RESEARCH PAPER

# Enhancing Bearing Fault Diagnosis in Three-Phase Induction Motors Using Motor Current Signature Analysis

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***Abstract*— The detection and analysis of faults in the ball bearings of induction motors are crucial for ensuring the reliable operation of motors. This paper deals with the use of Motor Current Signature Analysis (MCSA) together with Harmonics Fast Fourier Transform (FFT) to identify bearing defects. During operation, the bearings of induction motors are subjected to dynamic forces, which account for their deterioration is one of the leading causes of motor breakdowns in industrial systems. This study used a three-phase, 440V, four-pole, 1500 RPM induction motor for experimental testing.; three different bearing fault conditions of dry bearing, insufficient lubrication, and ball-damaged bearing were introduced in the setup. The performance analysis of the motor is carried out under no-load and rated-load conditions, and comparisons are drawn between the healthy and faulty states. From the results, it can be observed that due to the development of bearing faults, certain important parameters like torque, mechanical power, electrical power, power factor, three-phase voltage and current are increased; whereas the motor speed and efficiency decreased. Further, harmonic analysis indicates an increased harmonic content, with significant harmonics up to the 21st order. Hence, from the obtained results, it is concluded that MCSA and harmonic analysis are powerful tools that can be employed for early diagnosis and detection of induction motor bearing failures.**

***Keywords*—** Motor Current Signature Analysis (MCSA), Bearing Faults, Harmonics FFT, Induction Motor, Fault Detection, Vibration Analysis.

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## I. Introduction

Induction motors are among the most vital components in various industrial applications owing to their reliability, cost-effectiveness, efficiency, and ease of operation. Their speed control is so simple and convenient that it makes them highly suitable for diverse industrial processes where they serve an essential role in transforming electrical energy into mechanical energy. [1,2].

Ball bearings are an integral part of the rotating machinery system, and their performance and reliability have a significant effect on induction motors. The performance of the bearing assemblies is closely associated with the development of motor systems, and it's hard to upgrade machinery without considering the role played by ball bearings [3]. For instance, it's indicated that bearing failures account for approximately 41% of all induction motor breakdowns according to IEEE reports [4].

Traditional vibration monitoring has been one of the most applied methods for detecting bearing faults in induction motors, as it provides a reliable means of identifying failure [5]. However, in many industrial applications, particularly where a large number of motors are deployed-installation of vibration sensors is impractical due to their high cost, delicacy, and susceptibility to damage that may lead to enormous economic losses [6,7]. To surmount these shortcomings, MCSA combined with harmonic Fast Fourier Transform techniques has been proposed for monitoring the status of induction motors as an effective non-invasive tool [8,9]. Many works reported the effectiveness of the stator current analysis technique in detecting bearing faults, which could ensure higher reliability in operation [10,11].

Despite the availability of these techniques, unexpected bearing failures continue to pose challenges to industries, resulting in unscheduled downtime, economic losses, and reduced productivity [12,13]. Therefore, incipient fault detection in induction motors is necessary with the help of reliable and cost-effective methods.

Harmonic FFT analysis and MCSA are applied for the identification and evaluation of faults in ball bearings of induction motors in this paper. Experimental investigations have been conducted on a induction motor with three phases, one horsepower, 440 volts, four poles, and 1500 rpm under different bearing conditions, namely dry, less lubricated, and ball-damaged bearings. Data are collected under both healthy and faulty states at rated load and no-load conditions to determine the potential benefits of the proposed technique.

## II. FAULTS IN INDUCTION MOTOR

### A. *Electrical Faults*

Electrical faults include inter-turn faults, phase-to-phase faults, phase-to-ground faults, and stator insulation faults.

### B. *Mechanical Faults*

The mechanical faults are bearing faults, rotor faults, and eccentricity faults. Bearings reduce friction and support the shaft; failure of the bearings may severely affect motor operation [12]– [16].

### C. *Common Bearing Faults*

Brinelling: Raceway dents caused by improper mounting or shock loads.

• Cage Damage: Caused by excessive vibration, wear, or blockage.

• Contamination: Foreign particles causing scratches and pits on raceways.

• Electric Arcing: High temperatures caused by current passing through broken bearings.

• False Brinelling: Damage during transportation or vibration.

• Lubrication Failure: Indicated by darkened or contaminated lubricant.

• Misalignment: leads to high temperature and degradation of the lubricant.

## III. BEARING FAULT DETECTION METHODS

Different methods are used to identify bearing faults in induction motors. These methods largely make use of the examination of the motor current or associated signals to recognize tell-tale signs of mechanical or electrical faults. The prevailing techniques are explained as

### 1. *Fast Fourier Transform (FFT)*

This approach begins with readings of motor current in the time domain. Following signal conditioning, analogy-to-digital conversion occurs. FFT is then utilized to investigate the signals in the frequency domain. As a fast implementation of the discrete Fourier transform, FFT considerably decreases the computational effort while satisfactorily describing stationary signals. The technique is commonly utilized for the detection of frequency components that are characteristic of bearing faults. FFT transforms time-domain current signals of a motor into the frequency domain, allowing for efficient analysis of stationary signals [17].

### 2. *Instantaneous Power FFT*

This technique extends standard FFT analysis by including extra measurements of the supply voltage. Compared to the motor current itself, the instantaneous power signal has more information. In the absence of the essential power grid component, it has a well-bound dynamic range for harmonics and reduced noise levels. which increases sensitivity to fault detection. Offers voltage and current measurement with reduced noise, disclosing extra harmonics not found in current measurements alone [18].

### 3. *Demodulated Current Spectrum*

The noise presence may mask fault-related information in the existing spectrum. One way to extract the desired frequency components from the spectrum is by demodulation. In Motor Current Signature Analysis (MCSA), demodulation eliminates the carrier frequency, giving a demodulated current spectrum ready for additional detailed analysis of the faults in bearings. Demodulation isolates the components of fault-related frequency by eliminating the carrier frequency from the current spectrum [19].

### 4. *Wavelet Analysis*

Wavelet analysis is the application of a building block function that is localized both in time (or position) and frequency (or wavenumber). In contrast to the Fourier series, which gives a frequency-domain description, wavelets give a time-frequency description of signals. This has particular advantages in the analysis of non-stationary real-world induction motor fault characteristics that change over time. Discrete wavelet transforms allow for accurate localization of transient faults related to bearing defects. Wavelet transform offers time-frequency analysis in non-stationary signals, allowing for localized fault signal detection of transients [20].

### 5. *Park's Vector Method*

The vector method of the Park belongs to the electrical monitoring methods. Utilizing the motor's stator current enables real-time monitoring and diagnosis of faults such as imbalanced supply voltage situations, rotor failures, stator faults, bearing failure, and inter-turn faults. The method relies on the detection of particular current patterns related to these faults. Stator current monitoring is utilized for real-time diagnosis of bearing, rotor, stator faults, and unbalanced supply conditions [21].

### 6. *Motor Current Signature Analysis (MCSA)*

MCSA is a low-cost technique that makes use of monitoring an induction motor's stator current. Under normal circumstances, the stator current should be sinusoidal in nature; however, electrical and mechanical faults cause additional harmonics. Bearing faults modulate the motor current, generating sideband frequencies near the supply line frequency. These sidebands are created due to fluctuations inside the motor's magnetic field, which consequently influence the mutual and self-inductance. By examining these defective current signatures, both the existence and severity of Bearing defects can be identified. MCSA observes the modulation of the stator current. Bearing faults generate sideband harmonics near the line frequency, which are utilized to determine fault type and severity [14], [15].

## IV. INDUCTION MOTOR BEARING FAULTS

Two bearings in three-phase induction motors hold the rotating shaft for smooth rotation and friction reduction. A bearing comprises rolling elements (balls), an outer race, and an inner race, which are lubricated to reduce friction [14]. Bearing faults arise when one or several components are compromised by operational or physical elements, leading to motor failure. The major causes are foreign particle entry, corrosion, and contamination of lubrication.

Common Bearing Faults

| Fault Type | Description | Causes / Indicators |
|---|---|---|
| **Brinelling** | Raceway damage is characterized by small dents aligned with ball positions. | Mounting/dismounting mistakes, and shock loading of the fixed shaft |
| **Cage Damage** | Bearing cage damage | Large vibration, high speed, wear, blockage |
| **Contamination** | scratching, pitting, and lapping of raceways | Foreign particles entering the bearing |
| **Electric Arcing** | Pitting on balls and raceways as a result of local heating | An electric current flowing through a defective bearing |
| **False Brinelling** | Brinelling-like raceway marks appear without shaft rotation. | Transportation vibrations or from nearby running equipment |
| **Lubrication Failure** | Unbalanced travel of balls along the raceway causes high temperature and lubricant degradation. | Discolored lubricant, foreign substances |
| **Misalignment** | Uneven travel of balls along the raceway leads to high temperature and lubricant breakdown. | Improper bearing alignment during assembly |

These defects can drastically shorten the motor's operating life, and early detection is essential for preserving performance and avoiding catastrophic failure [16].

## V. MATHEMATICAL MODELLING

*Total Harmonic Distortion (THD)*

THD quantifies the effect of harmonic currents or voltages on the overall waveform quality. THD in current is defined as:

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} c_{n\,\mathrm{rms}}^2}}{c_{\mathrm{fund}_{\mathrm{rms}}}} \ldots\ldots\ldots\ldots\ldots (1)$$

Or

$$\mathrm{THD} = \frac{\sqrt{c_3^2 + c_5^2 + \cdots \ldots + c_n^2}}{C_1} \ldots\ldots\ldots\ldots (2)$$

Total harmonic distortion in the voltage harmonics results from the addition of current harmonics in the motor, which causes abnormalities in the voltage harmonics.

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_{n\,\mathrm{rms}}^2}}{V_{\mathrm{fund}_{\mathrm{rms}}}} \ldots\ldots\ldots\ldots (3)$$

*Crest Factor (CF)*

The CF is computed for both current and voltage and shows the ratio of peak to RMS value.

$$\mathrm{THD} = \frac{\sqrt{v_3^2 + v_5^2 + \cdots \ldots + v_n^2}}{V_1} \ldots\ldots\ldots\ldots\ldots (4)$$

The CF (K) for voltage and current is expressed as

$$\mathrm{CF} = \frac{I_{\mathrm{peak}}}{I_{\mathrm{rms}}} \quad \& \quad \mathrm{CF} = \frac{|V_{\mathrm{Peak}}|}{V_{\mathrm{RMS}}}$$

## VI. EXPERIMENTAL SETUP

A 3-phase,1 Hp, four-pole induction motor was used in studies to demonstrate the bearing defect detection technique. The Fluke 438-II Motor Analyzer was used for data collection. The motor specifications are listed in Table 1.

| Parameter | Rating |
|---|---|
| P | 3-Phase, 1Hp |
| F | 50 Hurtz |
| V | 415 Volt |
| I | 1.5 Ampere |
| Ns | 1500 RPM |
| Poles | 4 |

Table 1: Motor Rating

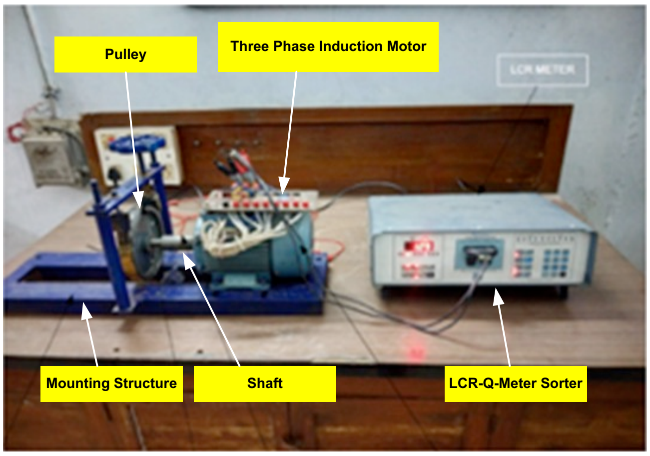


Fig. 1 Measurement of LCR Parameters

For measurement of motor R-L-C parameters, the LCR-Q-Meter Sorter was employed.

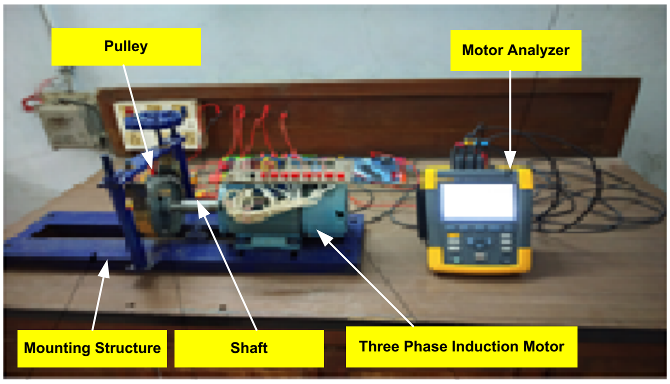


Fig. 2 Illustrate the measurement setup and motor parameter evaluation.

Bearing Specifications

Three 6205ZR bearings were used in the experiments. Each bearing contains 8 balls, has a width of 15 mm, an exterior diameter of 52 mm, and an interior diameter of 25 mm. Experiments were performed for three conditions healthy, dry, and damaged bearings under both rated-load and no-load conditions. Bearing faults were artificially introduced by creating holes in the inner and outer raceways with different dimensions (2 mm or 3 mm). These failures produce distinctive current harmonics and fault frequencies to illustrate bearing fault identification, even though they are not totally realistic.

| Parameter | Value |
|---|---|
| **Number** of balls | 8 |
| Exterior Dia. | 25 mm |
| Interior Dia. | 52 mm |
| Width | 15 mm |
| Weight | 0.129 Kg |

Table 2: Bearing Specifications

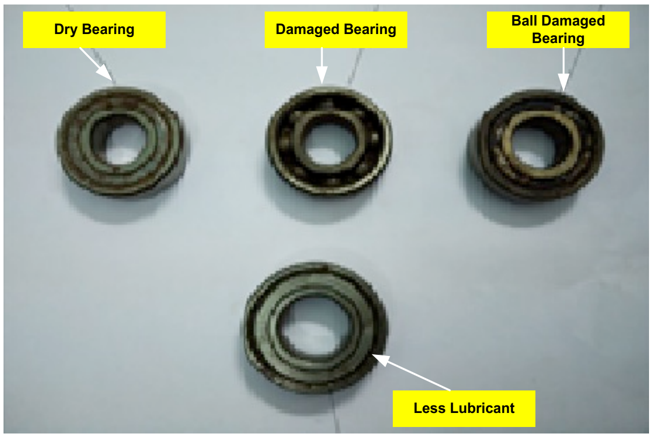


Fig. 3 shows the types of bearings used.

## VII. METHODOLOGY

Motor Current Signature and harmonic analysis were used to determine faults in bearings. The technique relies on the measurement of stator current of the induction motor and examination of its spectrum to identify ball bearing faults.

•The stator current output was recorded with current transformers that had probes connected to them.

• The Fluke 438-II Motor Analyzer received signals using patch cables.

• Mechanical and electrical parameters, including current, voltage, and frequency, were recorded for ten seconds.

•Data was recorded on the Fluke SD card and retrieved by Power Log software for analysis.

No-load and rated-load measurements were made for each bearing condition (healthy, dry, and damaged). Voltage, current, and mechanical and electrical metrics were calculated and graphed to monitor changes with varying conditions.

Lastly, harmonic analysis was carried out to compute THD up to the 21st harmonic for both voltage and current for all three bearing conditions both in rated-load and no-load scenarios.

## VIII. RESULTS AND DISCUSSION

Induction motor is an indispensable element in industrial systems and thus is commonly known as the "horsepower of the industry." A motor fault will result in substantial operational downtime, financial loss, and potential safety hazards. Thus, online condition monitoring and fault detection become mandatory to avoid potential risks and ensure uninterrupted industrial operation.

Induction motor faults can be categorically categorized as electrical faults and mechanical faults. The electrical faults consist of the stator's inter-turn, phase-to-ground, phase-to-phase, and stator insulation faults the mechanical faults involve bearing faults, faults in the rotor, and faults of eccentricity. This study used harmonic analysis and Motor Current Signature Analysis to analyse bearing faults. Healthy, dry, damaged, and ball-damaged bearings were the four bearing conditions that were assessed, rated-load and no-load conditions were used to assess the motor's performance. and the performance for each condition was evaluated using MCSA and harmonic FFT analysis.

The outcome of the work shows that the existence of bearing faults has a great impact on motor performance. Three-phase voltage raised from 234.38 V to 366.16 V and current raised from 2.37 A to 3.69 A under faulty conditions. While the motor speed decreased from 1439 rpm to 1352 rpm, mechanical power increased from 0.567 kW to 0.997 kW, torque enhanced from 3.77 Nm to 7.08 Nm, and electrical power enhanced from 0.778 kW to 20.5 kW. Consequently, the motor efficiency dropped from 74% to 59%.

Harmonic analysis also found that the harmonic content went up to the 21st harmonic, reflecting a distinct signature of bearing fault in the motor current. These results prove that MCSA and harmonic FFT analysis are potent diagnostics for spotting and diagnosing bearing faults in induction motors, thus preventing costly industrial breakdowns.

*1. Rated Phase Voltage and Current*

Table 3 presents measured voltages of phases and currents under various bearing conditions. Voltage and current rise progressively with worsening bearing condition, reflecting greater electrical stress and motor loading. Faulty bearings result in substantial departure from rated values, where scope exists for loss of efficiency and enhanced mechanical wear.

| **Condition** | **VRN (V)** | **VYN (V)** | **VBN (V)** | **IR (A)** | **IY (A)** | **IB (A)** |
|---|---|---|---|---|---|---|
| **Healthy** | 234.28 | 232.21 | 232.1 | 2.35 | 2.1 | 1.8 |
| **Dry** | 292.85 | 290.26 | 290.12 | 2.94 | 2.63 | 2.25 |
| **Damaged** | 366.06 | 362.82 | 362.65 | 3.67 | 3.28 | 2.81 |

Table 3: Rated Phase Voltage and Current (V & I)

Table 4 and Fig. 7 show electrical and mechanical power under different bearing conditions. An increasing trend in electrical power consumption is found from healthy bearings to damaged bearings. Mechanical power drops slightly with bearing damage, showing losses due to misalignment and friction. This illustrates that motor efficiency is directly influenced by faults in bearings.

| Condition | Phase Voltage (Vrms) | Phase Current (A) | Mechanical Power (kW) | Torque (N-m) | Electrical Power (kW) | Speed (RPM) | Efficiency (%) |
|---|---|---|---|---|---|---|---|
| Healthy | 234.28 | 2.35 | 0.565 | 3.76 | 0.777 | 1437 | 72 |
| Dry | 292.85 | 2.9375 | 0.78 | 4.2 | 1.23 | 1400 | 65 |
| Damaged | 366.0625 | 3.6718 | 0.996 | 7.05 | 2.04 | 1350 | 58 |

Table 4: shows the Motor performance.

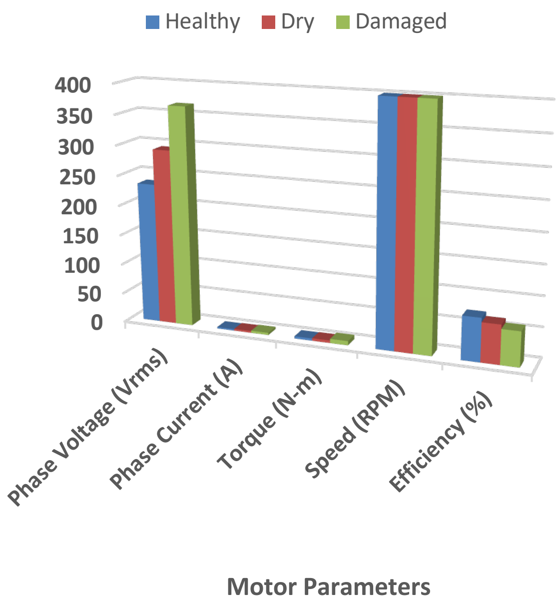


Fig. 4 shows the Motor performance.

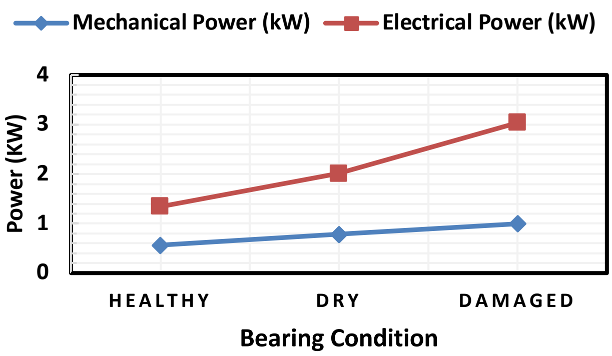


Fig. 5 Shows the Mechanical and Electrical Power

2. *Total Harmonic Distortion (THD) and Harmonics Analysis*

a) *Healthy Bearing*

THD values: Voltage ≈ 2.4–2.5%, Current ≈ 2.6%, Dominant harmonic: 1st (fundamental) with small contributions from 3rd, 5th, 7th, 9th.Low THD reflects smooth operation with little electrical distortion. Low THD and a little higher-order harmonic reflect smooth motor operation as shown in Table.5 and Fig.6.

b) *Dry Bearing*

THD values: Voltage ≈ 3.1–3.2%, Current ≈ 3.0–3.6%, Higher-order harmonics (3rd, 5th, 7th) increase, which signals the onset of electrical disturbances due to bearing degradation. THD rises in comparison with a healthy bearing. Higher-order harmonics (3rd, 5th, 7th) increase their amplitudes, which signals the onset of electrical disturbances due to bearing degradation.as shown in Table 6 and Fig.7

c) *Ball-Damage Bearing*

THD values: Voltage ≈ 0.0927, Current ≈ 0.0935 (note: scale may represent per-unit or normalized values), Sustained increase in higher-order harmonics (3rd, 5th, 7th, 9th, 11th), revealing large electrical distortion. Harmonic spectrum clearly reflects bearing fault severity and can be used as a diagnostic indicator. Large increase in higher-order harmonics. The harmonic spectrum clearly reflects a severe bearing fault and electrical distortion as shown in Table 7 and Fig.8

## IX. Conclusions

Electrical equipment plays a very important part in industrial processes. Induction motor failure causes production downtime, which in turn represents a substantial revenue loss and increased maintenance expenses. To prevent such losses, early fault diagnosis is therefore essential. Development of faults in the motor adds extra harmonic components to the motor waveform, which in turn causes both mechanical and electrical damage. MCSA and harmonic analysis are methods for continually monitoring ball bearing defects in induction motors that operate under both constant and variable loading situations. The diagnostic techniques can be applied for the extensive range of industrial uses where electric motors used as a strong condition monitoring and early fault detection tool.

Faulty induction motors will lead to extensive downtime and loss in industries dependent on such motors. Thus, faults need to be detected at an early stage to avoid these effects. Faults cause harmonic distortion in motor waveforms, which results in electrical and mechanical damage. MCSA and harmonic analysis allow for real-time monitoring of faults in ball bearings under constant and variable loads and offer a sound tool for condition monitoring. Further research may be directed at the application of these methods within predictive maintenance and IoT-based frameworks that could further increase motor reliability in industrial productivity.

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| Rated Load Harmonics (Healthy Bearing) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Conditions** | THD | K | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 21 |
| **$V_{RY}$** | 2.41% | 0 | 100 | 0.51 | 2 | 1.3 | 0.51 | 1 | 0 | 0 | 0 | 0 |
| **$V_{YB}$** | 2.41% | 0 | 100 | 0.72 | 2 | 1.23 | 0.72 | 1 | 0 | 0 | 0 | 0 |
| **$V_{BR}$** | 2.51% | 0 | 100 | 1 | 2 | 1.36 | 1 | 1 | 0 | 0 | 0 | 0 |
| **V** | 2.41% | 0 | 100 | 0.743 | 2 | 1.298 | 0.743 | 1 | 0 | 0 | 0 | 0 |
| **$I_{RY}$** | 2.61% | 1 | 100 | 1.31 | 1.31 | 1.42 | 0.25 | 0.52 | 0.25 | 0 | 0 | 0 |
| **$I_{YB}$** | 2.61% | 1 | 100 | 4.9 | 1.26 | 1.31 | 0.72 | 0.22 | 0.32 | 0 | 0 | 0 |
| **$I_{BR}$** | 2.61% | 1 | 100 | 4 | 2 | 1.4 | 1 | 0.3 | 0.5 | 0 | 0 | 0 |
| **I** | 2.61% | 1 | 100 | 3.37 | 1.5176 | 1.376 | 0.643 | 0.343 | 0.343 | 0 | 0 | 0 |

Table 5: Rated Load Harmonics (Healthy Bearing).

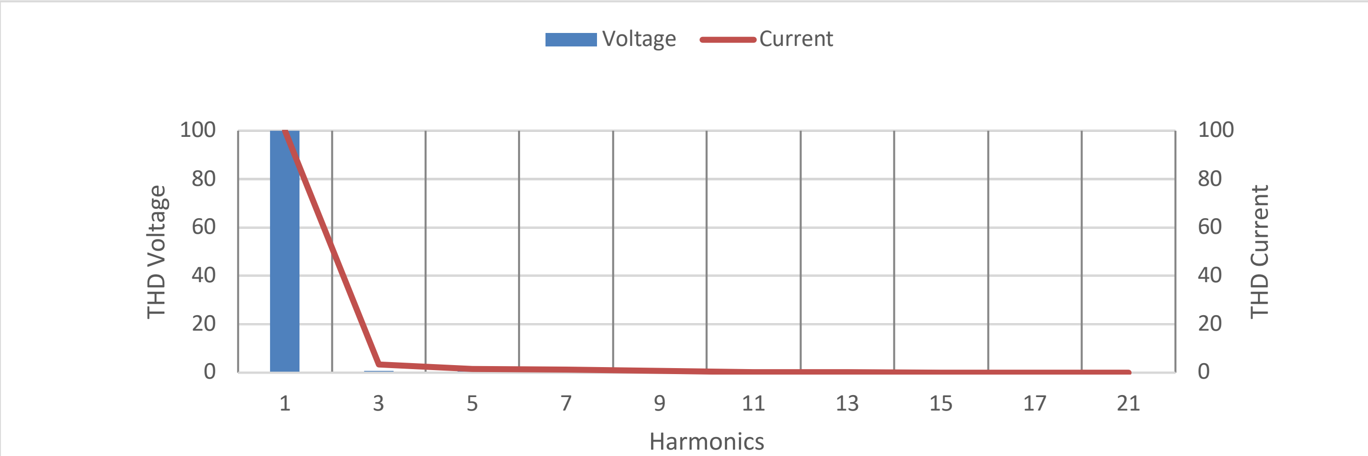


Fig. 6: Shows voltage and current harmonics for a healthy bearing.

| Rated Load Harmonics (Dry Bearing) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Conditions** | THD | K | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 21 |
| **$V_{RY}$** | 3.21% | 1.6 | 100 | 1.7 | 1.91 | 1.665 | 1 | 0.34 | 0 | 0 | 0 | 0 |
| **$V_{YB}$** | 3.12% | 1.5 | 100 | 1.9 | 1.643 | 1.334 | 1 | 0.485 | 0 | 0 | 0 | 0 |
| **$V_{BR}$** | 3.14% | 1.49 | 100 | 1.74 | 1.61 | 1.21 | 0.81 | 0.34 | 0 | 0 | 0 | 0 |
| **V** | 3.17% | 1.499 | 100 | 1.7077 | 1.721 | 1.396 | 0.9343 | 0.3823 | 0 | 0 | 0 | 0 |
| **$I_{RY}$** | 3.05% | 1.505 | 100 | 1.79 | 1.91 | 1.21 | 0.64 | 0.49 | 0.23 | 0.16 | 0 | 0 |
| **$I_{YB}$** | 3.61% | 1.519 | 100 | 2.52 | 1.91 | 1.39 | 0.81 | 0.51 | 0.21 | 0.12 | 0.011 | 0 |
| **$I_{BR}$** | 3.62% | 1.529 | 100 | 2 | 2.52 | 1.49 | 0.78 | 0.51 | 0.41 | 0.21 | 0.041 | 0 |
| **I** | 3.43% | 1.524 | 100 | 2.0943 | 2.12 | 1.3543 | 0.7343 | 0.4943 | 0.2743 | 0.16 | 0.0167 | 0 |

Table 6: Rated Load Harmonics (Dry Bearing)

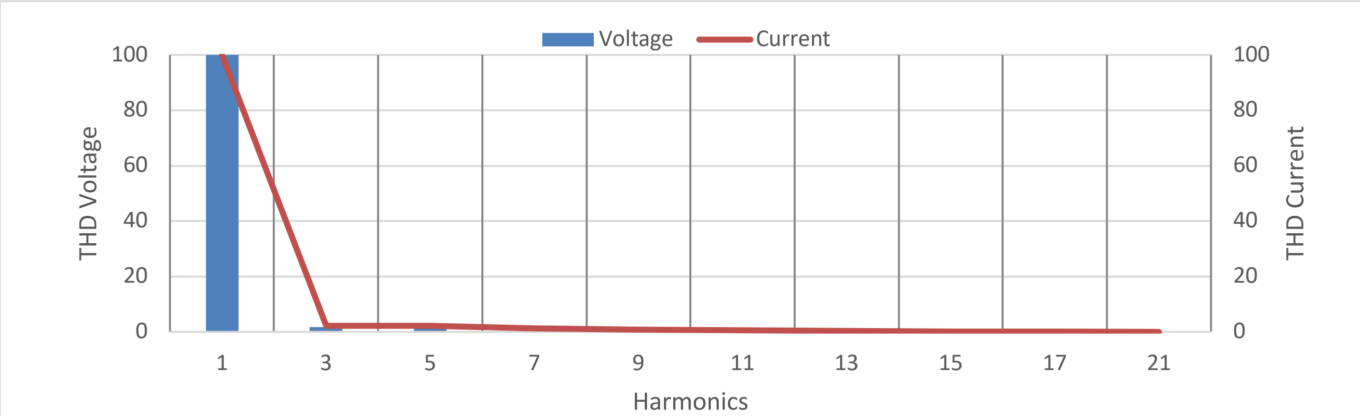


Fig. 7 shows an increase in THD compared to healthy bearings.

| Rated Load Harmonics (Ball-Damage Bearing) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Conditions** | THD | K | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 21 |
| **$V_{RY}$** | 0.097 | 1.74 | 100 | 4.88 | 5.6 | 4.77 | 2.8 | 2.1 | 1.55 | 1.09 | 0.1 | 0 |
| **$V_{YB}$** | 0.093 | 1.7 | 100 | 4.77 | 5.44 | 4.2 | 2.37 | 1.81 | 1.49 | 1.09 | 0 | 0 |
| **$V_{BR}$** | 0.093 | 1.72 | 100 | 4.69 | 5.66 | 3.91 | 2.44 | 1.777 | 1.398 | 1.51 | 0 | 0 |
| **V** | 0.0937 | 1.73 | 100 | 4.7743 | 5.5277 | 4.2877 | 2.54 | 1.8597 | 1.486 | 1.2277 | 0.0333 | 0 |
| **$I_{RY}$** | 0.095 | 1.73 | 100 | 4.41 | 5 | 4.57 | 3.61 | 2.84 | 1.21 | 0.81 | 0 | 0 |
| **$I_{YB}$** | 0.095 | 1.73 | 100 | 4.21 | 5.4 | 4.46 | 3.51 | 2.89 | 1.19 | 0.86 | 0 | 0 |
| **$I_{BR}$** | 0.094 | 1.7 | 100 | 4 | 5.37 | 4.39 | 3.48 | 2.71 | 1.81 | 0.71 | 0 | 0 |
| **I** | 0.0936 | 1.7143 | 100 | 4.21 | 5.23 | 4.4643 | 3.5243 | 2.8077 | 1.3943 | 0.7843 | 0 | 0 |

Table 7: Rated Load Harmonics (Ball Damaged Bearing)

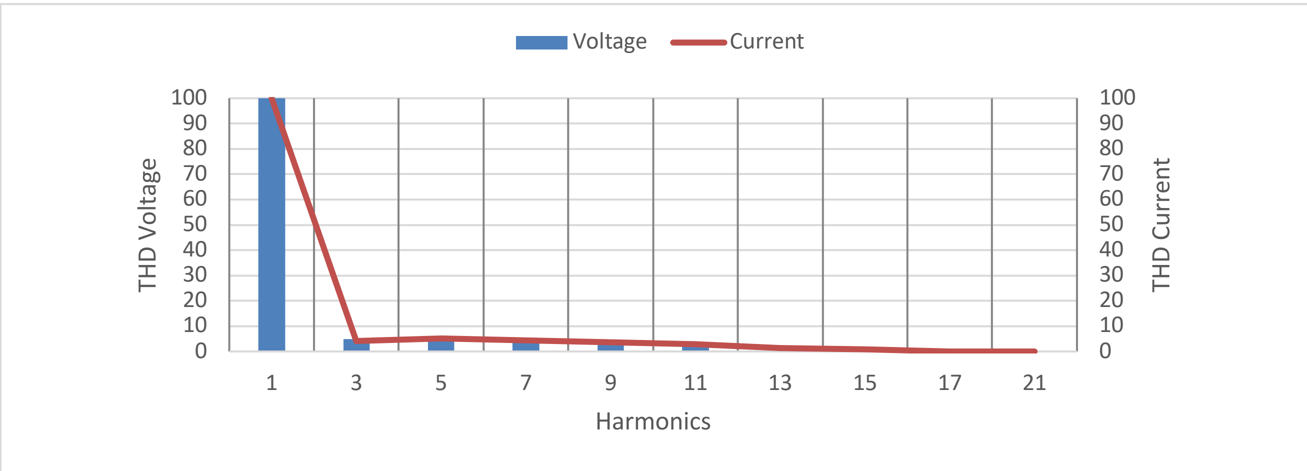


Fig. 8 Illustrates THD and harmonics for severely damaged bearings.