuracy than other well-known methods with fewer iterations. In [9], a study based on particle swarm optimization (PSO) algorithms is presented, validated through experimental testing on a 3 kVA transformer and a 2 hp induction motor, resulting in a simple and efficient methodology. For more complex studies, a method based on artificial neural networks and adaptive neuro-fuzzy inference systems (ANFIS) is introduced, as seen in [10], where single- and double-cage models are compared using experimental data from 20 motors of varying power ratings. The results demonstrate that both methods provide high accuracy, emphasizing the impor-

tance of advanced techniques in this field. Another study presents a comparative analysis using feedforward neural networks (ANFIS) and non-memorized Elman artificial neural networks (ANN) [11,12]. The authors provide an extended explanation of the application of neural networks for parameter estimation and conclude that while both methods are relevant, ANFIS outperforms ANN in parameter estimation when applied to manufacturer data from 20 motors at different power levels.

A significant number of studies focus on three-phase induction motors due to their widespread industrial application; however, the single-phase motor is also of great importance and should be considered. A simple approach is developed in calculations, as seen in [13], where the conventional method is compared with the Suhr method and the two-phase method for the SPSCIM. The study validates the results through simulations employing the finite element method (FEM) and electrical machine design calculations, confirming adequate accuracy for the methodology. Finally, an alternative method is proposed to compensate for the bifacial supply, utilizing autotransformers and a variable capacitor. In [14], a scheme is proposed to determine the stator parameters of the SPSCIM to generate circular rotating fields and maximize efficiency. The results showed that the rotating fields in the optimized models were more circular, significantly reducing the torque ripple by 85% and 81%, respectively. Additionally, the copper losses in the stator coil decreased to 174.54 W and 106.75 W, which improved efficiency by 0.57% and 1.16%. Finite element simulations corroborated the results through an appropriate distribution of main and auxiliary currents, improving overall efficiency.

Another study develops an aggregated model of the SPSCIM for residential heat pumps using classical testing and the IEEE 39-bus model to evaluate its behavior under three-phase faults of 15 and 90 cycles [15]. The study focuses on the model, which is verified by comparing it with simulations of individual motors. Another study for SPSCIM uses the “double revolution” model of a 0.5 hp motor for magnetic circuit optimization through finite element simulations (FEA) to validate the results. The findings indicate that improving the slot air density and optimizing the geometry reduces copper losses, enhancing efficiency without increasing manufacturing costs [16]. Despite the preference for single-phase induction motors in industrial and domestic applications, the optimization and behavior of these motors has been less extensively researched. The focus of this work is to integrate different methodologies related to parameter estimation and the evaluation of the characteristic performance curve of the Single-Phase Squirrel Cage Induction Motor (SPSCIM), highlighting its potential for future research in design optimization and control.

2. Materials and Methods

The methods used to obtain the parameters of the SPSCIM aim to determine the electrical and magnetic constants that characterize the behavior of the machine within a model or equivalent circuit. In this context, the presented work seeks to combine FEM simulations with experimental approaches to analyze the magnetic field distribution and performance of a single-phase induction motor, as well as the classical methods and the Suhr method for parameter estimation.

Experimental results are presented that validate the accuracy of the simulations and allow for a detailed comparison of the torque-speed curve obtained through load tests, which involved taking measurements in a test module with a load emulator. The machine used for determining the electrical parameters was a single-phase induction motor for continuous use of 373 W (0.5 hp) at 1720 RPM and four poles, rated for 110/220 V and 8.4/4.2 A from the WEG brand, illustrated in Figure 1. Also, in Figure 1, the simple cage model used for the calculations in the determination of the parameters can be observed. This model is based on the additional physical characteristics from the motor's name-

plate, such as the frame size FR of C48, insulation WS of class B, open enclosure with drip protection ODF, and an operating temperature of 40 °C. In the equivalent circuit of Figure 1, R_1 and X_1 represent the stator resistance and leakage reactance, while R_2 and X_2 are the rotor resistance and leakage reactance referred to the stator side. The magnetizing branch, formed by R_c and X_m , models the core losses and the magnetizing current. The term R_2/s accounts for the slip-dependent rotor power conversion. This standard single-cage model captures the essential steady-state behavior of the motor. This nameplate information, along with experimental validation, was used for the development of finite element simulations to validate the design of the SPSCIM.

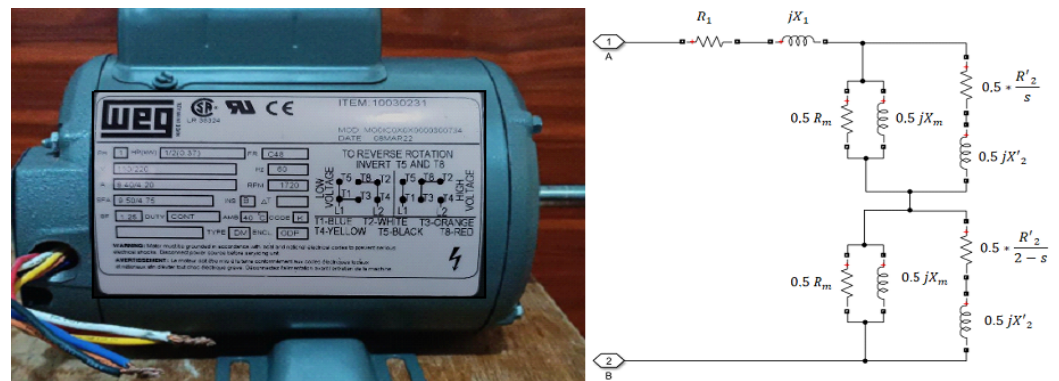


Figure 1. SPSCIM subjected to testing, and its classical equivalent circuit diagram in Simulink.

On the other hand, the classic equivalent circuit model shown in Figure 1 enabled, through calculations and simulations, the description of the classical and Suhr methods for determining the motor parameters in the characteristics and real distribution of the windings. These methods are based on direct current (DC) tests, the locked-rotor test, and the open-circuit test.

2.1. Simulations Using the Magnetic Finite Element Method

The Magnetic Finite Element Method (FEMM) software was used as a tool to analyze and visualize the magnetic field flux distribution of the SPSCIM. Detailed information was obtained regarding the flux linkage lines, trajectory, concentrations, and resulting magnitudes, considering the saturation effects from the core and winding construction details. Figure 2 describes the dimensions of the stator grooves (right) and rotor grooves (left), which are repeated in a total of 32 slots in the stator and 44 slots in the rotor of the SPSCIM.

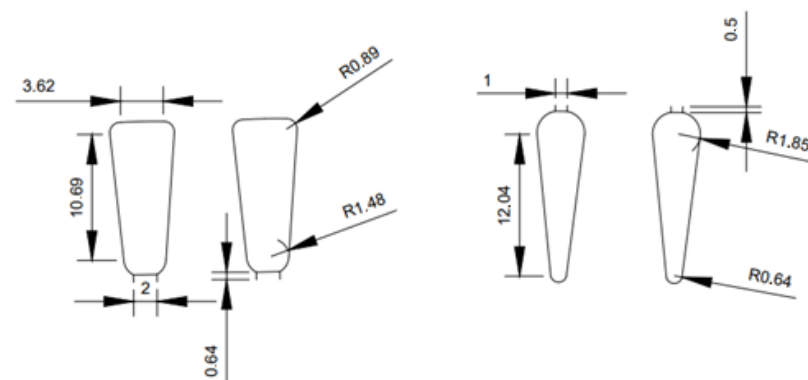


Figure 2. Stator slots (right), rotor slots (left). Both in millimeters.

Additionally, it is necessary to identify the winding configuration encapsulated in the stator of the SPSCIM. This can be detailed through the horizontal winding diagram developed in Figure 3 for the pole and terminal arrangement.

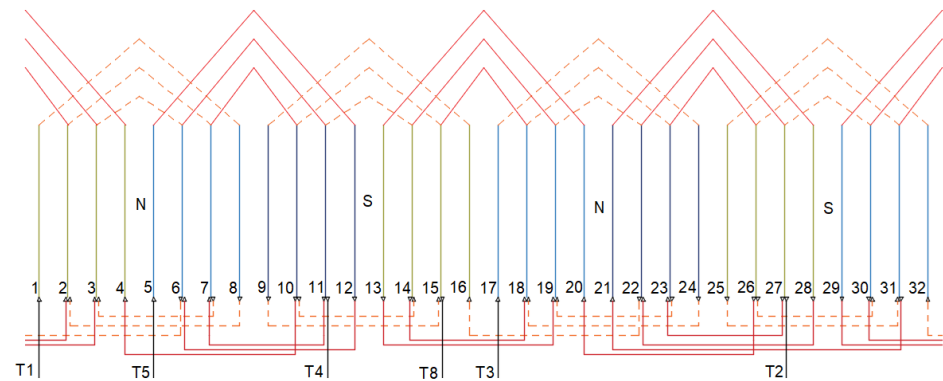


Figure 3. Winding and pole distribution in the SPSCIM motor.

The winding is of a concentric type in groups of three coils per pole, which is very common among manufacturers. This structure results in two pole pairs for the 1720 RPM rated speed after considering the slip. Additionally, certain constructive data about the total winding denoted q_T , can be obtained, such as its distribution around the number of slots N_{sl} of the stator for two magnetic poles p :

$$q_T = \frac{N_{sl}}{2p} \quad (1)$$

The $2/3$ of the total winding in Equation (1) was used for the working winding q_w and the remaining $1/3$ for the starting coil q_s following the standard construction practice for this type of motor. The angular pitch a between the slots N_{sl} is given by the Equation (2) as:

$$a = \frac{180 \cdot 2p}{N_{sl}} \quad (2)$$

The number of slots per phase for the working coil K_w , is calculated using a mathematical expression based on the described geometry with the Equation (3) as follows:

$$K_w = \frac{\sin \frac{q_w a}{2}}{q_T \sin \frac{a}{2}} \quad (3)$$

Similarly, for the starting coil K_s of the SPSCIM, the Equation (4), is used as:

$$K_s = \frac{\sin \frac{q_s a}{2}}{q_T \sin \frac{a}{2}} \quad (4)$$

To determine the total number of turns Z_w of the working coil, Equation (5) was used, which is a function of the slot length L_{sl} , the slot diameter D_{sl} , a current density factor K_d , the magnetic flux density B and an industrial design constant C . A value of 133 was considered for this study for a 60 Hz frequency of the grid, following standard practice for industrial machines operating.

$$Z_w = \frac{V_p}{CL_{sl}D_{sl}K_dB} \quad (5)$$

For the number of turns in the auxiliary or starting winding Z_s , a factor of 0.5 times Z_w , was considered, since the latter is only used during the startup phase. This is a design parameter that allows the coil to withstand the startup currents while using fewer turns. Finally, the number of slots used in each winding is determined by dividing the number

of turns by the number of slots N_{sl} which allows the evaluation of the electromagnetic operating characteristics of the SPSCIM through finite element simulations to determine its parameters. It is important to note that all these characteristics were essential for the development of the finite element simulations. A crucial value is the magnetizing inductance L_m which is calculated through the total energy stored in the magnetic circuit W_m and the no-load current I_{NL} as follows:

$$L_m = \frac{2W_m}{I_{NL}^2} \quad (6)$$

The magnetic stored energy from expression (6) can be considered from the simulation. Another alternative is based on expression (7), which involves the magnetic flux density B present in a volume v with magnetic permeability e . For the SPSCIM, this e represents the permeability of the core material along with other physical or standard characteristics of the motor.

$$W_m = \frac{B^2 v}{2e} \quad (7)$$

A similar approach can be used to determine the other parameters of the SPSCIM, such as the resistance and reactance of the windings, based on the available simulation results. Another parameter is magnetizing resistance, which can be determined through the power present in the magnetic core.

2.2. Classic Method

The classical method can be used for an induction motor, whether three-phase or single-phase, through standard tests that describe its electrical and mechanical behavior. The first test, performed with direct current (DC), allows the determination of the stator resistance R_1 of the SPSCIM by applying a DC source V_{DC} and measuring the current I_{DC} . The skin effect and the characteristics of the iron are included with a compensation factor of 1.15, as follows in Equation (8).

$$R_1 = \frac{V_{DC}}{I_{DC}} 1.15 \quad (8)$$

The second test is the locked-rotor or short-circuit test, which requires a variable alternating current (AC) voltage applied to the stator until full load is reached on the SPSCIM. In this test, the air gap resistance is very high, allowing the determination of (X_1, X_2, R_2) using R_1 obtained from Equation (1) and the voltage V_{BL} , current I_{BL} and power P_{BL} measurements under locked rotor conditions. To calculate R'_2 , we use:

$$R'_2 = \frac{P_{BL}}{I_{BL}^2} - R_1 \quad (9)$$

Equation (9) is in an implicitly form through the total reactance X_{eq} that can be calculated; its result allows the calculation of the equivalent impedance, and thus, the determination of the rotor and stator reactance through an estimated separation based on the recommendations for Class B motors with Equation (10), as follows:

$$X_1 = X_2 = 0.5X_{eq} \quad (10)$$

The no-load test of the SPSCIM facilitates the determination of rotational and magnetizing losses through the measurements of voltage V_{NL} , current I_{NL} and power P_{NL} . This is because most of the consumption occurs in the magnetizing branch and in the rotational losses:

$$P_{core+mech} = P_{NL} - I_{NL}^2 \left(R_1 + \frac{R'_2}{4} \right) \quad (11)$$

The Equation (11) provides information to calculate the internal induced voltage of the SPSCIM as an intermediate step for calculating the magnetization parameters. This internal voltage can be determined as follows in the (12) through parameters already calculated as:

$$E_F = V_{NL} - I_{NL} \left(\left(R_1 + \frac{R'_2}{4} \right) + j \left(X_1 + \frac{X_2}{2} \right) \right) \quad (12)$$

The next step in this classical methodology is to calculate the resistance, or real part of the magnetizing losses using the internal voltage and the losses obtained from Equations (11) and (12), as follows:

$$R_m = 2 \frac{E_F^2}{P_{core+mech}} \quad (13)$$

Finally, Equation (13) allows for the separation of the reactive part of the magnetization through Equation (14):

$$X_m = \frac{|E_f|}{\sqrt{I_{NL}^2 - \left(\frac{|E_f|}{R_m} \right)^2}} \quad (14)$$

2.3. Suhr Metod

The Suhr method, similar to the classical method, uses the DC, locked-rotor, and no-load tests, with the difference that it directly calculates the magnetic reactance X_m as follows:

$$X_Q + X_0 = X_1 + X_m \quad (15)$$

From Equation (15), we can deduce that X_1 can be determined from the locked-rotor test of the classical method, and for X_Q and X_0 the no-load test is required with power measurements in the auxiliary and main windings, respectively, as detailed in the work [13]. This characteristic makes the Suhr method suitable for the test station capacities. To determine X_Q , the reactive power is also measured in the auxiliary winding during the no-load testis given by Equation (16), in the function of the no load current I_{NL} as follows:

$$X_Q = \frac{Q}{I_{NL}^2} \quad (16)$$

And similarly, for X_0 , the calculation can be done with the power measurement in the main winding of the SPSCIM. A relevant detail of this method that must be remembered is that the method uses the same tests as used in the classical method that allows the reduction of number of meters to use.

3. Test Station Characteristics for the SPSCIM

To carry out this methodology regarding parameter calculation, computational tools and a test station focused on measuring experimental variables are required, such as voltage, current, power, and speed of the SPSCIM. The main components considered for the test station are detailed in Table 1 to meet the needs of the experiment.

Table 1. Main components in the test station.

Component	Model	Characteristics
SPSCIM	MO0IC0X0X0000300734	0.5 hp, 4 poles, 1800 RPM, 110 V
Autotransformer	TDGC-0.5KM	0–130 V _{ca} , 500 W
AC Meter	D52-2066	V _{DC} 40–300 V, 0–100 A
DC Meter	PZEM-004T	V _{AC} 80–260 V, 0–100 A
AC Meter	PZEM-017	V _{DC} 0–300 V, 0–300 A
Hall Effect sensor	A3144	5V _{DC}
Universal machine	4655	1200 W, 2400 RPM, 120 V
Disc-Brake	SM-RT54	160 mm

Figure 4 shows the test station, encapsulated in blocks and mounted on a control panel with terminal blocks connected to the SPSCIM and meters. The motor is coupled with a load emulator, which simulates different operating conditions. The station includes an Atmega2560 development board for data acquisition to a computer. Once the test station was configured according to the experimental requirements, the corresponding measurements were taken for the DC test, locked-rotor test, and open-circuit test, using the Classical and Suhr methods.



Figure 4. Description of the test station: (a) Internal distribution and connection of the test module. (b) Mechanical coupling between the SPSCIM and the load emulator.

These tests were crucial for obtaining the electrical parameters of the SPSCIM equivalent circuit and also allowed progress toward load evaluation for the determination of characteristic curves. For this reason, a series of measurements were performed to calculate the average value to be used.

4. Analysis of Methods for Parameter Determination.

The analysis of methods for obtaining electrical parameters of the SPSCIM involved performing experimental tests on the module and using mathematical models that assisted in obtaining the parameters of the motor's equivalent circuit. The data acquisition for the DC test was carried out using the PZEM-017 meter and a variable DC power source through the auto-transformer and rectifier. For the locked-rotor test, the D52-2066 meter was used with the mechanical disc brake SM-RT54, and for the open-circuit test, the PZEM-004T meter was used, respectively. Five representative values from this test were selected to calculate an average value for both current and voltage, as detailed in the following Table 2.

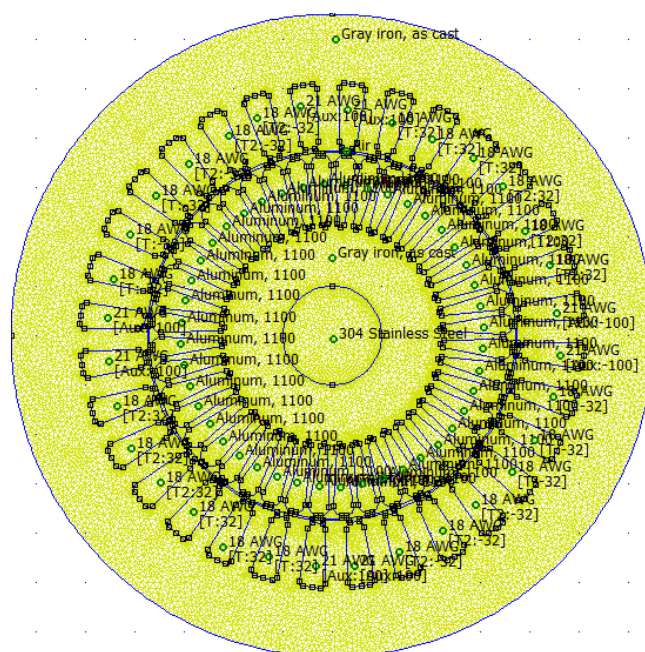
Table 2. Measurements from the tests: DC, locked-rotor, and no-load conditions.

Test	DC Test		Blocked-Rotor Test			DC Test		
	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
1	7.6	8.28	32	7.62	187.1	117.20	7.41	174.60
2	7.6	8.38	32	8.32	231.2	117.20	7.43	174.80
3	7.6	8.35	32	8.32	231.1	117.40	7.42	174.90
4	7.6	8.34	31.9	8.31	230.05	117.50	7.43	177.40
5	7.6	8.32	31.8	8.3	229.9	117.30	7.42	178.00
Average	7.6	8.334	31.94	8.314	230.71	117.32	7.422	175.94

As shown in the results table, the DC test was conducted at a constant voltage of $7.6 V_{DC}$. For the locked-rotor test, the nominal current of approximately 8.3 A was considered, while the no-load test was performed at a nominal supply voltage of approximately 117.2 V. Based on the experimental results, the motor parameters were calculated using the proposed methods and subsequently validated through simulations in MATLAB/Simulink 2023b. The equivalent circuit models incorporated the average values obtained from the different tests to ensure accurate comparison and validation.

4.1. Parameter Extraction Using the Finite Element Method.

After evaluating the various mathematical equations and expressions, a simulation was conducted using the FEMM software and physical parameters. The material properties were defined as follows: the stator core was modeled using “Gray Iron, As Cast” to represent the magnetic steel with its associated saturation curve, the shaft was modeled using “304 Stainless Steel”, the rotor consisted of “Aluminum 1100” bars, and the windings were specified as 18 AWG copper wire with 32 turns per slot for the main winding, and 21 AWG copper wire with 100 turns per slot for the starting winding of the single-phase squirrel-cage induction motor (SPSCIM) and air gaps were modeled using FEMM’s predefined air material. These definitions ensured a realistic magnetic response aligned with the motor’s physical construction, as illustrated in Figure 5.

**Figure 5.** Design and material assignment in FEMM.

After assigning the material properties, a total of 84,348 nodes were generated, as shown in Figure 5. The finite element analysis (FEA) was executed through 23 iterations to solve the magnetic field distribution. The results indicate that the magnetic field is concentrated in four specific regions of the rotor bars, forming the four poles of the machine.

The simulation provided a detailed visualization of the flux lines in the single-phase squirrel-cage induction motor (SPSCIM), as illustrated in Figure 6. The results revealed magnetic flux density peaks of 3.4 T, particularly in critical regions of the motor. Additionally, the simulation yielded key insights into the winding and core behavior, facilitating the parameter determination from this perspective in the FEA, supported by the previously described equations in the methodology. In a no-load simulation, a total power of 56.66 W was recorded in the windings at a current of 7.42 A, matching the experimental tests. This resulted in a stator resistance R_1 of 1.029. Additionally, the simulation calculated the magnetic energy stored in the windings W_m as 0.0777438 J, which, using Equation (6), yielded a stator reactance X_1 of 1.0647. It is important to note that, in standard designs, a single-phase squirrel-cage induction motor (SPSCIM) typically has a rotor reactance X_2 equal to that of the stator. Under the same no-load power conditions, and assuming zero mechanical losses in the simulation, the magnetizing resistance R_m was determined to be 213.55 ohms at an applied voltage of 110 V, using the fundamental power equation. It is evident that the only remaining parameters to determine are the magnetizing reactance X_m and the rotor resistance R_2 , as the corresponding circuit is magnetic. These values were obtained using Equation (7), which relates the stored magnetic energy to the physical dimensions of the single-phase squirrel-cage induction motor (SPSCIM). For a 6 cm radius and a 12 cm length, considering the nominal current of 8.4 A, an average magnetic flux density B of 2.7 T and a relative magnetic permeability of 1500. The stored magnetic energy W_m was calculated as 2.62 J. Applying Equation (6), this energy translates into a magnetizing reactance X_m of 28.04. Finally, assuming negligible mechanical losses in this simulation, the nominal current of 8.4 A, when reflected to the rotor, results in 39.84 A. The power transferred to the rotor was computed as 72.6 W, leading to a rotor resistance R_2 of 1.82 ohms.

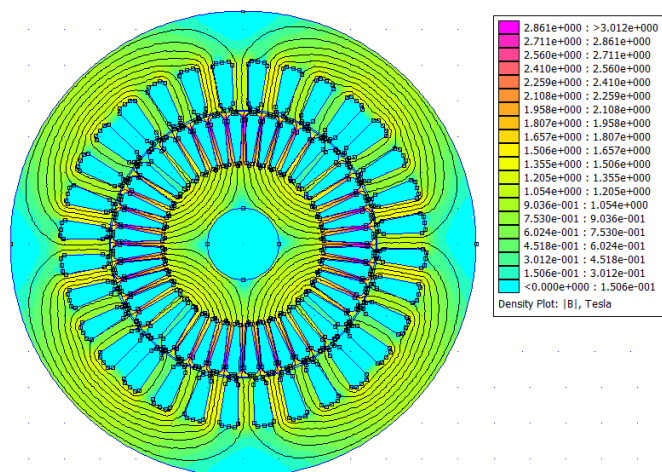


Figure 6. Magnetic flux density distribution.

4.2. Parameter Estimation Using the Classical Method

Table 3 presents the calculated parameters obtained using the classical method, based on the equations previously described. Additionally, these results are compared with MATLAB simulations of the equivalent circuit. As expected, the parameters derived from analytical calculations and simulations exhibit a close agreement, with an acceptable level of discrepancy.

Table 3. Calculated and simulated parameters using the classical method.

Test	DC Test	Blocked-Rotor Test		No-Load Test	
Parameter	R_1	R_2	X_1 and X_2	R_m	X_m
Test Station	1.0487	2.2889	0.9511	254.2936	28.4606
MATLAB Simulations	1.0530	2.2389	0.9574	237.6469	28.7889
FEMM Simulations	1.0290	1.8200	1.0647	213.5500	28.0400

It can be observed from an analysis in Table 3 that for the stator resistance R_1 , there is a difference between the calculations and simulations of 0.41% and 1.87%, respectively. For the rotor resistance R_2 , a 2.18% and 20% error is observed, and a difference of 0.66% and 11.9% for both reactances X_1 and X_2 , remembering that they are identical for stator and rotor in this SPSCIM. Finally, in the magnetization circuit, we see a discrepancy in the magnetizing resistance R_m of 6.5% and 16% with the simulations, and for the magnetizing reactance X_m 1.15% and 1.47%, respectively. The discrepancies, mainly in obtaining the results for the rotor resistance and series reactances, vary according to the physical characteristics of the SPSCIM, material, and are more affected by the number of turns into the windings, which could be adjusted with a more precise number, but it requires an intrusive action not addressed in this work.

4.3. Parameter Estimation Using the Suhr Method

The results obtained using the Suhr method are primarily reflected in the calculation of the magnetization circuit reactance using Equations (15) and (16) described for this method. The comparison with the value obtained from the simulation is also presented in Table 4.

Table 4. Parameters calculated using the Suhr method.

Suhr Metod	X_m
Test Station	30.002
MATLAB Simulations	30.5586

The parameters resulting from Table 4 show a variation of only 1.82% error between them. These results demonstrate the validity of the calculations, and, at the same time, the accuracy of the classical equivalent circuit used. On the other hand, it can be observed that the magnetizing reactance between methods shows a variation of 5.13%.

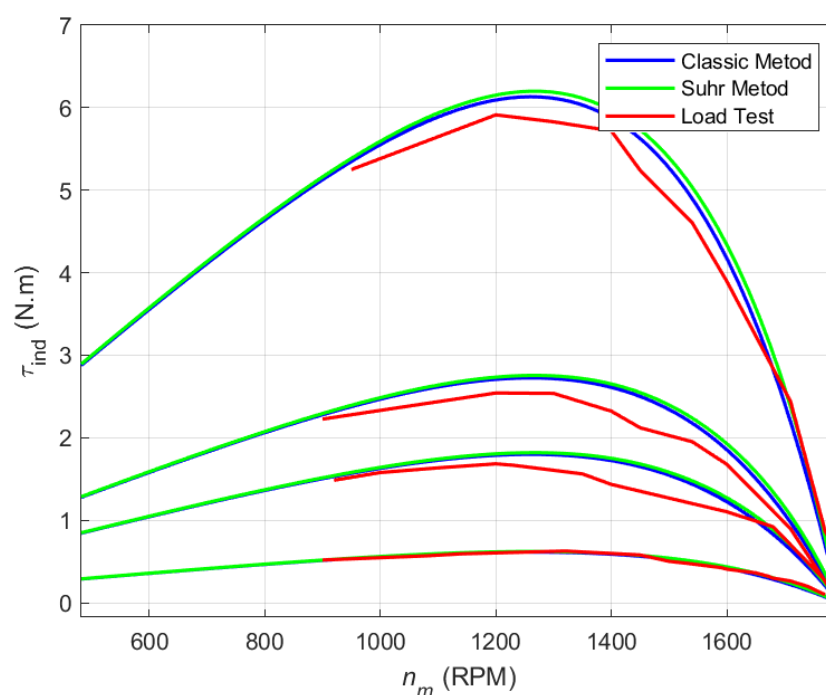
5. Load Test and Characteristic Curves Comparison

The load test for the SPSCIM is performed to determine the motor's operability and efficiency when fed with a specific voltage at different load levels, allowing for a comparison with simulations of practical scenarios of the torque-speed characteristic curve. To do this, a universal machine was mechanically anchored to the shaft of the SPSCIM and operated in generator mode to emulate a controlled load. To obtain the characteristic curve data, different load levels were gradually applied, as shown in Table 5.

In this procedure, a manual brake, initially intended for the locked-rotor test, was used as a gradual alternative during the 80 V and 120 V tests at higher load levels. The purpose of this was to minimize the time the SPSCIM was subjected to significant disturbances and prevent damage from overheating. The torque-speed curves were generated using MATLAB software, as shown in Figure 7, for the different test groups corresponding to the applied voltages.

Table 5. Load current and motor speed measurements at 39 V, 65 V, 80 V, and 120 V supply voltages.

Test	Test at 39 V		Test at 65 V		Test at 80 V		Test at 120 V	
N°	Current (A)	Speed (RPM)	Current (A)	Speed (RPM)	Current (A)	Speed (RPM)	Current (A)	Speed (RPM)
1	2.83	1770	3.45	1790	4.3	1790	7.3	1800
2	2.88	1710	4.81	1680	4.59	1770	8.4	1770
3	2.9	1680	5.2	1600	5.31	1710	8.75	1710
4	3.4	1600	7.0	1400	6.9	1600	10.5	1600
5	3.9	1530	7.5	1350	7.8	1540	11.97	1530
6	4.6	1450	8.3	1230	8.8	1450	13.7	1450
7	5.3	1320	8.5	1200	9.6	1400	14.8	1400
8	5.75	1140	8.8	1100	10.81	1300	16.1	1300
9	5.8	1080	9.0	1000	11.52	1200	17.42	1200
10	5.95	900	9.12	920	12.33	900	18.6	950

**Figure 7.** Torque-speed graphs at different voltages (38, 65, 80, 120).

As shown in Figure 7, the curves obtained using the classical and Suhr methods are very similar for all selected voltage levels and throughout the entire load range. On the other hand, the experimental load curves differ from the characteristic curves of the classical and Suhr methods, but with a small error, which becomes more evident as higher load levels are applied in the different voltage curves. This is largely due to errors introduced by the meters during extended test durations at high loads, such as temperature conditions, friction, and variable mechanical losses. It should be noted that the motor operates normally in the linear region near the rated speed. However, the measured range for the characteristic curves at the different voltage levels largely corresponds to the expected behavior.

6. Conclusions

There are several methods for the analysis and determination of parameters, and since the focus of the study is the parameterization of a SPSCIM through its physical and experimental characteristics rather than the efficiency of the method, the classical method and Suhr method were chosen, based on standard tests such as the no-load, blocked

rotor, and DC tests. Additionally, the MATLAB/Simulink simulation method is used for validation, along with finite element simulations to study the magnetic characteristics of the SPSCIM and as an alternative for estimating its parameters. The implementation of a test module was necessary for data acquisition, serving as a systematic record of information from the different tests for the SPSCIM parameters and the development of the final experiment based on multiple variable load tests. With the calculated parameters, the characteristic curves of the SPSCIM can be plotted for the proposed methods, with the additional detail of repeating the calculations for different voltage levels. This allowed for a comparison of the methods with the load test measurements, demonstrating the effectiveness of the experiment for determining the parameters of the studied SPSCIM and its magnetic analysis through the finite element method, based on its constructive characteristics and design criteria. A key innovation of this work lies in the integrated and comparative approach, combining classical estimation methods, FEM simulations, and dynamic MATLAB modeling to evaluate the torque-speed behavior of the SPSCIM under multiple voltage levels. A perspective rarely addressed in previous literature together, particularly for single-phase machines. Furthermore, most previous studies focus on three-phase induction motors, while this paper highlights the importance and characterization of single-phase motors, specifically SPSCIMs, as an extended basis for future work in the optimization of their design and control.

Author Contributions: Conceptualization, J.B.; methodology, J.B. and J.C.; software, J.C.; validation, J.B. and J.C.; formal analysis, J.B.; investigation, J.C.; resources, J.C.; data curation, J.C.; writing—original draft preparation, J.B.; writing—review and editing, J.B. and J.C.; visualization, J.B.; supervision, J.B.; project administration, J.B.; funding acquisition, J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. The APC was funded by the Universidad Técnica del Norte.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the results of this study, including simulations, experimental measurements, and calculations on the motor, are available upon reasonable request from the corresponding author. These data include voltage, current, and power measurements from the testing station.

Acknowledgments: The authors would like to thank the Universidad Técnica del Norte (UTN) for supporting the publication of this work. Special thanks to the Electrical Machines Laboratory of the Electrical Engineering Department (CIELE) for providing the experimental facilities and technical assistance during the testing phase of this study. We acknowledge the use of AI tools solely for grammar and language corrections in the English text of this manuscript. No AI-generated content was used for the creation of ideas, data analysis, or writing. The authors take full responsibility for the originality of the work.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SPSCIM	Single-phase squirrel-cage induction-motor
FEA	Finite element analysis
FEMM	The Magnetic Finite Element Method

References

1. Um, D.Y.; Park, G.S. Comparison of Electromagnetic Characteristics of Single-Phase Induction Motor between Balanced and Unbalanced Operation under Different Loads. *Energies* **2021**, *14*, 919. [\[CrossRef\]](#)
2. Iegorov, O.; Iegorova, O.; Kundenko, M.; Milenin, A. Single-Phase Induction Motors Winding Parameters Optimization with Maximum Efficiency. In Proceedings of the 2020 IEEE Problems of Automated Electrodrive, Theory and Practice (PAEP), Kremenchuk, Ukraine, 21–25 September 2020; pp. 1–4. [\[CrossRef\]](#)
3. Sharma, U.; Singh, B. Robust Design Methodology for Single Phase Induction Motor Ceiling Fan. *IET Electr. Power Appl.* **2020**, *14*, 1846–1855. [\[CrossRef\]](#)
4. Bortoni, E.C.; Bernardes, J.V.; da Silva, P.V.V.; Faria, V.A.D.; Vieira, P.A.V. Evaluation of Manufacturers Strategies to Obtain High-Efficient Induction Motors. *Sustain. Energy Technol. Assess.* **2019**, *31*, 221–227. [\[CrossRef\]](#)
5. Al-Jufout, S.A.; Al-Rousan, W.H.; Wang, C. Optimization of Induction Motor Equivalent Circuit Parameter Estimation Based on Manufacturer's Data. *Energies* **2018**, *11*, 1792. [\[CrossRef\]](#)
6. Haque, M.H. Determination of NEMA Design Induction Motor Parameters from Manufacturer Data. *IEEE Trans. Energy Convers.* **2008**, *23*, 997–1004. [\[CrossRef\]](#)
7. Bhowmick, D.; Manna, M.; Kar Chowdhury, S. Estimation of Equivalent Circuit Parameters of Transformer and Induction Motor from Load Data. *IEEE Trans. Ind. Appl.* **2018**, *54*, 2784–2791. [\[CrossRef\]](#)
8. Monjo, L.; Kojooyan-Jafari, H.; Corcoles, F.; Pedra, J. Squirrel-Cage Induction Motor Parameter Estimation Using a Variable Frequency Test. *IEEE Trans. Energy Convers.* **2015**, *30*, 550–557. [\[CrossRef\]](#)
9. Calasan, M.; Micev, M.; Ali, Z. M.; Zobaa, A.F.; Abdel Aleem, S.H.E. Parameter Estimation of Induction Machine Single-Cage and Double-Cage Models Using a Hybrid Simulated Annealing-Evaporation Rate Water Cycle Algorithm. *Mathematics* **2020**, *8*, 1024. [\[CrossRef\]](#)
10. Bhowmick, D.; Manna, M.; Chowdhury, S.K. Estimation of Equivalent Circuit Parameters of Transformer and Induction Motor Using PSO. In Proceedings of the 2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Trivandrum, India, 14–17 December 2016; pp. 1–6. [\[CrossRef\]](#)
11. Jirdehi, M.A.; Rezaei, A. Parameters Estimation of Squirrel-Cage Induction Motors Using ANN and ANFIS. *Alex. Eng. J.* **2016**, *55*, 357–368. [\[CrossRef\]](#)
12. Çetin, O.; Dalcı, A.; Temurtaş, F. A Comparative Study on Parameters Estimation of Squirrel Cage Induction Motors Using Neural Networks with Unmemorized Training. *Eng. Sci. Technol. Int. J.* **2020**, *23*, 1126–1133. [\[CrossRef\]](#)
13. Hrabovcova, V.; Kalamen, L.; Sekerak, P.; Rafajdus, P. Determination of Single Phase Induction Motor Parameters. In Proceedings of the SPEEDAM 2010, Pisa, Italy, 14–16 June 2010; pp. 287–292. [\[CrossRef\]](#)
14. Um, D.Y.; Park, G.S. Determination Scheme of Stator Parameters for Making Rotating Fields Circular in a Single-Phase Induction Motor. *IEEE Trans. Magn.* **2020**, *56*, 2949031. [\[CrossRef\]](#)
15. Poudel, B.; Shiwakoti, R.; Amiri, E.; Rastgoufard, P.; Field, T.E.; Ramamurthy, J. Aggregate Model of Single Phase Induction Motors. In Proceedings of the 2019 IEEE International Electric Machines and Drives Conference (IEMDC), San Diego, CA, USA, 12–15 May 2019; pp. 1373–1378. [\[CrossRef\]](#)
16. Karpe, M.; Ghosh, S.; Shindhe, N.; Birajdar, R.; Bhawe, D. Optimization of Single-Phase Induction Motor. In Proceedings of the 2019 IEEE Conference on Energy Conversion (CENCON), Yogyakarta, Indonesia, 16–17 October 2019; pp. 115–120.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.