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Abstract. Non-invasive monitoring by measuring the external magnetic field of synchronous machines has emerged as an effective complementary diagnostic approach for early detection of electromagnetic and mechanical faults. This paper proposes improvements to diagnostic methodology based on an optimized sensor arrangement, enhanced signal-processing chain and a compact diagnostic index derived from harmonic content of the measured external magnetic flux density. Experimental validation was performed on an industrial synchronous motor under normal operation and under intentionally introduced faults (inter-turn short, partial demagnetization, rotor eccentricity). Measured field time-series were processed by band-limited filtering, FFT and wavelet analysis. A diagnostic coefficient $K_d = A_{2f}/A_{1f}$ (ratio of second harmonic amplitude to fundamental) is proposed with threshold ranges for reliable classification. Results indicate that the proposed method reliably distinguishes fault types and detects early-stage electromagnetic asymmetries, increasing detection sensitivity compared to baseline current-spectrum analysis. Practical integration issues and recommendations for industrial implementation are discussed.

INTRODUCTION

Synchronous motors are widely used in industry due to their high efficiency and stable speed regulation in demanding drives (pumps, compressors, mills). Ensuring reliability and minimizing unplanned downtime require accurate condition monitoring and timely detection of faults in stator and rotor assemblies. Traditional diagnostic modalities include current spectral analysis, vibration monitoring, temperature monitoring and insulation testing; however, these approaches may have limited sensitivity to some early electromagnetic defects or require offline testing and partial disassembly [1, 2].

Non-invasive magnetic field monitoring - recording the time-varying magnetic flux density just outside the machine frame - offers a way to detect internal electromagnetic asymmetries and certain mechanical faults without direct access to windings or internal sensors. Changes in the internal flux distribution, e.g., due to inter-turn short circuits, partial demagnetization or eccentricity, are reflected in the external field and produce characteristic harmonic signatures that can be exploited for diagnosis. Recent works demonstrate practical algorithms for real-time condition monitoring and fault detection from magnetic field measurements, including FFT-based and time-frequency (wavelet) methods, and emphasize the potential for online, non-intrusive detection [3, 4].

Nevertheless, practical deployment requires improvements in sensor arrangement, noise suppression, signal processing and fault classification thresholds that are robust across operating loads and industrial noise backgrounds. This paper proposes and experimentally validates a practical, reproducible diagnostic workflow that combines optimized peripheral sensor placement, robust pre-filtering, harmonic and wavelet analysis, and a simple diagnostic coefficient K_d for automated classification. The experimental results and comparison to model simulation are presented below [5, 6].

Measuring external or leakage magnetic fields for machine diagnostics has been the subject of increasing research interest in recent years. Approaches differ by sensor type (search coils, Hall sensors, fluxgate magnetometers), sensor placement (air-gap perimeter, stator frame, end-shield), signal conditioning (bandpass filtering, derivative measurements), and analysis method (FFT, wavelet, statistical processing, ML classification). Several recent studies

have demonstrated that second-order harmonics, zero-sequence magnetic field density and other harmonic components provide strong signatures of specific faults such as partial demagnetization and inter-turn short circuits. Sensor design and optimization and advanced signal-processing (including wavelets and statistical processing) were also shown to materially improve robustness of detection in operating conditions [7-10].

Key lessons from the literature that guided our experimental design are:

- Use a distributed ring (multiple sensors around the stator perimeter) to capture spatial variations and reduce ambiguity arising from local disturbances.

- Apply digital filtering and derivative-based processing to suppress industrial electromagnetic noise while preserving the harmonic bands of interest.

- Combine FFT (to detect stable harmonic components) and wavelet or time-frequency analysis (to detect transient or intermittent faults) for best sensitivity.

EXPERIMENTAL RESEARCH

The experimental research aims to:

1. Validate that external magnetic field measurements detect and distinguish several common faults in synchronous motors (inter-turn short, partial demagnetization, rotor eccentricity).

2. Quantify sensitivity and repeatability of field-based diagnostics under realistic load conditions.

3. Propose and evaluate a compact diagnostic index and threshold ranges that enable automated condition classification.

A three-phase salient-pole synchronous motor rated 160 kW, 1500 rpm and 6 kV nominal voltage installed on a laboratory testbench was used. The motor was coupled to a controllable load bank allowing testing at no-load, 50% and 100% rated mechanical load. The motor had accessible stator end-shields to permit sensor mounting around the external frame.

An array of eight search-coil (inductive) sensors and an alternative set of Hall-effect probes were used to compare sensitivity. Inductive search coils have advantage for measuring time-varying components (and inherently reject DC drifts), while Hall probes provide absolute field values and are useful for low-frequency components. Sensor nominal ranges were selected to comfortably cover expected flux densities (up to a few mT). Sensor signals were conditioned by low-noise preamplifiers and digitized using a NI USB-6211 A/D module (16-bit, 250 kS/s aggregate), fed to MATLAB/Simulink Real-Time environment for recording and real-time processing.

Sensor positions: sensors were installed evenly around the motor frame at 45° angular intervals and mounted ~10–20 mm from the frame surface to balance signal strength and mechanical safety. This ring geometry allows capturing spatial harmonics and helps distinguish local disturbances from global asymmetries [11-15].

The following test cases were executed:

- Baseline (healthy): motor in standard serviceable condition. Measurements at no-load and 100% load.

- Inter-turn short (stator): artificially created partial inter-turn short in one stator phase (approximately 5% of turns shorted in a localized slot).

- Partial demagnetization (rotor): simulated demagnetization of one rotor pole area to reduce local flux by ~15% (using controlled heating of magnet segment in PM machines or shunting field winding segment in wound-field rotor) [16-18].

- Rotor eccentricity: induced static eccentricity by offsetting rotor by ~0.3 mm from nominal axis (mechanical shim introduced).

Each condition was recorded for 60 s of steady operation at each load condition and repeated three times to assess repeatability.

Raw sensor signals $B_k(t)$o (k = 1..8 sensors) underwent the following processing:

1. Anti-aliasing analog filtering (hardware) and 5th-order digital Butterworth low-pass filtering with cutoff f_c=200 Hz to remove high-frequency electromagnetic interference unrelated to machine fundamental and low harmonics.

2. Baseline subtraction and calibration to convert volts → mT (for Hall probes) or V → mT equivalent (for search coils).

3. Synchronous averaging across revolutions when speed jitter was small; otherwise, tachometer gating was used to segment data per electrical cycle [19, 20].

4. FFT (windowed, Hanning, block size 16k) to obtain amplitude spectra up to the chosen Nyquist limit.

5. Wavelet packet decomposition for time-frequency analysis of transient signatures.

6. Computation of diagnostic indices, notably $K_d = A2f/A1f$, where A_{1f} is amplitude of fundamental (*1f*) and A_{2f} of the second harmonic (*2f*) measured at the dominant sensor average. Other indices included odd-harmonic energy ratio and spectral kurtosis.

The combination of FFT and wavelet approaches was selected because FFT efficiently highlights stable harmonic content while wavelets reveal intermittent or short-duration anomalies (proven valuable in related works).

RESEARCH RESULTS

Typical time-series and spectra
Representative results are summarized below.

Table 1. Representative harmonic amplitudes (averaged across sensors) and diagnostic index K_d.

Test case	A_{1f} (mT)	A_{2f} (mT)	A_{3f} (mT)	$K_d = A_{2f}/A_{1f}$
Healthy (100% load)	1.25	0.08	0.05	0.064
Inter-turn short	1.38	0.22	0.09	0.159
Partial demag.	1.16	0.30	0.12	0.259
Eccentricity	1.21	0.18	0.16	0.149

These values show systematic increase of second harmonic amplitude for faults with electromagnetic asymmetry (inter-turn and demagnetization), while eccentricity increases both even and odd harmonic content depending on mechanical axis offset and load. Spectral plots display clear peaks at 1f (fundamental), 2f and 3f with magnitudes differing by condition; in demagnetization cases the 2f component increases most strongly. These observations are consistent with published findings that certain faults manifest as increased 2f or zero-sequence magnetic components.

From repeated measurements and statistical analysis (n = 9 per case across loads), the following decision ranges for the diagnostic coefficient K_d produced reliable separation with >90% correct classification in our data set:
-   $K_d < 0.10$: Healthy (normal);
-   $0.10 \leq Kd < 0.20$: Possible defect - require further inspection or confirm with other signals (current, vibration);
-   $K_d \geq 0.20$: High probability of significant electromagnetic fault (inter-turn short or demagnetization)

Receiver operating characteristic (ROC) analysis using combined fault vs healthy classification yields area under curve (AUC) ≈ 0.94 for the K_d classifier when trained on our experimental set - a strong indicator of diagnostic value.

Using the ring of sensors permitted spatial mode analysis. Inter-turn shorts localized to one stator slot produced a clear angular-dependent signature: the sensor nearest to the affected slot recorded heightened harmonic content and a phase shift relative to the healthy case. Applying a simple weighted sensor fusion (amplitude weighting by inverse distance) improved early detection sensitivity by $\approx 10\%$ over single-sensor detection.

Wavelet packet analysis exposed short-duration changes (sub-second) in harmonic energy during transient torque events and during intermittent arcing in the induced inter-turn short scenario. Some fault signatures were only visible in the time-frequency domain and not distinctly in average FFT spectra; this underlines the benefit of combining both approaches. The use of wavelet-based feature extraction followed by a small support-vector classifier produced improved classification of intermittent faults in noisy industrial conditions.

For the same fault cases, standard line-current spectrum analysis detected inter-turn faults reliably only after the fault severity exceeded ~10% of turns shorted, and had difficulty distinguishing partial demagnetization from eccentricity. The external magnetic field method detected smaller inter-turn faults (down to ~5% shorted) and provided clearer signatures for demagnetization. Combining both modalities (current + external field) achieved near-perfect classification in the experimental set.

DISCUSSION

The experimental results support the proposition that external magnetic field measurements provide a valuable, non-intrusive diagnostic channel for synchronous motors. Key practical findings and recommendations:

1. Sensor selection and placement: Search coils are excellent for dynamic content (harmonic amplitudes) and have good SNR for the frequency bands of interest; Hall probes complement by measuring low-frequency/ DC shifts. A ring of 6–8 sensors evenly distributed is an effective compromise between spatial resolution and system complexity.

Sensor spacing should be chosen to resolve lowest spatial harmonics of interest. Relevant literature also emphasizes sensor-design optimization for sensitivity and noise immunity.

2.   Signal processing: The Butterworth low-pass filter with cutoff near 200 Hz effectively removes high-frequency industrial EMI while preserving *1f..10f* bands. Use of synchronous averaging and tachometer gating improves spectral clarity under speed jitter. Wavelet analysis is necessary to detect transient faults or intermittent arcing that an averaged FFT may hide. Earlier studies similarly combine FFT and time-frequency tools for robust monitoring.

3.   Diagnostic metrics: The proposed K_d is simple, computationally cheap and robust across tested operating points. It complements other multi-feature classifiers (e.g., harmonic energy ratios, spectral kurtosis). In industrial use, combining K_d with secondary checks (current spectrum, vibration) reduces false positives.

4.   Noise and interference: External magnetic field measurements can be affected by nearby ferrous structures, bus bars and adjacent machines. Practical installations must use baseline mapping during commissioning and optionally differential measurement (reference sensor) to suppress environmental clutter - a recommendation supported by sensor-design literature.

5.   Integration and real-time constraints: Modern A/D modules and embedded computing enable real-time FFT and wavelet processing at moderate sampling rates. For industrial application, computationally light indices like K_d can be computed onboard for continuous monitoring while heavier wavelet analysis is performed periodically or on alarms.

Limitations: experiments were done on a single machine type and fault severities introduced manually; additional validation across different motor designs, sizes and field winding types (wound rotor vs permanent magnet) is recommended. Also, long-term drift, sensor aging and thermal effects need to be characterized before deployment.

CONCLUSIONS

1.   Measurement of the external magnetic field is a sensitive, non-intrusive method for early detection of electromagnetic faults in synchronous motors.

2.   The proposed diagnostic index $K_d=A_{2f}/A_{1f}$ provides a simple and effective classifier; thresholds $K_d<0.10$ (healthy), $0.10 \leq K_d<0.20$ (possible defect), $K_d \geq 0.20$ (high probability of significant fault) produced reliable classification in experiments.

3.   Combining FFT-based harmonic analysis with wavelet time-frequency processing increases the method's capacity to detect steady and transient faults.

4.   A ring of 6–8 sensors (search coils plus optional Hall probes) placed around the stator frame gives good spatial resolution and robustness.

5.   Field-based diagnosis complements traditional current and vibration monitoring and can be integrated into predictive maintenance systems to reduce downtime.

Further work: expand testing to diverse motor classes, develop automated calibration and baseline subtraction procedures for industrial environments, and integrate machine-learning classifiers trained on multi-modal sensor inputs.

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