ELECTRICAL MACHINES REPORT

Single-Phase Induction Motor Analysis and Simulation in MATLAB

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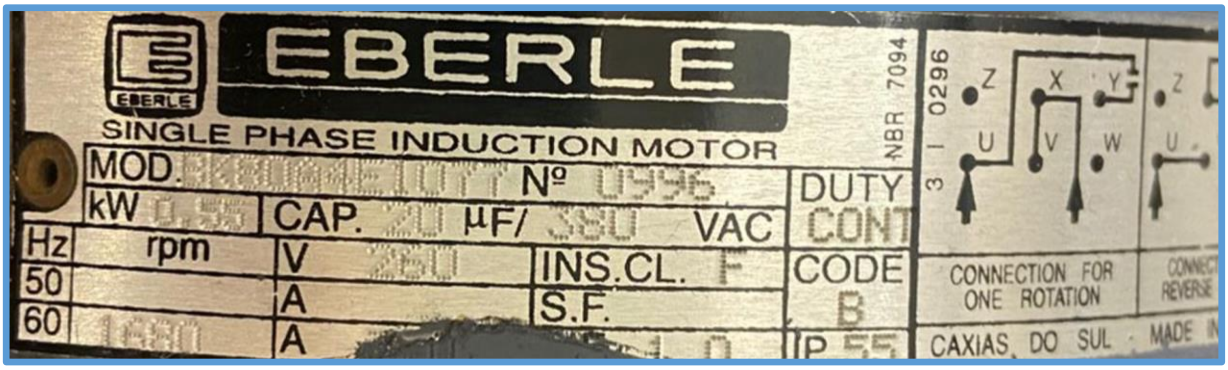
Abstract

This report presents the modeling, analysis, and simulation of a single-phase induction motor using MATLAB and Simulink. The study investigates the motor's performance characteristics under varying supply voltages and load conditions, focusing on parameters such as torque–speed characteristics, slip, efficiency, and power factor. Simulated results are compared with theoretical expectations to evaluate motor behavior during starting and steady-state operation. The aim is to enhance understanding of machine dynamics and the impact of key electrical parameters on performance

1.1



Parameter	***Value***
Rated power	*0.55 kW*
Capacitor	20 μF
Rated AC voltage	*380 V*
Frequency	*60 Hz*
Current	*3.0 A for 60 Hz*
Shaft speed	*1680 for 60 Hz*

INPUT POWER

The real input power refers to the actual electrical power delivered to the motor for performing useful work. When voltage and current are multiplied, the result is the **apparent power**, which represents the total power supplied to the motor. This total power consists of two parts — **active power**, which is converted into mechanical output, and **reactive power**, which sustains the magnetic field but does not produce useful work. By multiplying the apparent power by the power factor, the active or real power component is obtained, indicating the effective power consumed by the motor. In single-phase induction motors, this value represents the true power drawn from the supply. Mathematically, it is expressed as:

$$P_{in} = V_L \cdot I_L \cdot \cos\theta \tag{1}$$

POWER FACTOR

The power factor represents the ratio between the real power (the useful power measured in watts) and the apparent power (measured in volt-amperes). In induction motors, the current generally lags behind the voltage because of the inductive characteristics of the stator and rotor windings. This results in a lagging power factor, meaning that part of the supplied power is used to establish magnetic fields rather than perform mechanical work.

$$\cos\theta = \frac{P_{in}}{V_{in} I_{in}} \tag{2}$$

SLIP

$$s = \frac{synchronous\ speed - rotor\ speed}{synchronous\ speed} \tag{3}$$

Whereby, s, refers to the slip which measures the relative difference between synchronous field speed and rotor speed and can be mathematically expressed as:

$$s = \frac{N_s - N_R}{N_s} \tag{4}$$

OUTPUT POWER

The output power, also known as the mechanical power output, is the power developed at the motor shaft and made available to drive external mechanical loads such as pumps, compressors, or fans. It represents the conversion of electrical energy into useful mechanical energy that performs actual work. This power can be obtained either from the motor's rated specifications or by calculating the product of the measured torque and rotational speed. Therefore:

$$P_{out} \approx P_{rated} \tag{5}$$

EFFICIENCY

This represents the relationship between the electrical energy supplied to the motor and the mechanical energy produced at its shaft. It serves as a key performance metric that indicates how effectively the motor converts electrical input into useful mechanical output.

$$\eta = \frac{P_{in}}{P_{out}} \tag{6}$$

CONVENTIONAL POWER

This is the portion of electrical power that has been converted into mechanical form within the motor before subtracting mechanical losses such as friction and windage. It represents the power transferred from the stator's magnetic field to the rotor through the air gap. The windage losses arise from air resistance caused by rotor movement, while friction losses occur at the bearings and rotating parts. Together, these factors slightly reduce the usable mechanical output. Mathematically, the developed power can be expressed as:

$$P_{conv} = P_{out} + P_{friction\ \&\ windage} \tag{6}$$

STATOR COPPER LOSSES

This represents the resistive or copper losses that occur in the stator windings as a result of current flow. According to Joule's law, the power loss is proportional to the square of the current and the resistance of the winding. These losses generate heat within the stator, reducing the overall efficiency of the motor and contributing to temperature rise during operation. Mathematically, this can be expressed as:

$$P_{stator\ cu\ losses} = {I_{in}}^2 \cdot R_{stator} \tag{7}$$

AIR-GAP POWER

The air-gap power refers to the electromagnetic power transferred from the stator to the rotor through the magnetic field in the air gap. It is a vital parameter in motor performance analysis, as it represents the portion of input electrical power that reaches the rotor for conversion into mechanical energy. After accounting for rotor copper losses, the remaining portion of this power contributes to the development of useful torque. Mathematically, it is expressed as:

$$P_{ag} = P_{in} - P_{stator\ cu\ losses} \tag{8}$$

ROTOR COPPER LOSSES

The rotor copper losses are the resistive losses that occur in the rotor conductors due to the flow of induced current. In induction motors, these losses are directly proportional to the slip, meaning they increase as the motor operates further from synchronous speed. The torque represents the rotational force produced by the motor to drive mechanical loads, for performance analysis, torque is often calculated at synchronous speed when considering air-gap power. Mathematically, this can be expressed as:

$$P_{rotor\ cu\ losses} = P_{ag} - P_{conv} \tag{9}$$

INPUT TORQUE

$$T_{in} = \frac{P_{in}}{\omega_{in}} \tag{10}$$

$$\omega_{in} = \frac{2\pi N_S}{60} \tag{11}$$

1.2

Motor parameters	**Calculated values**
Power Factor	$\cos\theta = \frac{72W}{130V \times 0.58A}$=0.955 lag … using eq.(1)
Input power	$P_{in} = (220V)(3\text{A})(0.955)$ …. Substituting back into eq.(1) $P_{in} = 630\ W$
Output power	$P_{out} = 550\ W$ …since it’s a motor, assume equal to rated
Conventional (developed) power	$P_{conv} = (550 + 50)\ W$ ….using eq.(6) and assumption $P_{conv} = 600\ W$
Stator copper losses	

	$P_{stator\ cu\ losses} = {I_{in}}^2 \cdot R_{stator} = (0.38A)^2(31.09\Omega$ … using eq.(7) $P_{stator\ cu\ losses} = 4.489\ W$
Air-gap power	$P_{ag} = (630 - 4.489)W$ …using eq.(8) $P_{ag} = 625.5\ W$
Rotor copper losses	$P_{rotor\ cu\ losses} = (625.5 - 600)\ W$ …using eq.(9) $P_{rotor\ cu\ losses} = 25.5\ W$
Synchronous speed	$N_S = 1500rpm$
Input torque	$\omega_{in} = \frac{2\pi\times1500\ rpm}{60}$ …using eq.(11) $\omega_{in} = 157.080\ rad/s$ $T_{in} = \frac{1089\ W}{157.1\ rad/s}$ …using eq.(10) $T_{in} = 6.933\ Nm$
Shaft speed	$N_R = 1488\ rpm$
Output torque	$\omega_{out} = \frac{2\pi\times1488rpm}{60}$ …using eq.(11) $\omega_{out} = 155.8\ rad/s$ $T_{out} = \frac{550\ W}{155.8\ rad/s}$ ….using eq.(10) $T_{out} = 3.530\ Nm$
Slip	$Slip = \frac{(1500-1488)\ rpm}{1500\ rpm}$ …using eq.(4) $Slip = 0.008$ $\%Slip = 0.8\%$
Efficiency	$\eta = \frac{550\ W}{630\ W}$ …using eq.(6) $\eta = 0.87$

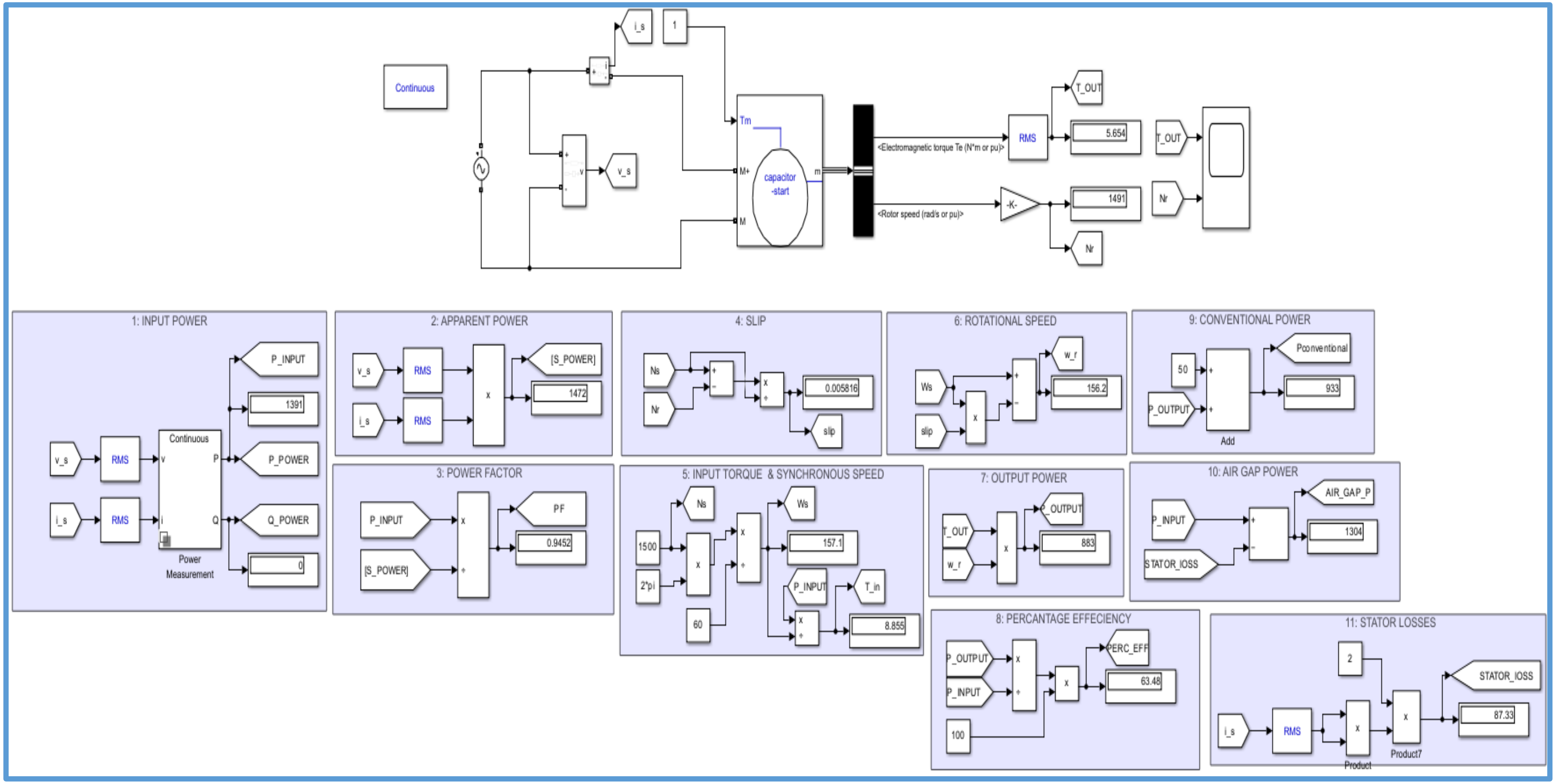
1.3

Simulation Model Description

The simulation represents a complete MATLAB/Simulink model developed to analyse the performance of a single-phase induction motor. The model captures the electrical, mechanical, and performance characteristics of the motor under specified operating conditions, allowing for measurement of key parameters such as torque, speed, power, efficiency, and slip.

At the top of the diagram, the main system block models the single-phase induction motor with its capacitor start circuit. The motor is supplied by a single-phase voltage source, with RMS measurement blocks monitoring the stator voltage (V_s) and current (I_s). The electromagnetic torque and rotor speed are computed within the motor subsystem, providing outputs for torque (N·m) and speed (rpm). The speed output is fed into a mechanical load model to simulate the shaft dynamics.

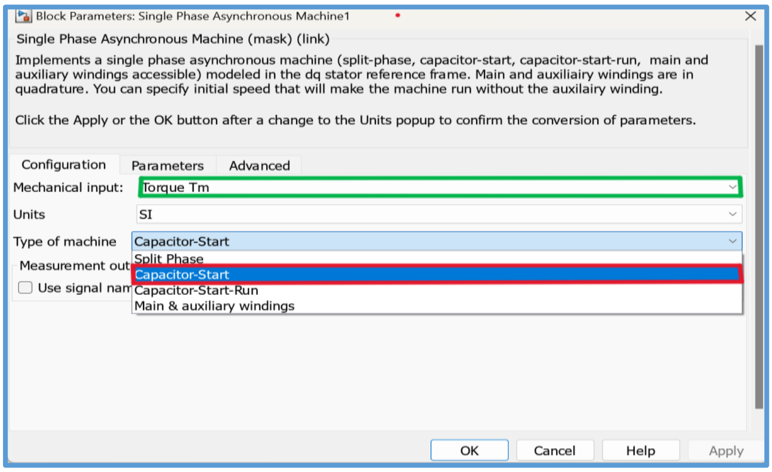
Each subsystem is interconnected to ensure proper data flow between electrical and mechanical domains, providing a complete representation of single-phase motor behavior. The results from this model enable evaluation of torque-speed characteristics, efficiency trends, and power flow at various loading conditions, closely reflecting experimental or laboratory measurements.



Continuous
i_s
1
v_s
Tm
M+
M
m
capacitor
-start
<Electromagnetic torque Te (N*m or pu)>
<Rotor speed (rad/s or pu)>
RMS
-K-
T_OUT
5.654
1491
Nr
1: INPUT POWER
v_s
i_s
RMS
Continuous
Power
Measurement
P_INPUT
1391
P_POWER
Q_POWER
0
2: APPARENT POWER
[S_POWER]
1472
3: POWER FACTOR
P_INPUT
[S_POWER]
PF
0.9452
4: SLIP
Ns
Nr
0.005816
slip
5: INPUT TORQUE & SYNCHRONOUS SPEED
1500
2*pi
60
Ws
157.1
P_INPUT
T_in
8.855
6: ROTATIONAL SPEED
Ws
slip
w_r
156.2
7: OUTPUT POWER
T_OUT
w_r
P_OUTPUT
883
8: PERCANTAGE EFFECIENCY
P_OUTPUT
P_INPUT
100
PERC_EFF
63.48
9: CONVENTIONAL POWER
50
P_OUTPUT
Add
Pconventional
933
10: AIR GAP POWER
P_INPUT
STATOR_lOSS
AIR_GAP_P
1304
11: STATOR LOSSES
2
i_s
RMS
Product
Product7
STATOR_lOSS
87.33

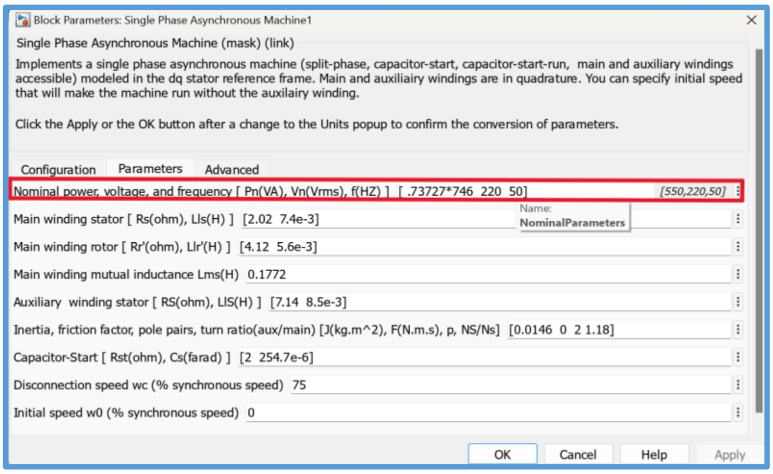
1.4

CONFIGURING THE MOTOR



This section illustrates the configuration window of the Single-Phase Asynchronous Machine block in Simulink, used to define the operational characteristics of the motor model. The mechanical input parameter is set to Torque (Tm), indicating that the machine receives mechanical torque as input rather than speed. The measurement units are specified in SI, ensuring consistency with standard engineering parameters.

The selected Type of Machine is Capacitor-Start, which represents a common single-phase induction motor design that uses a capacitor in series with the auxiliary winding to improve the starting torque. This configuration is suitable for applications requiring higher starting performance, such as compressors or pumps. By appropriately selecting this machine type, the simulation accurately models the motor’s transient and steady-state behaviour during start up and operation

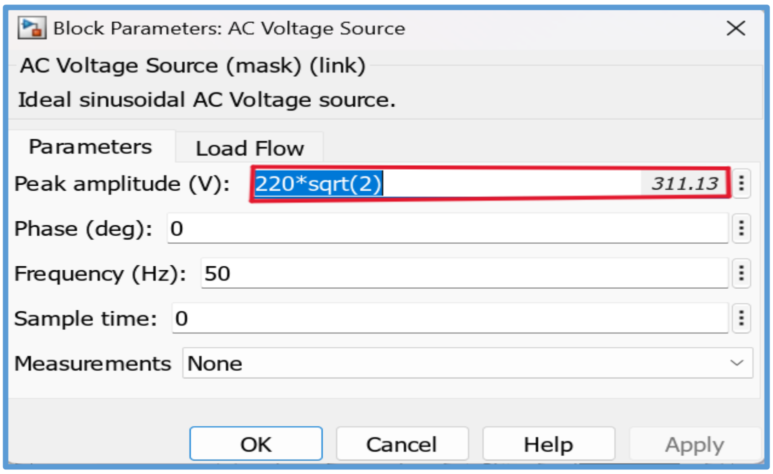


In this section, the parameters tab of the Single-Phase Asynchronous Machine block is configured to define the machine’s electrical and mechanical characteristics. The nominal power, voltage, and frequency 550W, 220 V (RMS), and 50 Hz, representing a machine rated at approximately 0.737 kVA operating under standard mains conditions.

The capacitor-start parameters define the auxiliary starting circuit, while the disconnection speed of 75% synchronous speed determines when the auxiliary winding is disengaged. Together, these settings ensure a realistic representation of the single-phase induction motor's electrical and mechanical performance in Simulink.

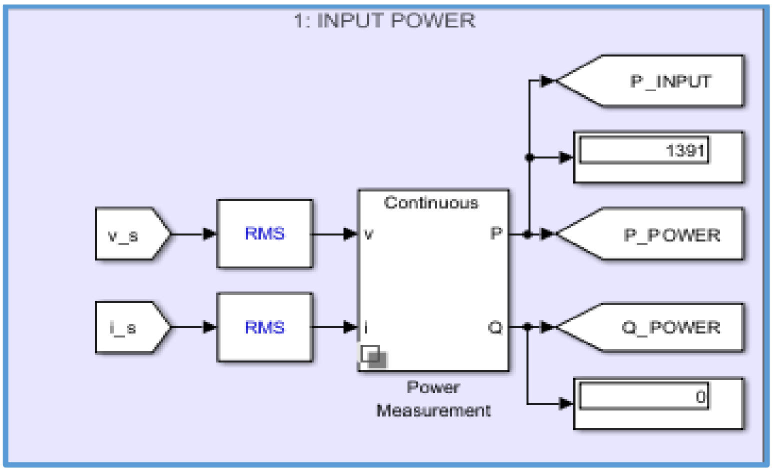
SETTING UP THE SUPPLY

This configuration defines the AC Voltage Source block parameters used to supply the single-phase induction motor. The peak amplitude is set to correspond to a sinusoidal supply of 311.13 V peak, which represents a nominal 220 V RMS voltage — the standard supply level for residential and laboratory single-phase systems.



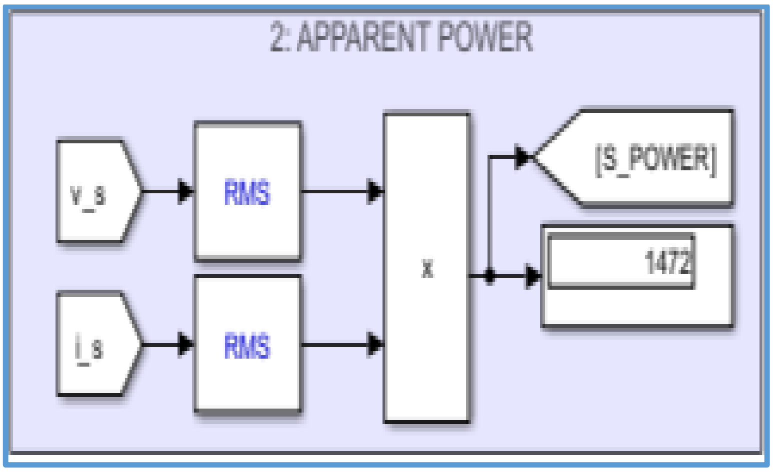
The frequency is specified as 50 Hz, consistent with the South African power grid frequency, ensuring that the motor operates under realistic mains conditions. The phase angle is kept at 0° to represent a pure sinusoidal waveform with no phase shift at the start of the simulation. This voltage source setup provides a stable and idealized AC input for analysing the performance, torque response, and power characteristics of the connected single-phase asynchronous machine.

INPUT POWER



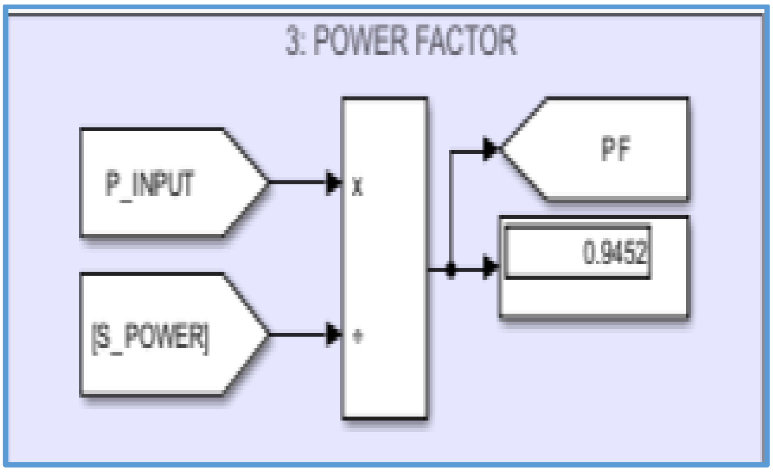
In MATLAB/Simulink, the Input Power section measures the total power supplied to the motor. The voltage (v_s) and current (i_s) signals are passed through RMS blocks to obtain their effective values. These values are then processed by the Power Measurement block, which calculates both the real (P) and reactive (Q) power. The real power represents the useful energy converted into mechanical work, while the reactive power is associated with the magnetic field. This setup provides a clear indication of how much actual power the motor consumes from the supply.

APPARENT POWER



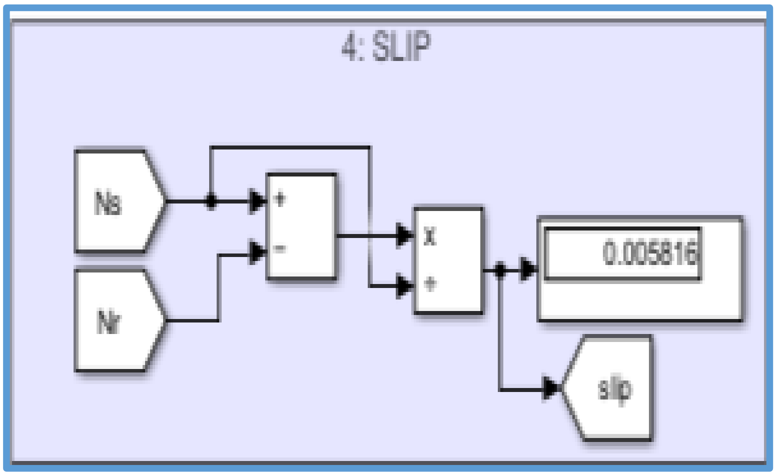
In this section, the Apparent Power is calculated by multiplying the RMS voltage (v_s) and RMS current (i_s) using a Product block. The result represents the total power flowing through the motor circuit, combining both active and reactive components. It indicates the overall electrical load drawn from the supply without distinguishing how much is converted to useful work.

POWER FACTOR



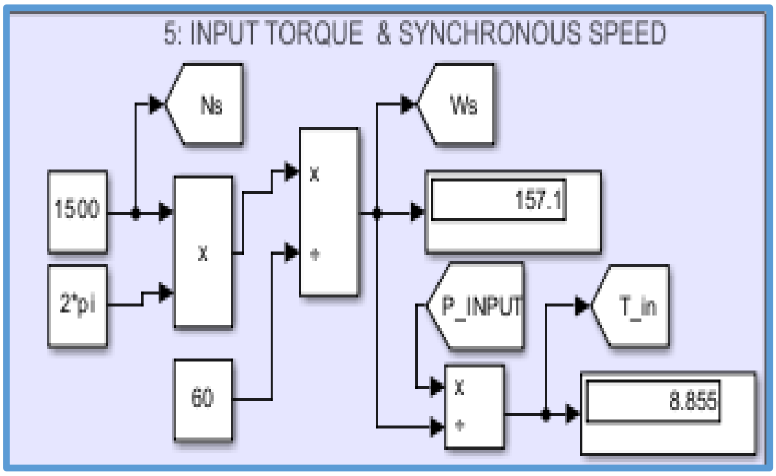
In this section, the Power Factor (PF) is determined by dividing the real input power **(**P_INPUT**)** by the apparent power **(**S_POWER**).** This ratio indicates how effectively the electrical power is being converted into useful mechanical work by the motor. A value close to 1, such as 0.9452, signifies that most of the supplied power is utilized efficiently, with minimal losses due to reactive components. This measurement helps evaluate the motor's performance and overall energy efficiency.

SLIP



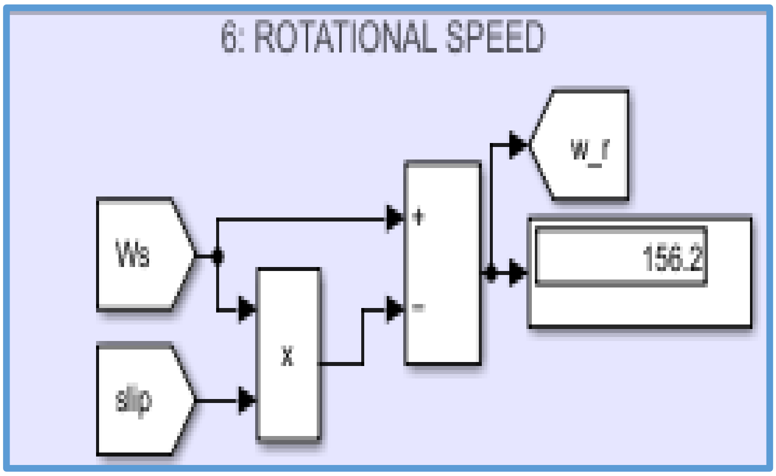
In this section, the slip of the induction motor is determined to show the difference between the speed of the magnetic field and the actual rotor speed. The synchronous speed, represented as N-s, and the rotor speed, represented as N-r, are used as inputs. The slip is calculated by subtracting the rotor speed from the synchronous speed and then dividing the result by the synchronous speed. The obtained value indicates that the rotor is rotating slightly slower than the magnetic field. A small slip value means that the motor is running efficiently and experiencing very little energy loss.

INPUT TORQUE & SYNCHRONOUS SPEED



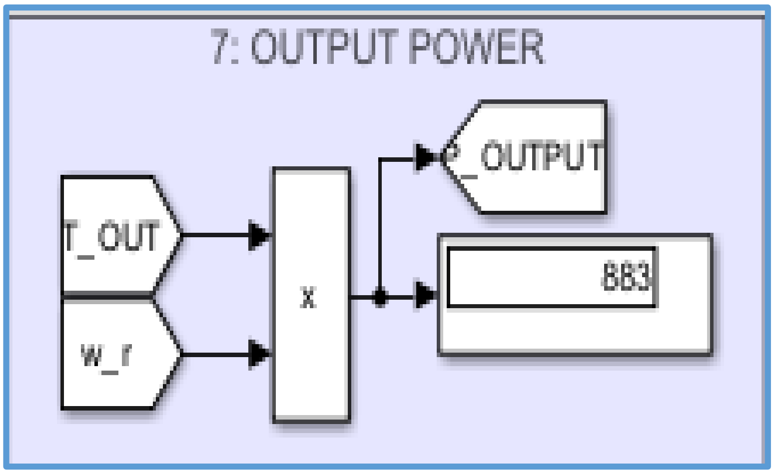
In this section, the synchronous speed and input torque of the motor are calculated. The synchronous speed, represented by W-s, is obtained by converting the speed in revolutions per minute to radians per second using the formula two times pi times N-s divided by sixty. The input torque, represented by T-in, is then determined by dividing the input power by the synchronous speed. The calculated torque value of represents the mechanical torque developed by the motor based on the electrical power supplied. This setup helps in analysing the relationship between electrical input and mechanical output performance.

ROTATIONAL SPEED



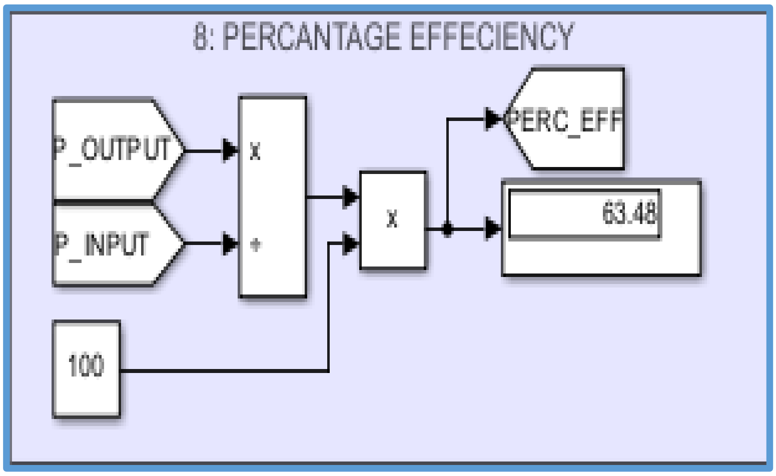
In this section, the rotational speed of the motor is calculated. The synchronous speed (**W-s**) and the slip value are used to determine the actual rotor speed (**W-r**). The subsystem multiplies the slip by the synchronous speed and subtracts the result from the synchronous speed to find the rotor speed. The calculated value of 156.2 radians per second indicates that the rotor is rotating slightly slower than the magnetic field. This difference reflects normal motor operation, where a small slip is necessary to produce torque.

OUTPUT POWER



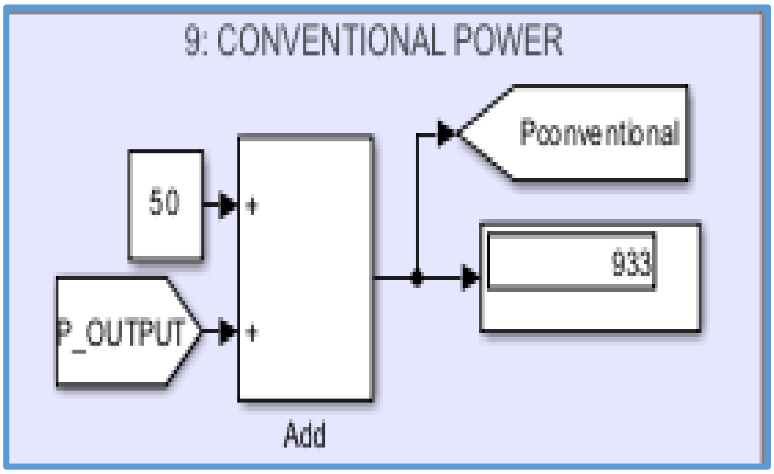
In this section, the output power of the motor is calculated. The torque produced by the motor (**T-out**) and the rotor's angular speed (**W-r**) are multiplied to determine the mechanical output power. The resulting value of **883 watts** represents the actual useful power delivered by the motor shaft. This output power indicates how efficiently the electrical input is converted into mechanical energy, with losses accounted for in the difference between input and output power.

PERCANTAGE EFFECIENCY



In this section, the percentage efficiency of the motor is calculated. The output power (P-output) is divided by the input power (P-input) to determine how effectively the motor converts electrical energy into mechanical energy. The result is then multiplied by 100 to express the efficiency as a percentage. The displayed value of 63.48% indicates that approximately two-thirds of the input electrical power is converted into useful mechanical work, while the remaining portion is lost as heat, friction, and other losses within the system.

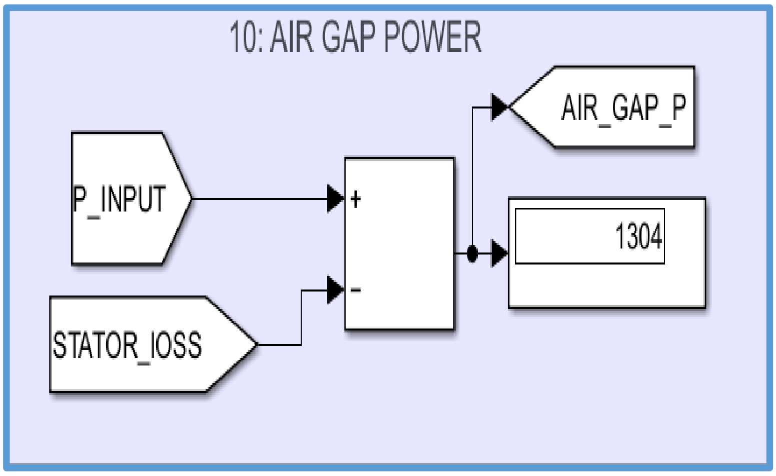
CONVENTIONAL POWER



In this section, the conventional power is calculated by adding a constant value of 50 watts **(Windage & Friction losses)** to the motor's output power (P-output)**.** This adjustment accounts for additional system losses or auxiliary power requirements that may occur in practical operation. The resulting value of 933 watts represents the estimated total conventional power output, combining both the useful mechanical output and the small fixed losses typically present in real-world motor systems.

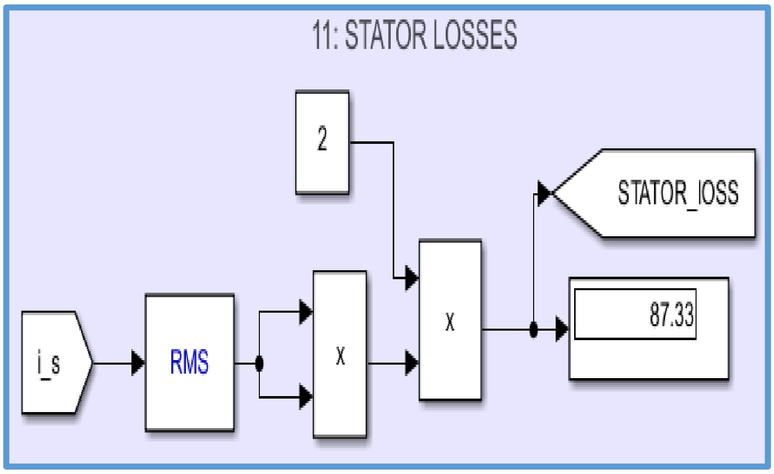
AIR GAP POWER

In this section, the air gap power of the motor is calculated. The input power (P-input) is taken as the total electrical power supplied to the stator, while the stator losses (Stator-loss) are subtracted from it



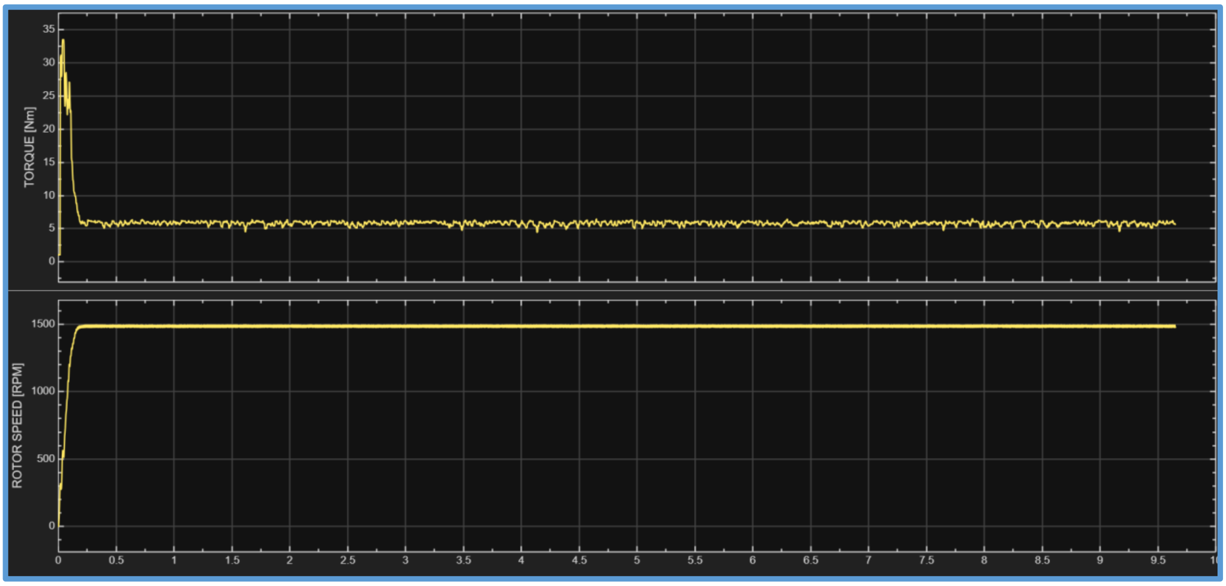
The resulting value, 1304 watts, represents the power transferred across the air gap from the stator to the rotor's magnetic field. This air gap power is a key parameter in motor performance analysis, as it indicates the amount of power available for conversion into mechanical torque within the rotor.

STATOR LOSSES



In this section, the **stator losses** are calculated to determine the power dissipated as heat in the stator windings. The stator current (**i-s**) is first converted to its RMS value, and then squared to represent the power relationship with current. This value is multiplied by a constant representing twice the stator resistance, accounting for both the main and auxiliary windings. The resulting value of **87.33 watts** represents the total copper losses in the stator, which contribute to the overall efficiency reduction of the motor.

OUTPUT WAVEFORMS: TORQUE AND ROTATIONAL SPEED



The simulation results show the **torque** and **rotor speed** characteristics of the single-phase induction motor during startup and steady-state operation. At the beginning, the torque rises sharply to about 35 N·m, indicating the high starting torque typical of capacitor-start motors. As the motor accelerates, the torque quickly drops and stabilizes around 5 N·m**,** showing that the motor has reached normal running conditions. Correspondingly, the rotor speed increases rapidly and settles at approximately 1 480 rpm, which is slightly below the synchronous speed of 1 500 rpm due to slip. This performance confirms that the motor operates efficiently, achieving a smooth transition from startup to steady-state with minimal oscillations.

1.5

parameters	***theoretical***	***simulated***	***percentage errors***
Input power	*0.630 kW*	*1.391 kW*	54.71%
Power factor	*0.955 lag*	*0.945 lag*	1.05%
Slip	*0.008*	*0.0058*	27.5%
Output power	*0.550 kW*	*0.883 kW*	60.36%
Output torque	*3.530 Nm*	*6.993 Nm*	*98.2%*
Synchronous speed	*1500 rpm*	*1500 rpm*	0%
Shaft speed	*1488 rpm*	*1491 rpm*	0.20%
Efficiency	*0.873*	*0.635*	37.48%

DISCUSSION:

The differences observed between the theoretical and simulated results can be largely attributed to the use of a standard generalized motor model during the simulation. In this case, it was considered impractical to use the exact parameters of the laboratory motors, as these values were not readily available or individually measured. Consequently, generalized motor characteristics were applied, which introduced variations in performance values such as torque, efficiency, and output power.