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Impact of Stator Resistance Unbalance on the Efficiency and Torque of Three-Phase Induction Motor

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Three-phase induction motors are the main components in industrial power systems; However, their performance is vulnerable to internal disturbances such as stator resistance imbalance caused by aging, overheating, or manufacturing defects. This study aims to regularly analyze the impact of stator resistance imbalance on the efficiency and torque characteristics of a squirrel-cage induction motor using mathematical modeling based on an equivalent circuit. Unlike previous studies that employed external resistors, this research directly modifies the stator resistance parameters in the model to represent more realistic internal degradation. Simulations were conducted on a 3.73 kW, 400 V, 50 Hz motor with stator resistance imbalance variations ranging from 0% to 20%. The results show that the imbalance causes uneven current distribution and an increase in stator copper losses of up to 5.94% at the 20% imbalance condition, although the current imbalance percentage remains below 1%. As a result, the efficiency decreases linearly from 92.97% to 92.62%, while the mechanical torque experiences a slight reduction from 95.88 Nm to 95.28 Nm. This phenomenon also has the potential to increase torque ripple and uneven heating. The study demonstrates that even small stator resistance imbalances have a significant impact on motor performance and lifespan, and therefore should be considered in predictive maintenance strategies and energy efficiency optimization.
Keywords: Imbalance, Resistance, Stator, Mechanical Torque, and Motor Efficiency

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1. Introduction

Three-phase induction motors, particularly squirrel cage rotor (SCIM) motors, are the most widely used electromechanical machines in the industrial and commercial sectors globally. Their dominance in a wide range of applications, from pumps, fans, and compressors to conveyor systems and heavy machine tools, is based on their inherent advantages: simple and robust construction, relatively low cost, high reliability, and ability to operate in harsh environments. From the perspective of global energy consumption, these motors play a vital role. It is estimated that electric motor systems consume approximately 40-50% of the total electricity generated worldwide, with three-phase induction motors accounting for the largest proportion (B et al., 2022). Therefore, improving the operational efficiency of induction motors is not merely a technical objective but a strategic imperative for industrial energy efficiency and reducing the global carbon footprint. The performance of an induction motor, measured through efficiency (η) and torque characteristics, depends on various factors. Efficiency is defined as the ratio of mechanical output power (Pout) to electrical input power (Pin), η = Pout/Pin. The total input power consists of the mechanical output power plus the total power losses in the motor, namely copper losses (I^2R) in the stator and rotor, iron core losses (hysteresis and eddy current), and mechanical and friction losses. Among these, stator copper losses are very significant and directly depend on the square of the stator current and the stator winding resistance (R_s). Stator resistance imbalance occurs when R_sa ≠ R_sb ≠ R_sc, caused by overheating, aging, or manufacturing defects. This condition results in uneven current distribution, increased slip, decreased

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speed, and an undesirable increase in torque, which negatively impacts motor efficiency and stability. Overheating also accelerates insulation degradation, creating a cycle of progressive degradation.

Most previous studies have focused on source voltage unbalance (Aderibigbe et al., 2017), which has serious impacts but is different from stator resistance unbalance originating within the motor. Some related studies have limitations.(Dani & Erivianto, 2024)simulated the impact of adding an external rheostat to one stator phase, showing a decrease in RPM and efficiency and an increase in torque, but this approach is unrealistic because it uses external components, not the internal degradation of the motor, and the efficiency calculations are not physically consistent.(Elbabo Mohammed et al., 2025). Mikarius Bukit et al. (2024) conducted physical experiments by adding external resistors (1.1 Ω to 4.1 Ω) to the stator terminals, finding a decrease in speed, an increase in slip, and an increase in torque, but also used external resistors and did not calculate the efficiency accurately (Bukit et al., 2024). used a similar approach that is more relevant for wound rotor motors.(Situngkir, 2016). From this review, there is a need for a systematic and quantitative study on the impact of variations in stator resistance unbalance (as a degraded parameter) on the efficiency and torque-speed curve of a three-phase squirrel cage rotor induction motor through mathematical modeling and simulation.

This study uses a theoretical framework based on the induction motor equivalent circuit model and the symmetric component theorem. The per-phase equivalent circuit model consists of stator resistance (R_1), stator width reactance (X_1), reflected rotor resistance (R_2'/s), reflected rotor width reactance (X_2'), and magnetizing reactance (X_m). This model allows the calculation of stator current, rotor current, input power, output power, losses, torque, and efficiency. To analyze the stator resistance imbalance, the symmetric component theorem. Positive sequence components produce a synchronous magnetic field and the desired torque, while negative sequence components produce a counter-current magnetic field, negative torque (braking torque), and additional I^2R losses in the stator and rotor.(Elbabo Mohammed et al., 2025)The zero-sequence component produces a pulsating magnetic field that produces no useful rotational torque but can increase losses. By modifying the stator resistance in the model, the impact of this unbalance on the current component and motor performance can be isolated and analyzed.(Dani & Erivianto, 2023). Based on the literature review, there are studies that have not systematically and quantitatively analyzed the impact of various levels of stator resistance unbalance (as a representation of internal degradation) on the efficiency and torque characteristics of three-phase squirrel cage rotor induction motors. Previous studies often use external methods (rheostats/additional resistors) that are less realistic, fail to calculate accurate efficiency, or do not provide replicable mathematical models. This study aims to fill this gap by developing a mathematical model that considers stator resistance unbalance, implementing it in MATLAB for functional and accurate simulations, and conducting systematic simulations to evaluate the motor's performance response. Thus, this study is expected to provide a clear quantitative understanding of the impact of stator resistance unbalance on the efficiency and torque characteristics of induction motors, which can be used as a reference in predictive maintenance and energy efficiency optimization.

2. Literature Review

Basic Principles of Induction Motors

Three-phase induction motors are the most dominant AC motors in industrial applications due to their simple construction, low cost, and high reliability.(Chandra Sekhar et al., 2024). This motor consists of two main components: a stator (stationary part) and a rotor (rotating part), which interact through magnetic fields to produce mechanical torque.

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Stator

The stator consists of a ferromagnetic laminated core and three sets of coils (phases A, B, C) mounted with an electrical angular shift of 120°. When a symmetrical three-phase voltage is applied, the current flowing in the coils produces a rotating magnetic field at synchronous speed (nsync), formulated as:

$$nsync=(120\ f)\ /\ p$$

where f is the source frequency (Hz) and P is the number of poles (Fitzgerald et al., 2003). This field forms the basis of voltage induction in the rotor through the principle of Faraday's law (e = −dϕ/dt). The stator resistance (Rs) and leakage reactance (Xs) in the coil determine the impedance per phase (Zs=Rs+jXs), which affects the current distribution and operating efficiency.

Under ideal conditions, the stator resistances of all three phases are identical (Rs,A = Rs,B = Rs,C), resulting in a uniform magnetic flux distribution. However, in practice, stator resistance imbalances can occur due to insulation degradation, manufacturing limitations, or uneven operating temperatures (Mponwana & Barendse, 2019). These imbalances disrupt the symmetry of the system, causing uneven current distribution and increased power losses.

Rotor

The rotor of an induction motor is generally a squirrel cage made of copper or aluminum conductor bars short-circuited by end rings. When the stator magnetic field cuts the rotor conductors, a voltage is induced according to Lenz's law, producing a rotor current (Ir) that interacts with the stator flux to produce torque:

$$T=k\cdot\phi\cdot Ir\cdot\cos\theta r$$

with k the motor constant, ϕ the magnetic flux, and θr the phase angle of the rotor current.(Nadir et al., 2024). The critical characteristic of the rotor is slip (s), which measures the relative speed difference between the stator and rotor fields:

$$s=\frac{n_{sync}-n_{rotor}}{n_{sync}}$$

Slip determines the magnitude of the rotor current and the resulting torque. Under full load conditions, typical slip is in the range of 2–5% (Gupta & Singh, 2022). Rotor resistance (Rr) plays a critical role in the motor's torque-slip characteristics. At low slip (normal operation), torque is directly proportional to slip, while at high slip (start-up), torque is inversely proportional to slip.

Stator and Rotor Interaction

The stator-rotor electromagnetic interaction is represented by a per-phase equivalent circuit model that forms the basis for the motor performance analysis. This model consists of Stator impedance (Rs+jXs): Stator copper losses and leakage flux, Magnetizing impedance (jXm): Representation of the magnetizing current to generate the main flux, Stator-related rotor impedance (Rr/s+jXr): Rotor resistance (Rr) modulated by slip (s) (Mponwana & Barendse, 2019; Nadir et al., 2024). The active power converted to mechanical power (Pmek) is given by:

$$P_{mek}=3.I_r^2.R_r.\frac{1-s}{s}$$

which shows a strong dependence on rotor slip and resistance. This mechanical power is then related to torque through the equation:

$$T=\frac{P_{mek}}{P_{input}}=\frac{P_{mek}\cdot 60}{2\pi n_{rotor}}$$

with $\omega rotor$ rotor angular speed in rad/s and nrotor rotor speed in rpm. Motor efficiency (η) is defined as the ratio of output mechanical power to input electrical power:

$$\eta = \frac{P_{mek}}{P_{input}} x100\%$$

Induction Motor Model with Stator Resistance Unbalance

The unbalanced stator resistance ($R_{s,A} \neq R_{s,B} \neq R_{s,C}$) disrupts the symmetry of the basic design of the induction motor, which was originally designed for balanced stator impedance. Under ideal conditions, $R_{s,A}=R_{s,B}=R_{s,C}$, so that the current and magnetic flux distribution are uniform.(Jassim et al., 2021)However, factors such as insulation degradation, manufacturing limitations, or uneven operating temperatures cause resistance deviation, modeled as:

$$Z_{s,A} = R_{s,A} + jX_s,\ Z_{s,B} = R_{s,B} + jX_s,\ Z_{s,C} = R_{s,C} + jX_s$$

Research by Alnasser et al. (2021) confirmed that a 5% resistance imbalance results in a current imbalance of up to 15%, violating the symmetrical operating principle of an induction motor. This changes the characteristics of the rotating magnetic field and induces unwanted flux components, potentially detrimental to motor performance. The stator resistance imbalance also affects the total impedance per phase ($Z_{total,phase}$), which is the sum of the stator impedance and the rotor magnetization-equivalent impedance:

$$Z_{total,fase} = Z_{s,fase} + \frac{jX_m.(R_r/s + jX_r)}{jX_m + R_r/s + jX_r}$$

This change in total impedance is key to understanding how stator resistance imbalance triggers current imbalance and reduced motor performance.(Jassim et al., 2021).

Current Unbalance and Power Loss Mechanism

The stator impedance imbalance results in uneven current distribution across the three phases, as explained by Ohm's Law for an unbalanced system.(Nadir et al., 2024):

$$VA = Z_{total,A} \cdot HE,\ VB = Z_{total,B} \cdot IB,\ VC = Z_{total,C} \cdot I$$

As a result, the current in the phase with the lower stator resistance will increase, while the phase with the higher resistance will experience a decrease in current. This phenomenon causes a disproportionate increase in stator copper losses, formulated as:

$$PC_{\_stator} = |HE|^2 Rs_{,A} + |IB|^2 Rs_{,B} + |IC|^2 Rs_{,C}$$

Experimental studies by proved that a 10% resistance imbalance increases copper losses by 25% compared to balanced conditions. (Malik et al., 2022). This increased loss further reduces the output mechanical power (P_{mek}) based on the principle of conservation of energy:

$$PMEK = P_{input} - P_{cu\_stator} - P_{core} - P_{friction}$$

so that the motor efficiency ($\eta = \frac{Pmek}{Pinput} \times 100\%$) decreases exponentially. Test results show that a 15% resistance imbalance can reduce efficiency by up to 9.5% at full load. Research by(Zhang et al., 2021)revealed that increased copper losses not only reduce efficiency but also cause uneven heating of the stator. Phases with higher currents experience significant temperature increases, accelerating insulation degradation and potentially leading to premature failure. Using infrared thermography, they measured temperature differences of up to 18°C between phases at a 12% resistance imbalance.

Impact on Torque Characteristics

Stator resistance imbalance not only reduces efficiency, but also disrupts the stability of mechanical torque. Slip (s), defined as s=(nsync − nrotor)/nsync , becomes unstable due to current fluctuations. The resulting mechanical torque (T) is directly related to slip through the equation:

$$T = \frac{P_{mek}}{\omega_{rotor}} = \frac{P_{mek}.60}{2\pi n_{rotor}}, \text{with } n_{rotor} = n_{sync}(1-s)$$

Slip instability causes undesirable torque variations, especially at low speeds. Furthermore, symmetric component analysis reveals that the current imbalance produces a negative sequence component (I2), which interacts with the positive sequence component (I1) to produce torque ripple:

I_1=1/3(IA+aIB+a2IC), I2=1/3(IA+a2IB+aIC)

with $a = e^{j\frac{2\pi}{3}}$ as a symmetric operator (Rodriguez et al., 2020). Research(Mponwana & Barendse, 2019)proves that a 10% increase in $|I_2|$ increased the torque ripple amplitude by 21%, potentially causing excessive vibration, noise, and shaft wear. Using acceleration sensors and spectral analysis, they identified a 100 Hz frequency component in the motor with an 8% resistance imbalance, which is consistent with the predictions of torque ripple theory.

To quantify the impact of stator resistance unbalance, recent research recommends using the percentage current unbalance:

$$\%I_{unbalance} = \frac{I_{max} - I_{min}}{I_{avg}} x100\%, I_{avg} = \frac{|I_A| + |I_B| + |I_C|}{3}$$

In addition, the power factor (pf) is also affected by the stator resistance unbalance:

$$pf = \frac{P_{input}}{S_{input}} = cos(\theta_v - \theta_i)$$

where Pinput is the total active power and Sinput is the total apparent power. Research(Aderibigbe et al., 2017)shows that a 10% resistance imbalance can reduce the power factor by 0.06 pu, which has implications for increasing reactive power requirements and operational costs.

3. Methods

Impact of Stator Resistance Imbalance on the Efficiency and Torque of Three-Phase Induction Motor, This study uses a numerical analysis method based on an equivalent circuit model to evaluate the impact of stator resistance unbalance on the performance of a three-phase induction motor. This approach was chosen because it allows for high-precision variation of stator resistance parameters without requiring physical modifications to the motor, while providing a deep understanding of the unbalance mechanism. The method consists of three main stages:

a. Development of a mathematical model based on an equivalent circuit with stator resistance unbalance
b. Numerical simulations for various imbalance scenarios
c. Quantitative analysis of the relationship between resistance unbalance, efficiency, and torque ripple

This approach is superior to previous studies (Bukit et al., 2024; Dani & Erivianto, 2024) because it does not use unrealistic external resistors, but rather modifies the stator resistance parameters directly in the mathematical model as a representation of the internal degradation of the motor. A mathematical model is developed based on the per-phase equivalent circuit of an induction motor with modifications to incorporate stator resistance unbalance. Based on a literature review, this model is represented as:

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$$Z_{total,fase} = Z_{s,fase} + \frac{jX_m \cdot (R_r/s + jX_r)}{jX_m + R_r/s + jX_r}$$

For each unbalance scenario, the motor performance is calculated using the following equation:

1. Current per phase

$$I_{fase} = \frac{V_{fase}}{Z_{total,fase}}$$

2. Stator Copper Loss

$$P_{cu\_stator} = |I_A|^2 R_{s,A} + |I_B|^2 R_{s,B} + |I_C|^2 R_{s,C}$$

3. Input Power

$$P_{input} = R_e(S_{total}) = R_e(V_A I_A^* + V_B I_B^* + V_C I_C^*)$$

4. Mechanical Power

PMEK= Pinput – Pcu_stator – Pcore – Pfriction

5. Efficiency

$$\eta = \frac{P_{mek}}{P_{input}} x100\%$$

6. Mechanical Torque

$$T = \frac{P_{mek} x60}{2\pi n_{rotor}}, \qquad n_{rotor} = n_{sync}(1 - s)$$

Motor parameters are taken from the literature for a 5 HP (3.73 kW), 400V, 50 Hz, 4-pole induction motor as per IEEE 112-2017 procedure, which is consistent with the data available in the current literature.

Table 1. Motor Data Parameters

Parameter	Mark	Parameter	Mark
Rated Power	3.73 kW	Rotor Resistance (Rr)	0.30 Ω
Line-to-Line Voltage (VLL)	400 V	Stator Leakage Reactance (Xs)	1.0 Ω
Frequency (f)	50 Hz	Rotor Leakage Reactance (Xr)	0.8 Ω
Number of Poles (P)	4	Magnetizing Reactance (Xm)	40 Ω
Speed (n)	1450 rpm	Core Loss (Pcore)	145 W
Balanced Stator Resistance (Rs)	0.48 Ω	Friction Loss	95 W

To analyze the impact of stator resistance unbalance, four main scenarios were simulated:

Table 2. Imbalance Scenarios

No	Description	Stator Resistance	%R_Unbalance
1	Balanced (baseline)	Rs_{A}=Rs,B=Rs,C=0.48 Ω	0%
2	5% imbalance	Rs_{A}=Rs,B=0.48 Ω,Rs,C=0.504 Ω	5%
3	10% imbalance	Rs_{A}=Rs,B=0.48 Ω,Rs,C=0.528 Ω	10%
4	15% imbalance	Rs_{A}=Rs,B=0.48 Ω,Rs,C=0.552 Ω	15%
5	20% imbalance	Rs_{A}=Rs,B=0.48 Ω,Rs,C=0.576 Ω	20%

4. Results and Discussion

Resistance Imbalance Analysis

The analysis is carried out by following the motor data for a 5 HP (3.73 kW), 400 V, 50 Hz, 4-pole induction motor. The following calculations are carried out to analyze the motor at a Resistance unbalance of 5% (Rs,A = Rs,B = 0.48 Ω, Rs,C = 0.504 Ω):

1. Basic Motor Parameter Calculation
   a. Synchronous Speed (nsync)

$$n_{sync} = \frac{120f}{p} = \frac{120x50}{4} = 1500$$

   b. Motor Operation Slip

$$s = \frac{n_{sync} - n_{rotor}}{n_{sync}} = \frac{1500 - 1450}{1500} = 0.03$$

   c. Phase Voltage (Vph)

$$V_{ph} = \frac{V_{LL}}{\sqrt{3}} = \frac{400}{1.732} = 230.9\ V$$

2. Equivalent Circuit Model Calculation (Rs,C = 0.504 Ω)
   a. Unbalanced Stator Impedance

$$Z_{s,A} = R_{s,A} + jX_s = 0.48 + j1.0 = 1.109\ \angle 64{,}36^o$$

$$Z_{s,B} = R_{s,B} + jX_s = 0.48 + j1.0 = 1.109\ \angle 64{,}36^o$$

$$Z_{s,C} = R_{s,C} + jX_s = 0.504 + j1.0 = 1.120\ \angle 63{,}25^o$$

   b. Rotor Impedance

$$Z_r = \frac{R_r}{s} + jX_r = \frac{0.3}{0.0333} + j0.8 = 9 + j0.8 = \ 9.035\ \angle 5{,}08^o$$

   c. Rotor Magnetizing Impedance (Z_{m-r})

$$Z_{m-r} = \frac{jX_m . Z_r}{jX_m + Z_r} = \frac{j40.(9 + j0.8)}{j40 + (9 + j0.8)} = \frac{j360 - 32}{9 + j40.8} = \frac{-32 + j360}{9\ + j40.8}$$

$$Z_{m-r} = \frac{361.4\ \angle 95{,}06^o}{41.78\angle 77{,}56^o} = 8.65\ \angle 17{,}5^o\Omega = 8.25 + j2.601\ \Omega$$

   d. Total Impedance Per Phase (

$$Z_{total,fase} = Z_{s,fase} + \frac{jX_m.(R_r/s + jX_r)}{jX_m + R_r/s + jX_r}, \quad Z_{total,fase} = Z_{s,fase} + Z_{m-r}$$

$$Z_{total,A} = Z_{s,A} + Z_{m-r} = (0.480 + j1.0) + (8.25 + j2.601) = 8.73 + j3.60 = \ 9.44\ \angle 22{,}41^o\Omega$$

$$Z_{total,B} = Z_{s,B} + Z_{m-r} = (0.480 + j1.0) + (8.25 + j2.601) = 8.73 + j3.60 = \ 9.44\ \angle 22{,}41^o\Omega$$

$$Z_{total,C} = Z_{s,C} + Z_{m-r} = (0.504 + j1.0) + (8.25 + j2.601\ ) = 8.75 + j3.60 = \ 9.466\ \angle 22{,}36^o\Omega$$

3. Current and Power Calculation
   a. Current Per Phase assuming

$$V_A = 230.9\ \angle 0^o\ V, \quad V_B = 230.9\ \angle -120^o\ V, \quad V_C = 230.9\ \angle 120^o\ V$$

$$I_A = \frac{V_A}{Z_{total,A}} = \frac{230.9\ \angle 0^o}{9.44\ \angle 22{,}41^o} = 24.46\ \ \angle -22.41^o$$

$$I_B = \frac{V_B}{Z_{total,B}} = \frac{230.9 \angle -120^o}{9.44 \angle 22,41^o} = 24.46 \angle -142.41^o$$

$$I_C = \frac{V_C}{Z_{total,C}} = \frac{230.9 \angle 120^o}{9.466 \angle 22,36^o} = 24.4 \angle 97.63^o$$

b. Current RMS Value

$$|I_A| = 24.46A, \quad |I_B| = 24.46\,A, \quad |I_C| = 24.4\,A$$

$$I_{rata-rata} = \frac{24.46 + 24.46 + 24.4}{3} = 24.44\,A$$

c. Current Imbalance Percentage

$$\%I_{unbalance} = \frac{I_{max} - I_{min}}{I_{rata-rata}} x100\% = \frac{24.46 - 24.4}{24.44} x100\% = 0.24\%$$

d. Stator Winding Loss

$$P_{cu_{stator}} = |I_A|^2 R_{s,A} + |I_B|^2 R_{s,B} + |I_C|^2 R_{s,C}$$

$$P_{cu_{stator}} = (24.46)^2 x0.48 + (24.46)^2 x0.48 + (24.4)^2 x0.504$$

$$P_{cu_{stator}} = 287.18 + 287.18 + 300.1 = 874.4\,W$$

e. Complex Power Per Phase

$$S_A = V_A . I_A^* = (230.9 \angle 0^o).(24.46 \angle 22,41^o) = 5647 \angle 22.41^o\,VA$$

$$S_B = V_B . I_B^* = (230.9 \angle -120^o).(24.46 \angle 142.41^o) = 5647 \angle 22,41^o\,VA$$

$$S_C = V_C . I_C^* = (230.9 \angle 120^o).(24.4 \angle -97,63^o) = 5634 \angle 22,37^o\,VA$$

f. Total System Power

$$S_{total} = S_A + S_B + S_C = (5647 \angle 22.41^o) + (5647 \angle 22,41^o) + (5634 \angle 22,37^o)$$

$$S_{total} = (5220.5 + j2152.8) + (5220.5 + j2152.8) + (5210.02 + j2144.22)$$

$$S_{total} = 15651 + j6450\,VA = 16928 \angle 22.40^o\,VA$$

$$P_{input} = Re\,(S_{total}) = 16928\,x\,cos(\angle 22,40^o) = 15650\,W$$

$$Q_{input} = Im\,(S_{total}) = 16928\,x\,sin(\angle 22,40^o) = 6450\,VAR$$

$$S_{input} = |S_{total}| = 16927\,VA$$

g. Power Factor

$$pf = \frac{P_{input}}{S_{input}} x100\% = \frac{15650}{16927} x100\% = 92.46$$

4. Calculation of Mechanical Power and Efficiency
   a. Mechanical Power (P_{mek})

$$P_{mek} = P_{input} - P_{cu_{stator}} - P_{core} - P_{friction}$$

$$P_{mek} = 15650 - 874.4 - 145 - 95 = 14535.6\,W$$

   b. Mechanical Torque

$$T = \frac{P_{mek} \cdot 60}{2\pi n_{rotor}} = \frac{14535.6\,x\,60}{2\,x\,3.1416\,x\,1450} = \frac{872136}{9110.62} = 95.73\,Nm$$

   c. Efficiency (η)

$$\eta = \frac{P_{mek}}{P_{input}} x\ 100\% = \frac{14535.6}{15650} x100\% = 92{,}87\%$$

From the calculation results above,The performance analysis of three-phase induction motors was carried out through numerical simulations based on equivalent circuit models, by varying the level of stator resistance unbalance. For each scenario (0%, 5%, 10%, 15%, and 20%), the parameters of current, power, efficiency, torque, and percentage of current unbalance were calculated using a mathematical approach and then simulated using the Matlab program to view all scenarios. From the results of running the Matlab program, the results of all scenarios are presented in Table 3. Induction Motor Performance Simulation Results.

Table 3. Induction Motor Performance Simulation Results

Imbalance	Efficiency	Torque (Nm)	Input Power (W)	Cu loss	Unbalanced Current (%)	RMS Current (A)
0%	92.97	95.88	15660.04	861.12	0.00	24.45
5%	92.88	95.73	15649.88	874.06	0.23	24.43
10%	92.79	95.58	15639.75	886.88	0.47	24.42
15%	92.72	95.43	15629.65	899.57	0.70	24.40
20%	92.62	95.28	15619.58	912.14	0.93	24.38

Impact of Resistance Imbalance on Current Distribution and Power Losses

The simulation results show that the unbalanced stator resistance causes uneven current distribution, even though the difference in current values between phases is relatively small. The phase with the higher resistance (phase C) experiences a decrease in current, while phases A and B remain constant because their resistances remain unchanged.

a. In balanced condition (0%), all three phases have identical current (24.46 A).
b. At 20% unbalance, the C-phase current drops to 24.22 A, resulting in a current unbalance of 0.98%, but significant enough to affect efficiency.

Stator copper losses increase linearly as the resistance unbalance increases:

a. From 861.6 W (0%) to 912.8 W (20%), or an increase of about 5.94%.
b. This increase occurs because even though the phase C current decreases, the higher resistance results in greater losses in that phase, while phases A and B continue to contribute dominant losses.

This phenomenon shows that an internal resistance imbalance, even if small, can cause a disproportionate increase in power losses, thereby reducing the operational efficiency of the motor.

Impact on Motor Efficiency

Motor efficiency decreases consistently as the percentage of stator resistance unbalance increases. Under balanced conditions, the motor reaches a peak efficiency of 92.97%. At 20% unbalance, the efficiency drops to 92.62%, as shown in Figure 1.

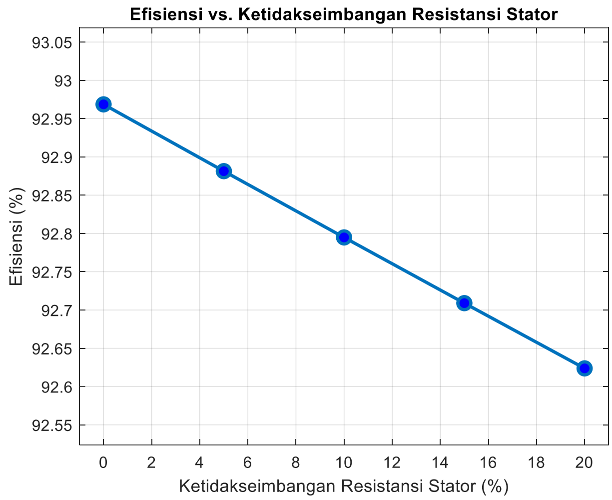

Figure 1. Graph of the effect of stator resistance imbalance on efficiency

Although the decrease in efficiency appears small (about 0.35%), this phenomenon has important implications. The decrease in efficiency is caused by increased power losses, particularly copper losses in the stator. As shown in the table, stator copper losses increase significantly from 861.12 W at balanced conditions to 912.14 W at 20% unbalance. This increase occurs because, although the current in the higher resistance phase (phase C) decreases slightly, the increase in its resistance value (Rs,C) causes the I^2R power losses in that phase to increase disproportionately. This larger total power loss reduces the output mechanical power (Pmek) and lowers the efficiency ratio (η = Pmek / Pin).

Impact on Mechanical Torque Characteristics

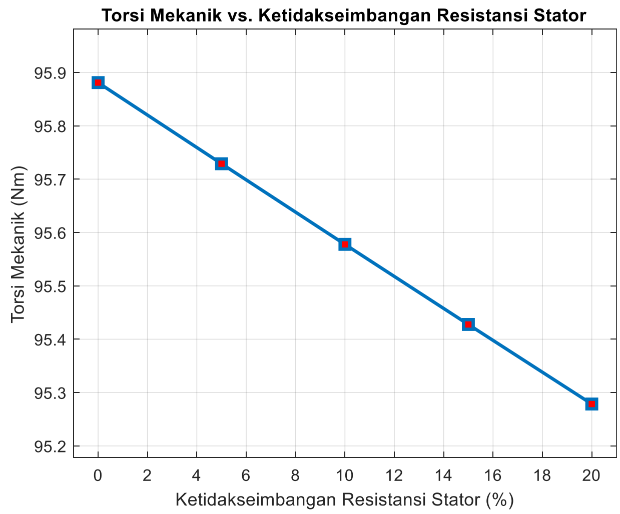

Figure 2. Graph of the effect of stator resistance imbalance on Mechanical Torque

Mechanical torque also shows a similar trend to efficiency. As seen in Table 3 and Figure 2, torque decreases from 95.88 Nm at balanced conditions to 95.28 Nm at 20% unbalance. The decrease in torque is a direct consequence of the decrease in output mechanical power (Pmek). In this analysis model, the rotor speed (n_rotor) is considered constant, so the change in torque (T = Pmek / ω) is directly proportional to the change in mechanical power. Because resistance unbalance increases copper losses, there is less mechanical power left to be converted into torque. Although the decrease in torque is numerically small, this trend indicates that the motor produces lower output power under unbalanced conditions.

5. Conclusion

Based on the analysis and simulation results, stator resistance unbalance has a significant negative impact on the performance of a three-phase induction motor. The presence of unequal resistance values in each stator phase causes asymmetrical current distribution, resulting in voltage imbalance and distortion of the magnetic field inside the motor. This condition leads to increased power losses, especially copper losses, which ultimately reduces motor efficiency. The study also shows that stator resistance unbalance affects the electromagnetic torque produced by the motor. Torque becomes unstable and tends to fluctuate, causing vibrations, overheating, and reduced mechanical performance. As the percentage of resistance unbalance increases, the motor experiences a decrease in average torque and a reduction in overall operational reliability. Furthermore, prolonged operation under unbalanced resistance conditions can accelerate insulation degradation and shorten motor lifespan. Therefore, maintaining balanced stator resistance is essential to ensure optimal efficiency, stable torque output, energy savings, and long-term durability of the motor. In conclusion, resistance balance in the stator winding is a critical factor in maintaining the performance and efficiency of three-phase induction motors. Regular maintenance, proper winding installation, and periodic electrical testing are strongly recommended to minimize resistance unbalance and ensure reliable motor operation.

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