Fault Detection in a Three-Phase Squirrel-Cage Induction Motor Using Voltage Unbalance, Torque Overload, and Braking Torque Cases Simscape Electrical Simulation with Machine Learning Classification

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***Abstract*— Three-phase squirrel-cage induction motors are widely used due to robustness and low maintenance, yet they remain sensitive to electrical and mechanical abnormalities such as supply voltage unbalance and torque disturbances. This work presents a simulation-driven fault detection pipeline that models four operating conditions: healthy operation, voltage unbalance, positive torque overload, and negative (braking) torque. A Simscape Electrical motor model is used to generate labelled operating data by inducing faults through phase voltage magnitude perturbations and mechanical load-torque sign/magnitude changes. From logged currents, speed, torque, and slip, a feature dataset is formed using sliding windows and statistical descriptors, including a current unbalance index. Classical machine learning models are compared, and a Random Forest classifier provides the best overall performance.**

Keywords— Induction motor, squirrel-cage, Simscape Electrical, voltage unbalance, overload, braking torque, slip, feature extraction, Random Forest, fault classification.

I. INTRODUCTION

Induction motors drive a large fraction of industrial loads (pumps, compressors, conveyors) due to simple construction, low cost, and reliability. However, abnormal electrical supply conditions and mechanical loading can increase losses, heating, and torque pulsations, reducing lifetime. This project develops an end-to-end **simulation-to-ML** workflow:

- Build a physics-based induction motor model in Simscape Electrical (MATLAB/Simulink R2025b).
- Inject electrical and mechanical fault cases using controllable parameters.
- Log motor signals and extract diagnostic features using windowing.
- Train and compare machine learning models in a Python Jupyter Notebook.

[1]

II. MOTOR CONSTRUCTION AND WORKING PRINCIPLE

A. Construction

A squirrel-cage induction motor consists of a three-phase stator winding that produces a rotating magnetic field and a rotor formed by conductive bars shorted with end rings. Rotor currents are induced due to the relative motion between the rotor and the rotating stator field.

B. Synchronous Speed and Slip

For supply frequency f and pole pairs p, the synchronous mechanical speed is

$$\omega_s = \frac{2\pi f}{p}. \tag{1}$$

With rotor mechanical speed ω_r, slip is

$$s = \frac{\omega_s - \omega_r}{\omega_s}. \tag{2}$$

In normal motoring, $0 < s \ll 1$. During braking/generating, slip can become negative depending on the operating point.

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[1]Modeling approach and starting-circuit concepts were implemented using standard Simscape Electrical blocks; the structure was inspired by MATLAB/Simulink R2025b documentation examples.

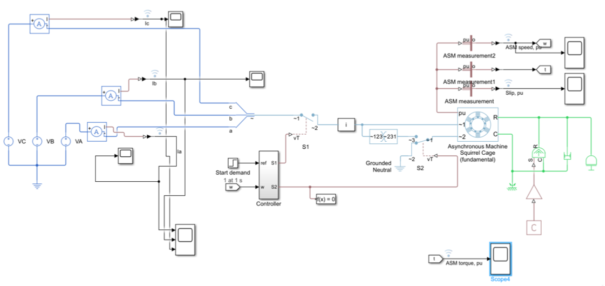

Fig. 1. Simscape Electrical induction motor model for dataset generation and fault injection.

III. Simulation Model in Simscape Electrical

A. *Overall Structure and Measured Signals*

The motor is modeled using Simscape Electrical machine blocks. Electrical terminals are fed by three-phase sources, and the shaft is connected to a rotational mechanical load network. Logged signals are: I_a, I_b, I_c, speed (pu), electromagnetic torque (pu), and slip (pu).

B. *Wye–Delta Starting Operation (Working Operation)*

A wye–delta starting strategy reduces inrush current:

- When the supply is applied through switch $S1$, switch $S2$ is initially OFF, resulting in a **wye (star)** connection.
- Once the motor is close to synchronous speed, $S2$ is operated to reconnect the machine in **delta**.
- The higher impedance seen by the supply in wye reduces starting current and causes less disturbance to other connected loads.

[2]

IV. Fault Injection Methodology and Operating Cases

All cases start from rest, and a torque step is applied at $t = 1\,\mathrm{s}$ to separate start-up dynamics from loaded behavior.

[2]This is standard star–delta starting behavior; the implementation approach was inspired by Simscape Electrical examples in MATLAB/Simulink R2025b.

A. *Electrical Fault: Voltage Unbalance*

Voltage unbalance is created by perturbing phase RMS magnitudes around a nominal V_{phase}:

$$\begin{aligned} V_a &= V_{\text{phase}}(1+\Delta_A), \\ V_b &= V_{\text{phase}}(1+\Delta_B), \\ V_c &= V_{\text{phase}}(1+\Delta_C). \end{aligned} \tag{3}$$

Healthy operation uses $\Delta_A \approx \Delta_B \approx \Delta_C \approx 0$. The unbalance fault reduces one phase by 10–35%:

$$\Delta_{\text{sel}} \in [-0.35, -0.10], \quad \Delta_{\text{others}} \approx 0. \tag{4}$$

This produces unequal phase currents and increased torque pulsations due to negative-sequence effects. [3]

B. *Mechanical Faults: Overload and Braking Torque (Load Network Details)*

Mechanical faults are induced using the rotational mechanical network connected to the machine:

- **Port R**: rotor mechanical shaft port.
- **Port C**: casing (housing) port.

Why Port C is connected to Mechanical Reference: the casing is assumed fixed; connecting C to the *Rotational Mechanical Reference* defines an absolute zero-speed reference and closes the mechanical network. [4]

Load components and purpose:

- **Rotational Inertia**: models combined inertia; determines acceleration/deceleration.
- **Rotational Damper**: models viscous friction/damping; reduces oscillations.
- **Ideal Torque Source**: applies commanded load torque on the shaft.
- **PS Constant + PS Gain**: provides adjustable torque magnitude and sign.

A base torque T_{BASE} is set by PS Constant, and scaled using PS Gain:

$$T_{\text{load}} = T_{\text{BASE}} \cdot T_{\text{FACTOR}}. \tag{5}$$

Overload uses $T_{\text{FACTOR}} > 1$; braking uses $T_{\text{FACTOR}} < 0$.

[3]Background: voltage unbalance introduces negative-sequence components that increase heating and torque ripple; this is widely reported in induction motor power quality literature.

[4]This connection is consistent with Simscape rotational mechanics requirements and is described in MATLAB/Simulink R2025b documentation.

C. Class 0: Healthy Operation (Balanced Supply, Nominal Load)

Balanced voltages and nominal torque load produce nearly equal RMS currents in all phases. Speed rises and settles; slip becomes a small positive steady value; torque settles to match load demand.

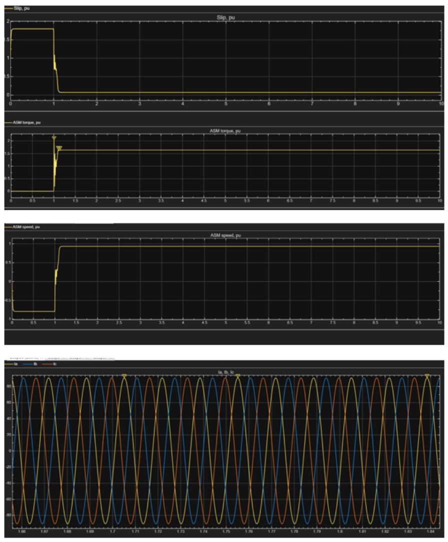

Fig. 2. Healthy operation waveforms (currents/speed/torque/slip).

D. Class 1: Voltage Unbalance Fault (How It Is Induced + Waveforms)

One phase RMS voltage is reduced via $(V_{\text{phase}}, \Delta_A, \Delta_B, \Delta_C)$ while maintaining the same mechanical load as the healthy case. The motor may reach a similar average speed, but the phase currents become unbalanced and the unbalance index increases. Fault induction and waveforms generated is shown in Fig. 3.

E. Class 2: Positive Torque Overload (How It Is Induced + Waveforms)

Overload is induced by increasing the applied load torque using the torque scaling factor $T_{\text{FACTOR}} > 1$. The motor settles at a lower speed with higher steady slip and increased current magnitude, as electromagnetic torque rises to match the new load. Fault induction and waveforms generated is shown in Fig. 4.

F. Class 3: Braking Torque (How It Is Induced + Waveforms)

Braking is induced by applying negative load torque ($T_{\text{FACTOR}} < 0$). This produces a distinct speed trajectory and torque behavior compared to motoring cases, and can push operation toward braking/generating depending on severity. Fault induction and waveforms generated is shown in Fig. 5.

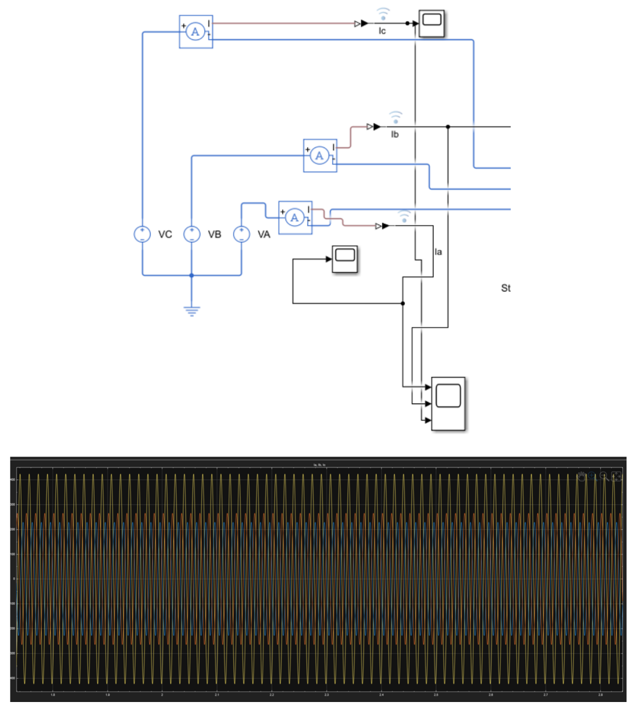

Fig. 3. Voltage unbalance fault: (top) block-level implementation using V_{phase} and $\Delta_A, \Delta_B, \Delta_C$; (bottom) representative waveforms showing unequal phase current magnitudes.

V. Dataset Collection and Feature Extraction

A. Data Collection from Simulation

For each class, multiple simulation runs are executed with randomized parameter values (e.g., voltage reduction level or torque scaling factor). Signals are logged after the load step; early start-up transients are discarded (e.g., data before $t \approx 1.2\,\text{s}$). Each run is labelled by its operating class.

B. Windowing

To obtain many labeled samples, a sliding window is used:

- Window length: $0.2\,\text{s}$
- Hop size: $0.1\,\text{s}$

C. Extracted Features

For each window, features are computed:

- RMS currents: $I_{a,\text{rms}}, I_{b,\text{rms}}, I_{c,\text{rms}}$

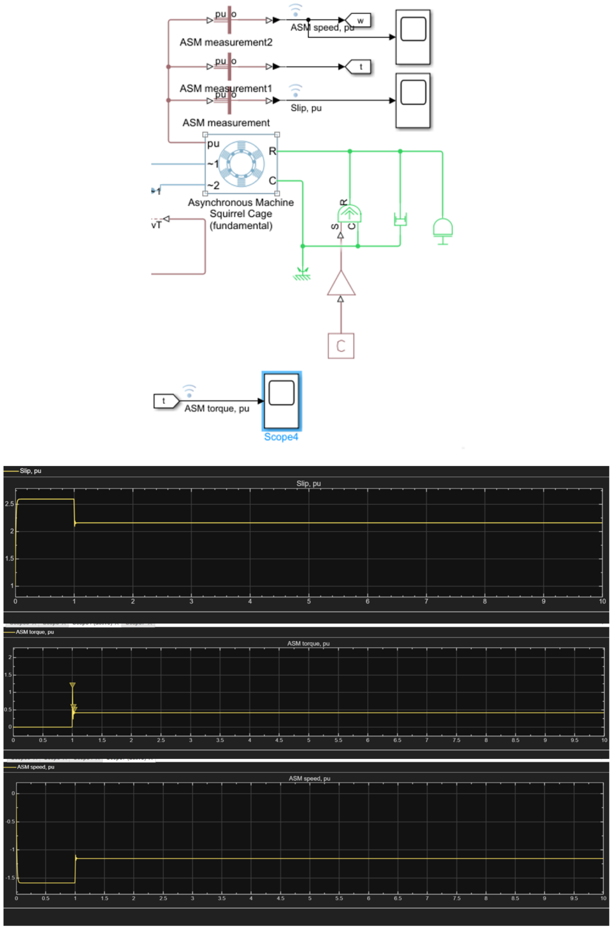

Fig. 4. Overload fault: (top) torque-source scaling implementation ($T_{\text{FACTOR}} > 1$); (bottom) representative waveforms showing increased torque demand and reduced steady speed.

- Current unbalance index:

$$UI = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{avg}}} \tag{6}$$

- Mean and standard deviation of speed, electromagnetic torque, and slip

VI. Machine Learning in Python (Jupyter Notebook)

A. Pipeline

Machine learning is implemented in Python (Jupyter Notebook):

1) Load feature matrix X and labels y.
2) Standardize features (zero mean, unit variance).
3) Train/test split (stratified).
4) Train models and evaluate with accuracy and confusion matrix.

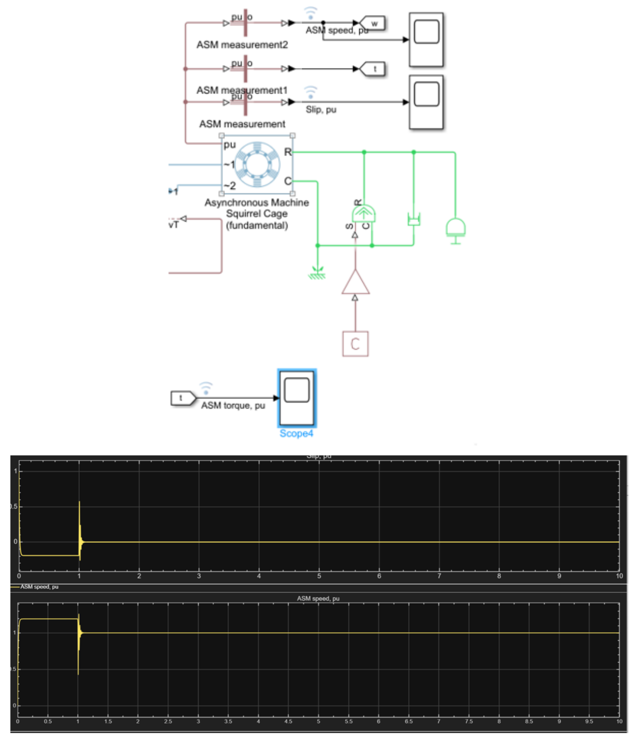

Fig. 5. Braking fault: (top) negative torque scaling implementation ($T_{\text{FACTOR}} < 0$); (bottom) representative waveforms showing distinct speed and torque response.

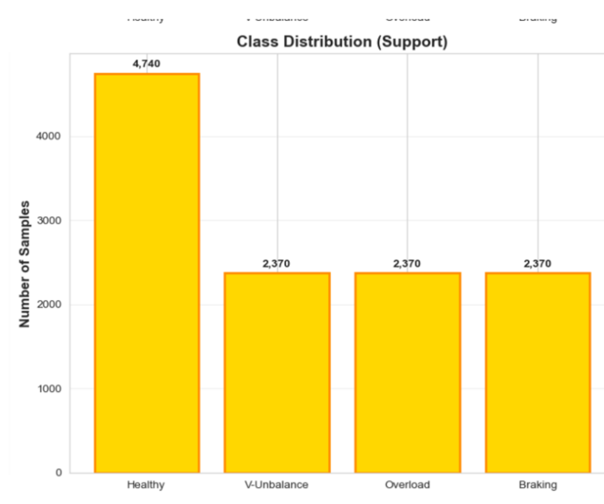

Fig. 6. Class distribution of the generated dataset windows.

B. Models Tested and Tabulated Performance

The following models were tested sequentially:

- **SVM (RBF):** baseline, observed accuracy $\approx 82\%$.
- **Decision Tree:** improved non-linear separation and interpretability.
- **Random Forest:** best overall performance and robustness.

TABLE I

MODEL COMPARISON ON HELD-OUT TEST DATA.

Model	Accuracy
SVM (RBF)	82%
Decision Tree	92.4%
Random Forest	99.3%

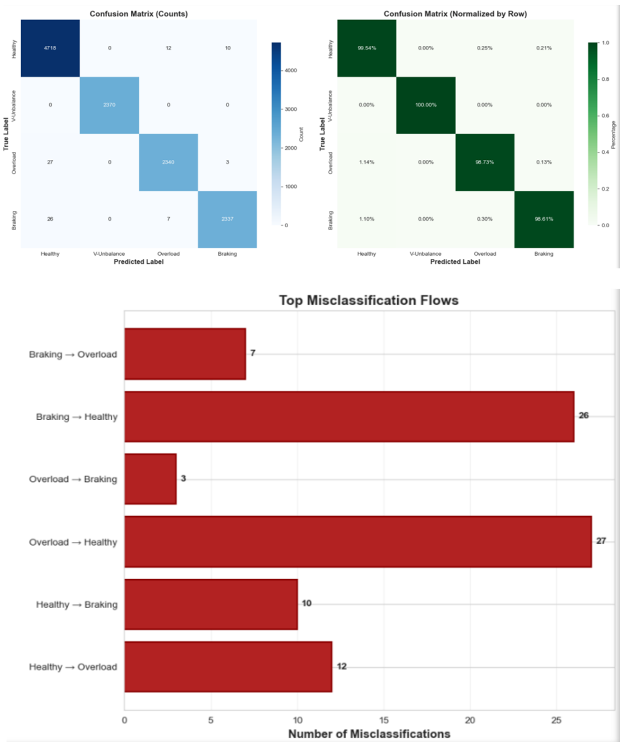

Fig. 7. Model evaluation: (top) Random Forest confusion matrix; (bottom) misclassification analysis (errors mainly between torque-related cases).

C. Random Forest Detailed Results

Random Forest achieves the strongest results because it captures feature interactions (e.g., current unbalance index with torque/speed statistics) and generalizes well under randomized simulation parameters. Voltage unbalance is particularly separable due to strong phase current asymmetry; remaining errors are typically between torque-related classes in windows near transients.

VII. DISCUSSION AND CURRENT RESEARCH DIRECTIONS

Current research in induction motor fault diagnosis includes: (i) using simulation-driven learning when real fault data is scarce, (ii) deep learning models (1D CNN/TCN) on raw current signatures, (iii) robustness to sensor noise and parameter mismatch, (iv) multi-fault severity estimation, and (v) lightweight edge deployment for online monitoring. [5]

VIII. LIMITATIONS AND FUTURE WORK

This work is simulation-based and uses idealized load characteristics and limited fault types. Future work includes adding noise and uncertainty, expanding faults (single-phasing, bearing faults, broken rotor bars, stator inter-turn shorts), testing time-series deep learning, and validating on laboratory measurements.

IX. CONCLUSION

A complete simulation-to-ML pipeline for induction motor fault classification was developed using Simscape Electrical modeling (MATLAB/Simulink R2025b) and Python-based machine learning in a Jupyter Notebook. Faults were induced through phase voltage perturbations (V_{phase} with $\Delta_A, \Delta_B, \Delta_C$) and mechanical torque sign/magnitude manipulation via a rotational mechanical network (inertia, damper, torque source, and reference). Feature engineering using RMS currents, current unbalance index, and speed/torque/slip statistics enabled accurate classification. Among tested models, Random Forest achieved the best results (about 99.3% accuracy).

REFERENCES

- MATLAB/Simulink R2025b Documentation (Simscape Electrical): Three-Phase Asynchronous Machine Starting (Wye–Delta) example (used as inspiration).
- MATLAB/Simulink R2025b Documentation (Simscape Electrical): Asynchronous Machine (Squirrel-Cage) block documentation (ports, measurements, and mechanical connections).
- Standard induction motor power quality literature: voltage unbalance effects (negative-sequence currents, heating, torque ripple).
- R. Raja Singh, G. Bhatti, D. Kalel, I. Vairavasundaram, and F. Alsaif, "Building a Digital Twin Powered Intelligent Predictive Maintenance System for Industrial AC Machines,"

[5] These directions are commonly reported in modern motor condition monitoring surveys and application-driven research in predictive maintenance.

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- Y. Chen, L. Zhao, L. Li, K. Liu, and C. Ye, “Digital Twin-Based Online Diagnosis Method for Inter-Turn Short Circuit Fault in Stator Windings of Induction Motors,” *Energies*, vol. 18, no. 12, Art. no. 3063, 2025. DOI: 10.3390/en18123063.