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Current Imbalance Analysis in Three-Phase Induction Motors: Causes, Performance Impacts, and Mitigation Efforts

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Abstract: *The three-phase induction motor is the most widely used electromechanical drive in the industrial sector due to its simple construction, reliability, and relatively low cost. However, its performance strongly depends on the quality of a balanced three-phase voltage supply. Even a small voltage unbalance is amplified into a much larger stator current unbalance, causing excessive heating, reduced efficiency, torque and speed oscillation, increased vibration, and accelerated degradation of winding insulation. This article aims to analyze, through a literature-based approach, the causes, mechanisms, calculation methods, impacts, and mitigation strategies of current imbalance in three-phase induction motors by synthesizing previous studies, both simulation-based (MATLAB/Simulink) and experimental laboratory/industrial testing. The method used is a literature review of national scientific articles in electrical engineering discussing voltage/current unbalance in induction motors. The review shows that, based on the NEMA standard, a 1% voltage unbalance can produce approximately 6-10 times greater current unbalance, and at 5% voltage unbalance the motor experiences significant overheating requiring derating of about 25% of its rated capacity. Extreme conditions such as single-phasing faults can cause voltage unbalance of 3.64%-6.30% accompanied by a sharp temperature rise that risks damaging winding insulation. Recommended mitigation strategies include real-time current and voltage monitoring based on the Internet of Things (IoT), phase-unbalance and single-phasing protection, motor derating according to the NEMA standard, and preventive maintenance of the three-phase supply system. This review is expected to serve as a reference for further research on the protection and reliability of three-phase induction motors in industrial settings.*

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Introduction

Three-phase induction motors are the most widely used electric machines as drivers in the industrial sector, due to their simple construction structure, strength, durability, and relatively low maintenance costs compared to other types of motors. This motor has three identical stator coils separated by 120° electrically, so it is designed to operate optimally under balanced three-phase voltage supply conditions, both in magnitude and phase angle.

In practical operation, a truly balanced supply voltage is very difficult to achieve. Unbalance can arise from uneven single-phase loading in the distribution system, asymmetrical transmission lines, transformer winding damage, or disturbances such as single-phasing due to a damaged or broken stator phase. A relatively small supply voltage imbalance can be amplified into a much larger stator current imbalance because the negative sequence impedance of an induction motor is much smaller than its positive sequence impedance.

Current imbalance in three-phase induction motors impacts various aspects of performance, including increased power losses, increased stator and rotor winding temperatures, torque oscillations and rotational speed, increased mechanical vibrations, decreased efficiency and power factor, and accelerated insulation damage that can shorten the motor's operational life. Several previous studies have examined this phenomenon through simulation approaches using MATLAB/Simulink as well as direct experimental testing on test motors in the laboratory and in the field (industry and power plants).

Based on the description, this article aims to: (1) explain the concept and causes of current unbalance in three-phase induction motors; (2) summarize the analysis and calculation methods of current/voltage unbalance used in previous studies, including NEMA standards; (3) analyze the impact of current unbalance on motor torque, speed, temperature, and efficiency; and (4) formulate mitigation and protection strategies that can be applied to maintain the reliability of three-phase induction motors.

Literature Review

The Concept of Voltage and Current Imbalance in Induction Motors

Voltage imbalance is defined as a condition where the voltage magnitudes in the three phases are not the same, or the phase angle between the voltages deviates from 120° electrically. Phase angle imbalance occurs due to differences in magnitude or angle points at each stage of a three-phase induction motor circuit, and can be caused by different loads in the power circuit, damaged transmission lines, uneven load circulation, or transformers that are not working optimally. When an induction motor is supplied with an unbalanced voltage, the current flowing in the stator becomes unbalanced as well, and according to the results of MATLAB Simulink simulations, this condition also causes oscillations in the torque wave and motor speed so that motor vibrations increase.

Unbalance Calculation Standards and Methods (NEMA)

The definition of unbalance in induction motors generally refers to the NEMA (National Electrical Manufacturers Association) standard. Based on this standard, the motor can operate normally according to its specifications if the voltage unbalance is not more than 1%; whereas at a voltage unbalance of 5% the motor will experience overheating and significantly increased losses, so that a reduction in the motor's working capacity (derating) is required. Induction motor derating studies based on the NEMA standard compared with field measurement data at generating units show that derating calculations through phase unbalance can be used as a practical reference in determining the safe limits of motor loading.

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Previous Research Results

Research using MATLAB Simulink simulation on a three-phase induction motor with a voltage unbalance of 5% (phase A voltage = 420 V, phase B = 400 V, phase C = 380 V) shows that the stator current becomes unbalanced, accompanied by oscillations in the torque waveform and motor speed. Under no-load conditions, the motor torque is 574 Nm with a speed of 1501 rpm, and at a load of 360 Nm the torque increases to 934 Nm with a speed decrease to 1497 rpm, confirming that the greater the load, the torque will increase while the motor speed decreases. Similar research using the phase angle unbalance approach (not voltage magnitude) also found comparable torque and speed oscillation patterns.

In the thermal aspect, research on the effect of single-phasing disturbances on a 0.75 kW 3-phase induction motor shows that damage to one of the stator phases causes a voltage unbalance of 3.64% at zero load conditions to 6.30% at loaded conditions, which is accompanied by a significant temperature increase in the motor and risks damaging the winding insulation resistance if it lasts for a certain time interval. Another study on the effect of voltage unbalance on induction motor temperature found that the temperature increase in unbalanced voltage conditions is much higher than in balanced conditions, which is around 0.72°C/min at 1% unbalance and 0.84°C/min at 3% unbalance, compared to only 0.36°C/min in balanced conditions based on infrared thermometer measurements.

In terms of monitoring and protection, the development of the NETMOTOR (network-enabled three-phase motor performance recorder) system based on the Internet of Things (IoT) shows that real-time voltage and current monitoring can be carried out with a good level of accuracy, namely an average difference in current measurements of 4.32% and phase-neutral voltage of 0.43% compared to standard measuring instruments, so it has the potential to be used as an early detection system for current/voltage imbalances in industrial induction motors. Other research has also developed an intelligent monitoring system based on wireless sensor networks and the Blynk application for similar purposes. In addition, the use of auxiliary capacitors in three-phase induction motors operated with a single-phase source has been shown to reduce current imbalances and increase motor starting torque, although motor performance remains lower than normal three-phase operation.

Research Methods

This article was compiled using a descriptive-analytical literature review approach. The data sources were national journal articles in the field of electrical engineering that discussed voltage/current imbalance in three-phase induction motors, both through simulation approaches (MATLAB/Simulink) and experimental testing, published in the period 2012–2024. The research stages included: (1) searching for articles through national journal databases (Garuda, ResearchGate, and university journal repositories); (2) selecting articles based on the suitability of the topic with current/voltage imbalance in three-phase induction motors; (3) data extraction in the form of analysis methods, imbalance values, impacts on motor performance, and mitigation recommendations; and (4) synthesis and comparative analysis of these findings.

Voltage and Current Imbalance Calculation Method

Based on NEMA standards, the percentage of voltage unbalance (Voltage Unbalance Factor) is calculated using the maximum deviation approach to the mean value, with the equation:

%VU = (Maximum deviation from mean voltage / Mean voltage) × 100%

with the average stress calculated as:

$$V_{average} = (V_{AB} + V_{BC} + V_{CA}) / 3$$

The same approach applies to calculating the percentage current unbalance (%IU), by replacing the voltage values in the above equation with the stator phase current values (I_R,

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I_S, I_T). Since the negative sequence impedance of an induction motor is much smaller than the positive sequence impedance, an empirical relationship widely cited in the literature states that the current unbalance can be approximately 6 to 10 times the voltage unbalance causing it. Furthermore, the motor derating factor due to voltage unbalance according to the NEMA MG-1 standard curve is expressed qualitatively: the motor operates without capacity degradation up to 1% unbalance, and the capacity degradation increases sharply as the percentage unbalance increases until it approaches 5%, at which point the recommended derating can reach approximately one-quarter of the motor's rated capacity.

Thermal analysis was carried out by comparing the rate of temperature increase (°C/min) under balanced and unbalanced voltage conditions through direct measurements using an infrared thermometer or winding resistance measurement method, while dynamic analysis of motor torque and speed in various studies was carried out through modeling the equivalent circuit of an induction motor in MATLAB/Simulink simulation software.

Results and Discussion

Recapitulation of Findings from Various Studies

Table 1 summarizes the seven studies that are the subject of synthesis in this article, including simulation approaches (MATLAB/Simulink), laboratory experimental testing, field studies in generating units, and the development of an IoT-based monitoring system.

Table 1. Summary of the Results of the Voltage/Current Imbalance Study on Three-Phase Induction Motors

Object/Method of Study	Imbalance	Main Impact	Source
MATLAB Simulink simulation, voltage unbalance	5% (420/400/380 V)	Unbalanced stator current; torque & speed oscillation	Rang Teknik Journal (2023)
MATLAB simulation, phase angle imbalance	5% (phase angle)	Torque–velocity oscillation; vibration increases	Rang Engineering Journal / RG (2023)
0.75 kW motor, single-phasing fault (experimental)	3.64%–6.30%	Sharp temperature rise; risk of insulation damage	UNDIP Transmission (2017)
Unbalanced stress thermal testing	1%–3%	Temperature rise rate 0.72–0.84°C/min	UNPAB Repository (2024)
NEMA-based motor derating vs. PLTU field data	Varies	Reduction in motor working capacity (derating)	UGM ETD (2015)
Capacitor start motor, single phase supply	Reduced with capacitor	Current imbalance down; starting torque up	ITScience Journal (2025)
IoT-based NETMOTOR monitoring system	Real-time detection	Current measurement difference of 4.32% vs standard tool	E-JOINT PNC (2024)

Causes of Current Unbalance in Induction Motors

Based on literature synthesis, the main causes of current unbalance in three-phase induction motors can be grouped as follows:

1. Supply voltage imbalance due to uneven single-phase loading in the upstream distribution system.
2. Damage or interference to one of the stator phases (single-phasing) due to lack of maintenance or poor operating environment.
3. Transmission/distribution lines that are asymmetrical or partially damaged.

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4. The supply transformer is not working optimally or is experiencing a load imbalance on the secondary side.
5. Three-phase induction motor operation with a single-phase source uses an auxiliary capacitor, which inherently produces an unbalanced magnetic field.

Impact of Current Imbalance on Motor Performance

The most consistent impact found across all studies reviewed is the amplification of supply voltage unbalance into a much larger stator current unbalance, due to the small negative sequence impedance of induction motors. This current unbalance has cascading effects: first, increased power losses (copper losses) in the stator and rotor windings; second, a rise in winding temperature that under single-phasing conditions can reach a very rapid rate, risking insulation damage; third, oscillations in the torque waveform and motor speed that increase mechanical vibration and can accelerate wear of mechanical components; and fourth, a reduction in the overall efficiency and power factor of the motor. These effects cumulatively shorten the operational life of the motor if the unbalanced condition is allowed to persist for a long period without corrective action.

Mitigation and Protection Strategies

Literature synthesis shows several mitigation strategies that have been tested and recommended to maintain the reliability of three-phase induction motors against current unbalance, including:

1. Real-time voltage and current monitoring based on the Internet of Things (IoT), such as the NETMOTOR system or a wireless sensor network-based monitoring system, as an early detection mechanism for imbalances before they cause damage.
2. Implementation of phase unbalance protection relay and single-phasing protection on the motor control panel, to automatically cut off the supply if the imbalance exceeds the safe threshold.
3. Reduction of motor working capacity (derating) according to the NEMA MG-1 standard curve if the motor must continue to operate under supply voltage conditions that are known to be not completely balanced.
4. Preventive maintenance on the distribution system and supply transformers to ensure that the distribution of single-phase loads remains proportional across the three phases, in order to prevent voltage imbalance on the upstream side of the motor.
5. The use of an auxiliary capacitor with the correct value in motor applications that are forced to operate from a single-phase source, to minimize current unbalance and maintain adequate starting torque at light loads.

These five strategies are complementary: IoT-based monitoring and automatic protection serve as rapid detection and safeguard mechanisms, while derating and preventive maintenance serve as long-term prevention mechanisms against motor degradation due to current imbalance.

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Conclusion

Based on a literature review of seven scientific articles discussing voltage/current unbalance in three-phase induction motors, it can be concluded that a relatively small supply voltage unbalance will be amplified into a much larger stator current unbalance due to the small negative sequence impedance of the induction motor. This current unbalance causes cascading impacts in the form of increased power losses, rising winding temperatures, torque and speed oscillations, increased vibration, and reduced motor efficiency and power factor, which cumulatively accelerate insulation degradation and shorten the motor's operational life. According to NEMA standards, a voltage unbalance above 1% requires attention, and at 5% unbalance the motor requires derating to approximately one-quarter of its nominal capacity. Extreme conditions such as single-phasing faults can cause voltage unbalances of up to 6% accompanied by very rapid temperature increases. The most widely recommended mitigation strategies include IoT-based real-time monitoring, phase and single-phasing unbalance protection, NEMA-compliant motor derating, and preventive maintenance of the supply system. Further research is recommended to conduct empirical validation on specific capacity induction motors by quantitatively comparing the effectiveness of various protection and mitigation schemes.

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