Performance degradation analysis of induction motors using Simulink and hybrid method

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ABSTRACT

Voltage unbalance faults (VUF) have a significant adverse impact on the performance and operational lifespan of induction motors. This paper presents a hybrid method that integrates multi-sensor analysis to evaluate induction motor behavior under different levels of electrical fault conditions. The research methodology comprises the development of a three-phase induction motor model in MATLAB/Simulink, combined with experimental monitoring of current, voltage, rotational speed, acoustic signals, and torque. The collected data are analyzed using linear regression to quantify performance degradation. The results indicate that increasing fault severity correlates with reductions in motor efficiency and operational stability. Furthermore, a hybrid technique incorporating modulation analysis of acoustic signals derived from vibration and resonance is proposed to improve the accuracy of efficiency and loss estimation. This approach outperforms conventional methods and demonstrates strong potential for industrial applications, as it effectively mitigates the negative effects of voltage supply faults.

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1. INTRODUCTION

Induction motors (IMs) are designed to operate under specific electrical conditions indicated on their nameplates, where the rated parameters serve as fundamental indicators of expected performance. Among these parameters, the balance of the supply voltage is particularly critical because even slight deviations can substantially affect the operating characteristics of an IM. Voltage-related issues whether undervoltage, overvoltage, or voltage unbalance, directly influence motor torque, efficiency, heat generation, and mechanical integrity [1]-[5]. Previous studies have shown that voltage imbalance leads not only to increased temperature rise and negative-sequence currents but also induces excessive vibration and accelerates insulation degradation, ultimately shortening motor lifespan. According to ANSI/NEMA MG 1-2011 and IEEE 112, the permissible deviation of voltage applied to an IM should not exceed 5% of its rated value; exceeding this threshold causes notable increases in rotor temperature and intensifies negative-sequence effects [6]-[10].

Significant efforts have been made to investigate voltage unbalance and its impacts on IM performance [8]. Conducted a comprehensive review using the complex voltage unbalance factor (CVUF), demonstrating that the phase-angle component can identify the underlying cause of increased heat generation.

The CVUF method has also been integrated with positive-sequence voltage analysis to evaluate pull-out torque, starting torque, full-load torque, and efficiency. These approaches have additionally been adopted for estimating motor lifetime and losses induced by voltage unbalance, achieving high predictive accuracy. Other researchers [11]-[15] have experimentally developed methods for approximating IM efficiency under voltage unbalance and established the correlation between voltage unbalance factor (VUF) and phase-angle variations, which can be used to diagnose heating phenomena.

Harmonic-based analysis has also gained attention as presented in [16]-[19], where the harmonic loss factor (HLF) is introduced as an indicator correlated with voltage and frequency components. In addition, rotor harmonic studies reported in [20]-[24] reveal that VUF-related harmonics depend on the motor's pole number, rotor slot configuration, and the emergence of new frequency components under unbalanced conditions. Beyond voltage-based diagnostics, a wide range of data-driven techniques has been employed for fault detection, monitoring, classification, and diagnosis using current and vibration signals. Approaches such as the auto-regressive moving average (ARMA) model for stator current analysis, spectral and digital signal processing for vibration assessment, artificial intelligence (AI) methods for transient current and torque estimation, and wavelet-based current signature analysis for mechanical failure identification have collectively contributed to advancing IM fault analysis. Despite these advances, each technique presents specific limitations, and several require further development before large-scale industrial adoption. Based on the gaps identified in the existing literature, this study introduces an improved hybrid technique for evaluating IM efficiency and diagnosing faults under voltage unbalance conditions.

The proposed method integrates simulation and experimental testing to generate comprehensive performance assessments, with the voltage unbalance levels referenced to ANSI/NEMA MG 1-2011 and ISO 2372-1974 standards. The content of this article is as follows: Section 1 outlines the problem and summarizes relevant analytical approaches; Section 2 describes the proposed method; Section 3 presents the methodology and experimental procedures; Section 4 discusses the simulation and experimental results; and the final section provides the conclusions.

2. RELATED WORK

The detection standard for voltage unbalance can be described as the phenomenon as defined by the NEMA standard. This standard calculates the ratio of the maximum voltage deviation to the average line voltage, commonly referred to as the voltage unbalance percentage (VUP), as expressed in (1) and (2).

$$VUP(\%) = \frac{Maximum,Linevoltage(deviation)}{voltage(average)} \times 100 \quad (1)$$

Similarly, the IEEE standard would define the voltage unbalance in terms of the phase voltage as (2).

$$PVU(\%) = \frac{Max[V_a - V_{av}],[V_b - V_{av}],[V_c - V_{av}]}{V_{av}} \times 100 \quad (2)$$

The Park's vector is adopted to use for detecting stator fault and voltage unbalance supply in this work. The concept of obtained transformation from the line current of *abc* into the *qd0* current as presented in (3).

$$T(\theta) = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} cos(\theta) & cos(\theta - 120^{\circ}) & cos(\theta + 120^{\circ}) \\ sin(\theta) & sin(\theta - 120^{\circ}) & cos(\theta + 120^{\circ}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3)$$

Where $\theta = 0$, balance phase of supply, which zero component of *qd0* current become zero. Also, park vector components, i_{ds} and i_{qs} are given by (4).

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{6}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \quad (4)$$

Where i_{ds} and i_{qs} represent the direct and quadrature axis. This component is required to yield a unique transformation of the three phase stator quantities.

3. METHOD

This section outlines the methodology using both simulation and experimental approaches. The simulation model developed for this study was implemented in MATLAB/Simulink, as illustrated in Figure 1. The model represents the dynamic behavior of a three-phase induction motor under varying voltage-unbalance fault conditions.

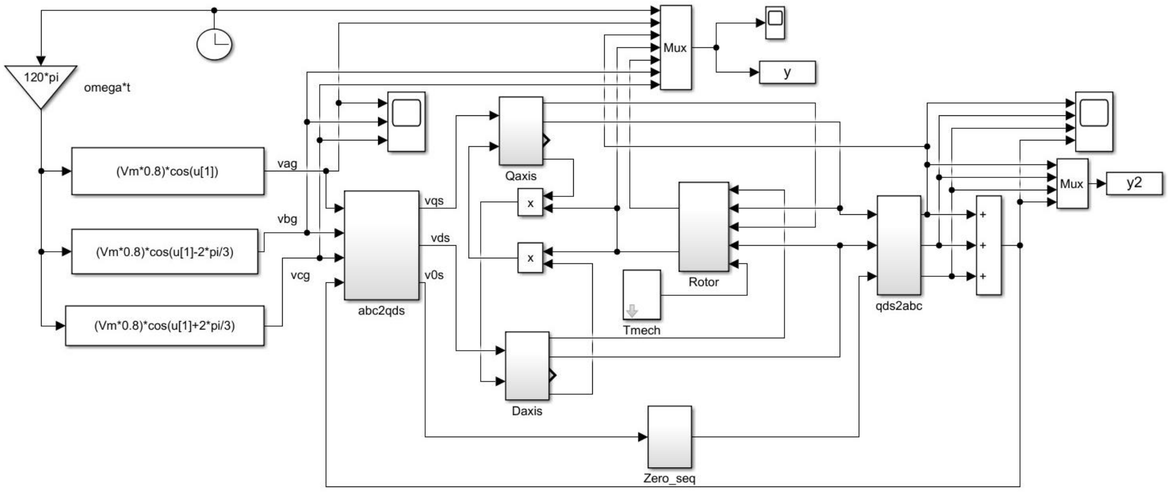

Figure 1. Simulink diagram of induction motor fault case voltage unbalance

The simulation model corresponds to the experimental setup, with detailed parameters of the induction motor and sensors, which include current, voltage, torque, speed, vibration, and acoustic sound. The parameters investigated include isolated current measurement (±20 A) and isolated voltage measurement (10 A:1 V), as well as the induction motor specifications. Further details are provided in Tables 1 and 2.

Table 1. Parameter of induction motor

Parameter	Values
Power rated	370 W
Voltage rated	380 V
Current rated	0.3 A
Speed rated	1500 rpm
Electromagnetic break	0.4 kW

Table 2. Parameter of sensors

Parameter	Values
Current isolated measuring	±20 A, 10 A: 1 V,
Torque-speed instrument	50 Nm, 6000 rpm
Vibration	Frequency range 10Hz – 1 kHz, the sensitivity relative meet ISO 2954 Measurement range is 30 to 130 dB
Sound	Accuracy up to ±1.5 dB, IEC PUB 651 TYPE2 standard
Oscilloscope	Real time sampling rate 2GSa/s

Figure 2 illustrates an individual experimental device setup for the three-phase IM under different VUF condition. The experiment set included a three-phase IM 380 V, 50 Hz, load motor, a detection sensor with voltage and current isolation max 10 A, a vibration sensor with frequency range of 10 Hz-1 kHz, an acoustic sound sensor with a range of 30-130 dB, a power supply for voltage adjustment of 0-380 V, and an oscilloscope. The experiment procedures are as the following steps.

i) Step 1: Create situation with different VUF in term of percentage (% VUF) by adjusting voltage power supply voltage unbalance at 5%, 10%, 15% and 20%.
ii) Step 2: Take load torque at 50% medium load for observing the parameters related and behavior of the IM.

iii) Step: 3 Record and store the parameters related for analysis and estimation an effect of VUF such as the voltage, current, torque, speed, vibration, and sound.
iv) Step 4: Analyze and interpret interpretation the obtained results from the experiment (steps 1-3) using MATLAB programming transformed to waveform graph, and analyze using linear regression statistic.
v) Step 5: Create an equation obtained from the experimental results (steps 3-4) for evaluating performance under the effect of various VUF conditions.
vi) Step 6: Discuss and summarize the proposed method for estimating efficiency of IM under VUF conditions.

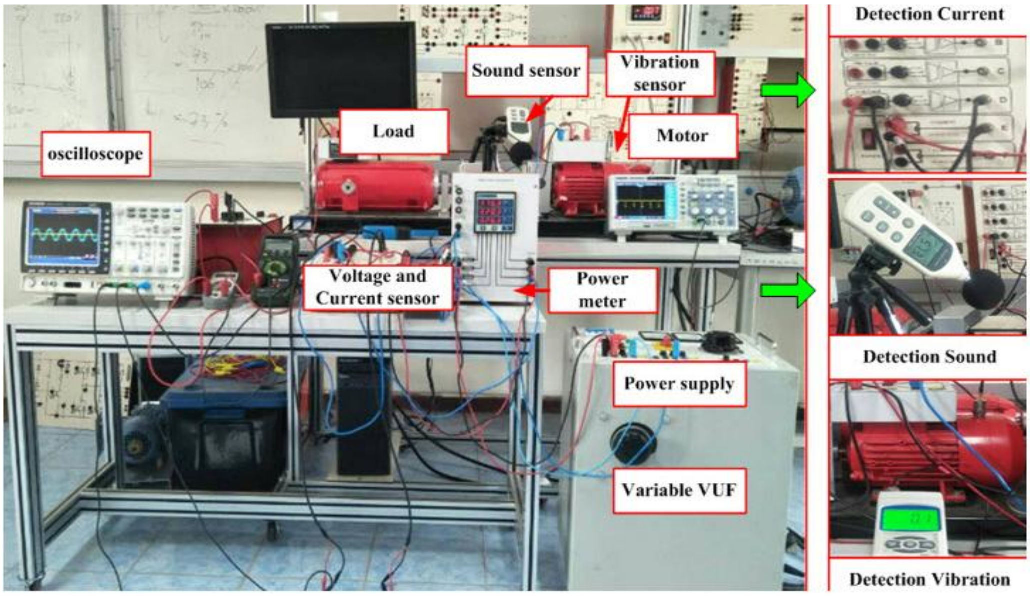

Figure 2. Experimental setup of induction motor fault

4. RESULTS AND DISCUSSION

In this section it is the experimental results under VUF conditions are analyzed and discussed. The evaluated parameters include total harmonic distortion (THD) of voltage, current, torque, rotor speed, vibration, and acoustic sound, with comparisons made between normal and faulted operating conditions. Table 3 presents the results and the analysis method based on the park vector, as defined in (4). The variables examined include torque, rotor speed, vibration, and sound. The voltage-unbalance level was adjusted to four settings (5%, 10%, 15%, and 20%), resulting in increases in current, torque, THD, vibration, and sound as VUF increased, whereas the rotor speed decreased.

4.1. Experimental and simulation results

This section presents the experimental results of the induction motor (IM) under different VUF levels. The key electrical and mechanical responses current, torque, rotor speed, vibration, acoustic sound, and voltage distortion summarized in Table 3 were measured to evaluate the impact of ΔVUF on motor performance. The results highlight how increasing VUF influences these parameters and supports their use for fault detection and condition monitoring.

Figure 3 shows torque signal obtained from the simulation under VUF conditions when the supply voltage was reduced by 5%. As shown in Figure 3(a), the torque waveform remains smooth, exhibiting only minor fluctuations at the transition point, which corresponds to the normal operating state of the induction motor (IM). This behavior is consistent with findings in the literature, which indicate that voltage unbalance causes limited disturbance to the electromagnetic torque profile. In contrast, Figure 3(b) illustrates the fault condition, where noticeable oscillations appear in the torque waveform between 3-5 seconds. These oscillations are characteristic of the negative-sequence components induced by VUF, which generate torque pulsations and mechanical instability in the IM. The increased oscillatory behavior verifies the sensitivity of the torque response to unbalanced supply voltage and highlights its usefulness as an early diagnostic indicator of VUF-related faults. Figure 4 shows the rotor speed signals under normal conditions and under a 5% voltage unbalance fault (ΔVUF). The variations in the waveform clearly distinguish the rotor speed in normal operation from that in fault conditions.

Table 3. The experimental results of induction motor faults

VUF	Iq	Id	T_e (Nm)	Speed (rpm)	Vibration (mm/s)	Sound (dB)	THD (%)
0%	0.046	0.125	0.4686	1499	0.4	40.2	0.05
5%	0.972	1.186	3.454	1494	5.5	82.4	13.24
10%	3.080	1.236	6.483	1489	5.9	102.1	17.64
15%	3.847	2.506	9.303	1484	6.1	103.3	21.24
20%	4.172	4.469	12.01	1479	6.2	104.5	25.96

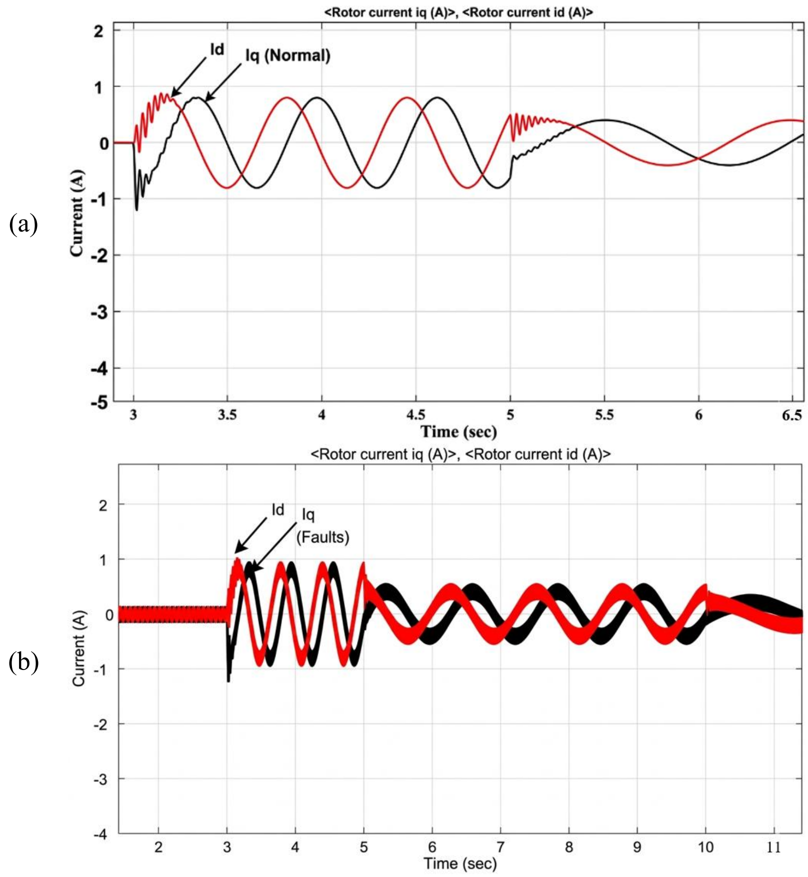

Figure 3. Torque signal: (a) normal and (b) fault condition

Figure 5 presents the acoustic signals measured under load conditions for VUF levels ranging from 5% to 20%. The experiment was performed at a medium-load operating point to examine how increasing voltage unbalance influences the acoustic characteristics of the induction motor (IM). Acoustic measurements are widely recognized as an effective indicator of electromagnetic and mechanical disturbances in IMs, and several studies have shown that VUF increases torque pulsations, vibration, and airflow noise, which directly alter the recorded sound patterns. These relationships are reflected in the measured signals of Figure 5, where the sound amplitude and spectral components vary proportionally with the severity of VUF.

The experimental results were analyzed and were then interpreted. The linear regression statistic is used to analyze the correlation of the parameters studied between the ΔVUF and signal detection. Table 4 presents the experimental results, which were then analyzed and interpreted. The linear regression statistic was used to analyze the correlation of the parameters studied between the ΔVUF and signal detection.

Table 4. The calculation results of induction motor efficiency

Parameter	Intercept		Slope		Statistic
	Value	SD	Value	SD	R^2
Current (Iq)	0.198	0.422	0.222	0.0345	0.910
Current (Id)	0.097	0.458	0.200	0.037	0.873
Torque (Nm)	0.557	0.096	0.578	0.007	0.955*
Vibration (mm/s)	2.38	1.401	0.244	0.114	0.469
Sound (dB)	56.6	12.450	2.99	1.016	0.656
THD (%)	3.734	2.613	1.192	0.213	0.883

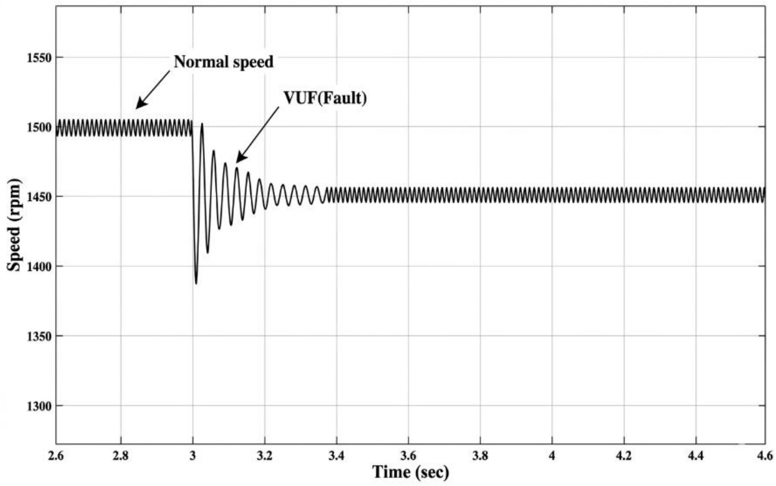

Figure 4. Rotor speed signal on load at VUF 5%

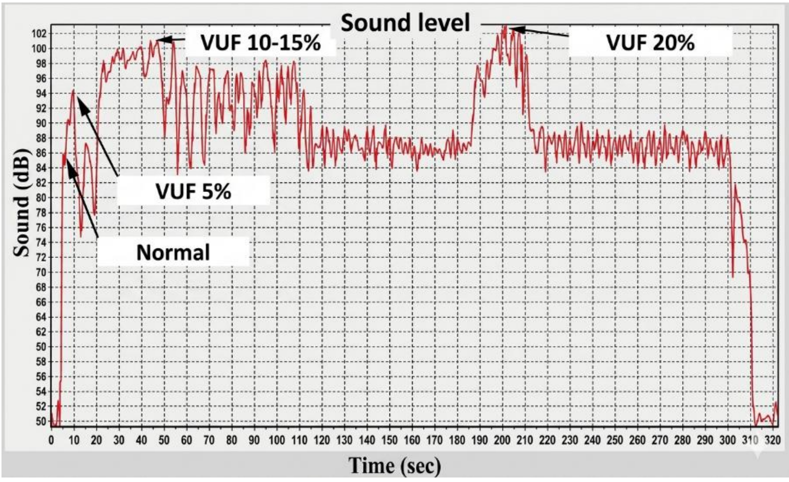

Figure 5. Acoustic signals under medium-load operation with VUF

From a statistical relationship analysis result by using linear regression, it was found that the torque was most significantly associated with the difference of ΔVUF, torque (T_e = 0.955*). Therefore, the oscillation torque value can be used to create the motor efficiency index equation as (5).

$$P_{stayloss} = aT_e{}^2 + b \tag{5}$$

Where $P_{stayloss}$ is the stay load loss, in W, T_e is the torque in Nm., a is the slope, b is the intercept.

$$\eta = \frac{P_{in} - P_{stayloss}}{P_{in}} \times 100 \tag{6}$$

Where η is the efficiency estimation, P_{in} is the power input from nameplate motor, in Watt, $P_{Stayloss}$ is the stay loss. Table 5 shows the efficiency calculation with different ΔVUF. Namely, VUF effects the harmonic magnetic fields.

Based on the regression analysis using the data from Table 5, the results show a strong linear relationship between the VUF% and key motor performance parameters. As observed, the efficiency decreases almost linearly with VUF, following the equation $\eta = -1.98x + 104.8$, which indicates a reduction of approximately 1.98% efficiency for every 1% increase in VUF. This decline corresponds to increased heating and current unbalance within the stator windings. Conversely, the electromagnetic torque (T_e) increases linearly according to $T_e = 0.5786x + 0.5574$, showing that torque pulsations become more pronounced under unbalanced supply conditions. The input power (P_{in}) remains constant at 370 W, as recorded in Table 5, confirming that the tests were conducted at a fixed input supply. However, the stray losses (P_{loss}) increase sharply with VUF $y = 7.3921x - 20.7076$, indicating severe magnetic distortion and thermal stress. Overall, Table 5 highlights that voltage unbalance significantly degrades motor efficiency due to increased stray losses and torque irregularities, emphasizing the importance of maintaining VUF below acceptable limits for reliable operation.

Table 5. The calculation results of induction motor efficiency

VUF (%)	T_e (Nm)	P_{in} (W)	$P_{Stayloss}$ (W)	Efficiency (%)
0%	0.4686	370	0.684	99
5%	3.454	370	7.458	97
10%	6.483	370	24.869	93
15%	9.303	370	87.681	76
20%	12.01	370	145.375	60

4.2. Discussions

The obtained results are presented in graphical form to facilitate clear interpretation and discussion. The findings demonstrate a strong relationship between the voltage-unbalance factor and several key performance parameters of the induction motor, including current, torque, rotor speed, vibration, acoustic sound, and voltage distortion [25]. As ΔVUF increases, the distribution of phase voltages becomes increasingly asymmetric, producing negative-sequence components that lead to higher current imbalance, torque pulsation, mechanical vibration, and acoustic noise. These effects collectively reflect the degradation of motor performance and provide meaningful indicators for assessing the severity of voltage-unbalance conditions [26].

Figures 6(a) and 6(b) present the current in stator and rotor with ΔVUF and magnetic flux in the air gap is in unbalance condition. It influences the current in I_d and I_q increases. The I_q has relation with ΔVUF. Similarly, the %THD has increased and indicated the ripple current waveform.

Figures 6(c) and 6(d) present the ΔVUF, which effected with slip speed (different synchronous speed and rotor speed), resulting in decreased a rotor speed and more severe as the change in supply voltage and load increase, which is clearly shown as in Figure 6. On the other hand, the torque increases due to a decrease in %VUF, the oscillation of the torque signal causes the current rises. This can be calculated by the (2)-(5). In addition, the signal effect is expressed the torque's oscillation as in Figure 6(b).

Figures 6(e) and 6(f) present the ΔVUF curves, which cause resonance oscillation vibration and noise sound. VUF induces magnetic flux formation in the air chamber asymmetric, gap non uniform that Δ VUF ~ Δ mmf ~ Δ T_e, resulting in resonance of vibration (mm/s) and noise (dB). This effect causes the losses, which are written by (5) and (6).

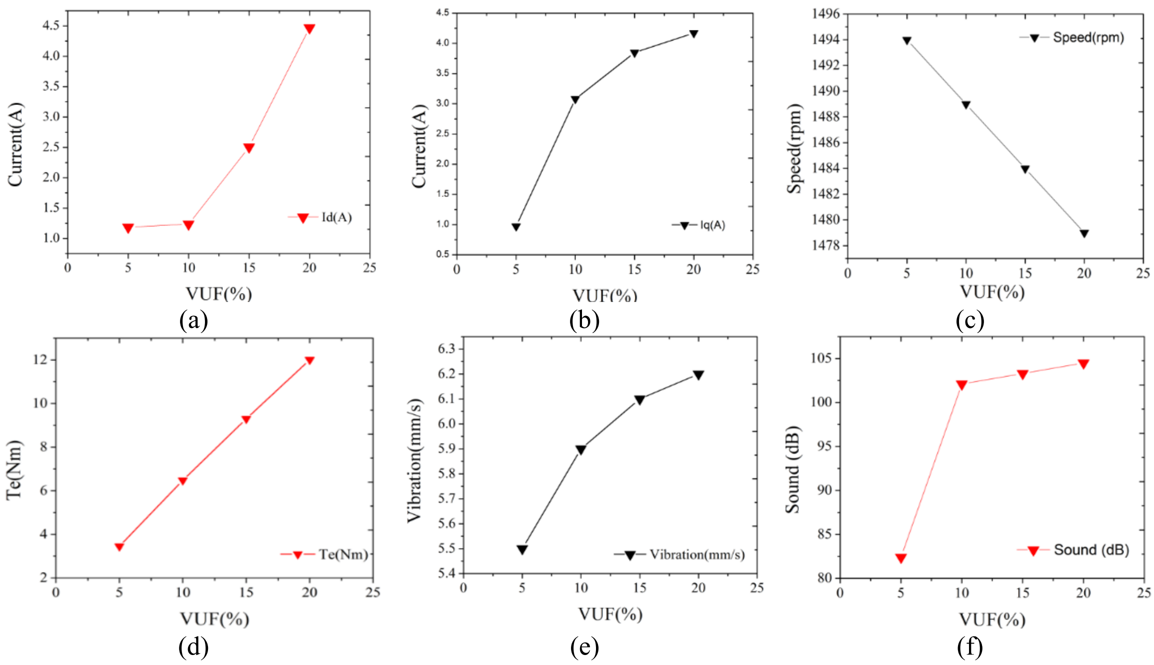

Figure 6. Relationship between the effects of voltage unbalance and key parameters: (a) current I_d, (b) current I_q, (c) speed, (d) torque, (e) vibration, and (f) acoustic signals

The relationship of Δ VUF in a stator current is translated into torque harmonics form in the air gap between the stator and rotor. This phenomenon, it becomes resonance vibration and sound acoustic noise. Moreover, ΔVUF causes high temperature in motor. Eventually, leading to performance degradation [27]-[30].

5. CONCLUSION

This paper analyzed the performance and efficiency of a three-phase induction motor under voltage unbalance fault conditions using both simulation and experimental. The findings confirm that increasing VUF leads to a significant reduction in motor efficiency, while torque fluctuation, stray losses, and thermal stress increase correspondingly. When the unbalance exceeded approximately 3–5%, the motor exhibited higher vibration levels and acoustic noise, indicating mechanical resonance and electromagnetic distortion. These results are report that voltage asymmetry and harmonic effects contribute to reduced efficiency, torque pulsation, and premature component degradation in induction motors.

The propose demonstrates that maintaining balanced voltage conditions is critical to ensure efficient and reliable operation. However, the present analysis is limited by its linear modeling approach, fixed input power conditions, and the absence of detailed harmonic and thermal mapping. Future work should address these limitations by applying nonlinear or AI-based modeling, adaptive control strategies, and real-time monitoring systems to automatically detect and compensate for unbalanced voltages. Such developments would enhance fault tolerance, extend motor lifespan, and support the long-term stability of industrial power systems in Thailand.

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AUTHOR CONTRIBUTIONS STATEMENT

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Natchanun Prainetr	✓	✓	✓		✓			✓	✓					
Supachai Prainetr	✓	✓		✓	✓	✓			✓	✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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