

# USING MOTOR CURRENT SIGNATURE ANALYSIS TO DETECT THE NUMBER OF BROKEN ROTOR BARS IN INDUCTION MOTORS

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**Abstract:** Cracked/Broken rotor bar(s) is one of the commonly encountered induction motor faults that may cause serious damage to the motor if not detected timely. Past efforts on broken rotor bar diagnosis have been focused on both vibration analysis and motor current signature analysis (MCSA). These methods require accurate slip estimation along with high resolution spectral data which enables the analyst to precisely judge the severity of the problem, and confidently pull out the motor to the workshop with no doubt.

This paper will not only focus on collecting current signature, but also will deeply cover the analysis part to determine the number of broken bars if exist, and explicitly evaluate the severity level and needed corresponding corrective actions. This will be clearly shown through two real case studies for two (1.2 MW) induction motors in a large integrated steel plant.

**Keywords:** Broken Bars, Current Signature, Cracked Bars, Induction Motor, MCSA, Slip Frequency, Steel Industry, Vibration Analysis.

**This paper presents results from an in-depth investigation of using current signature technique and its impact on the fault detection of rotor bars in induction motors. The analysis is performed based on both vibration data and current signature, where the first indication of anomaly came from vibration Time-domain data. The paper includes two case histories**

## 1.INTRODUCTION:

Induction motors play a significant role in the safe and efficient operation of industrial plants. Usually, they are designed for 30 years fault-free lifetime, but most of them are not available at all times.

Most failures in induction motors can be classified in two main groups: isolation failures and mechanical failures (Botha, 1997). Isolation failures are commonly characterized by stator coils short-circuits, while mechanical faults are commonly associated to rotor or rotor related damage. The most important mechanical failures are: rotor broken bars and

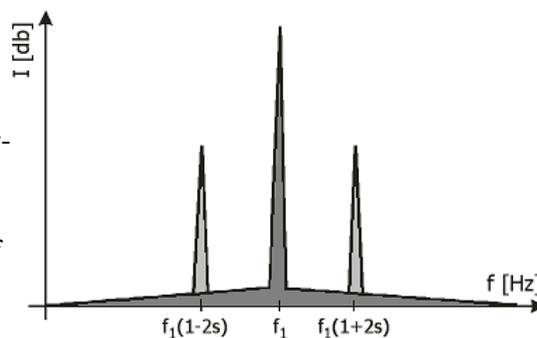
rings, bearings damage, irregular gaps (static and dynamics eccentricities), unbalances, etc.

Motor Current Signature Analysis (MCSA) is a condition monitoring technique used to diagnose problems in induction motors. Concept originates from early 1970s and was first proposed for use in nuclear power plants for inaccessible motors and motors placed in hazardous areas, [1]. It is rapidly gaining acceptance in industry today. Tests are performed online without interrupting production with motor running under the load at normal operating conditions, [1]. MCSA can be used as predictive maintenance tool for detecting common motor faults at early stage and as such prevent expensive catastrophic failures, production outages and extend motor lifetime. It can be used as a diagnostic tool and powerful addition to vibration and thermal monitoring (verifying a fault with more than one technology), [1].

A crucial point about motor current signature analysis (MCSA) is that it is sensing an electrical signal that contains current component that are a direct by-product of unique rotating flux components caused by faults such as broken rotor bars, airgap eccentricity, and shorted turns in low voltage stator windings, etc. MCSA can detect these problems at an early stage and thus avoid secondary damage and complete failure of the motor, as reported by Hargis, et al. (1982), Thomson (1984), Thomson and Rankin (1987), and Kliman and Stein (1990). It is true that broken rotor bars will result in a change to the vibration spectrum, but vibration is traditionally sensed at the bearings. And for each motor there is a different mechanical stiffness between the electromagnetic forces caused by broken bars and the position where the vibration is sensed. This adds an additional complexity when attempts are made to quantify the severity of the problem via vibration analysis. Electromagnetic forces are proportional to the flux density squared waveform (Alger, 1965; and Yang, 1981) in an induction motor. Hence, the vibration from unique electromagnetic forces from broken bars, etc., is a second order effect compared to current components directly induced from the specific rotating flux waves. In many cases the fault severity (e.g., number of broken rotor bars) has to be serious before it can be detected by vibration analysis, and even then, the prediction of fault severity is another order of magnitude more difficult, [2].

## 2.HOW MCSA WORKS:

The technique depends on spectrum analysis of harmonic components in the line current produced of unique rotating flux components caused by faults such as broken rotor bars, air-gap eccentricity and shorted turns in stator windings, etc. The method needs only one current transducer, and it can be in any one of the three phases.



An ideal current spectrum is shown in Fig. 1. The two slip frequency sidebands due to broken rotor bars near the main harmonic can be clearly observed.

Figure 1- Current Spectrum

Usually a decibel (dB) versus frequency dynamic range and to detect the unique current signature patterns that are characteristic of different faults [2, 3].

In the three-phase induction motor under perfectly balanced conditions (healthy motor) only a forward rotating magnetic field is produced, which rotates at synchronous speed,[6]

$$n_1 = f_1/p, \text{ where:}$$

$f_1$ : Supply Frequency

$p$ : Pole Pairs

The rotor of the induction motor always rotates at a speed ( $n$ ) less than the synchronous speed.

$$f_2 = n_2 p = s n_1 p \quad (1)$$

The speed of the rotating magnetic field produced by the current carrying rotor conductors with respect to the stationary stator winding is given by:

$$n + n_1 = n_1 + n_1 - n = n_1 \quad (2)$$

With respect to a stationary observer on the fixed stator winding, then the speed of the rotating magnetic field from the rotor equals the speed of the stator rotating magnetic field, namely, the synchronous speed.

Both mentioned fields are locked together to give a steady torque production by the induction motor. With broken rotor bars in the motor there is an additional, backward rotating magnetic field produced, which is rotating at the slip speed with respect to the rotor. The backward rotating magnetic field speed produced by the rotor due to broken bars and with respect to the rotor is:

$$n_b = n - n_2 = n_1(1 - s) - s n_1 = n_1 - 2s n_1 = n_1(1 - 2s) \quad (3)$$

The stationary stator winding now sees a rotating field at:

$$n_b = n_1(1 - 2s) \quad (4)$$

Or expressed in terms of frequency:

$$f_b = f_1(1 - 2s) \quad (5)$$

This means that a rotating magnetic field at that frequency cuts the stator windings and induces a current at that frequency ( $f_b$ ). This in fact means that ( $f_b$ ) is a twice slip frequency component spaced  $2s f_1$  down from  $f_1$ . Thus speed and torque oscillations occur at  $2s f_1$  and this induces an upper sideband at  $2s f_1$  above  $f_1$ .

Thus, twice slip frequency sidebands occur at  $\pm 2s f_1$  around the line frequency:

$$f_b = (1 \pm 2s)f_1 \quad (6)$$

While the lower sideband is specifically due to broken bar, the upper sideband is due to consequent speed oscillation. In fact, several papers shows that broken bars actually give rise to a sequence of such sidebands given by:

$$f_b = (1 \pm 2ks)f_1 \quad , K = 1,2,3 K \quad (7)$$

### 3.CASE HISTORY 1

Fume Treatment Plant – ID Fan Motor # 2, EzzSteel, Suez, Egypt

Case Information:

<b>Case Date</b>	July -2017
<b>Location</b>	EzzSteel Plant, Suez City, Egypt
<b>Division</b>	Melt Shop, Fume Treatment Plant
<b>Motor Brand</b>	WEG
<b>Duty</b>	Special
<b>Motor Power</b>	1.2 MW
<b>Supply Current</b>	50 HZ
<b>HP</b>	1630
<b>Volt</b>	11000
<b>Amp</b>	77.2
<b>RPM</b>	1000
<b>No. of Poles</b>	6
<b>No. of Slots</b>	58

#### 3.1 Analysis Procedures and Interpretation

##### 3.1.1 Routine Vibration Data:

Vibration data at this plant is used to be collected on bi-weekly basis, as this area has been classified as “Critical” due to its importance in the process, safety, and work environment. Emerson, CSI 2130 was used on these measurements, and “MHM” machine Health Management was used in analysis of the data.

##### 3.1.2 Vibration Spectral Data:

Spectral data for this motor was very common for most of vibration analyst, residual rotating looseness presented in 1x turning speed, and its harmonics. According to this information, its not evident to diagnose a critical event in the motor.

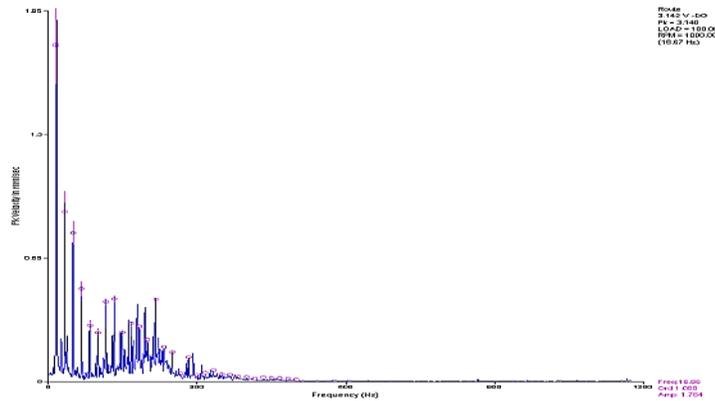


Fig 2- Motor Spectrum shows Some looseness

**3.1.3 Vibration Time-Domain Data:**

While spectral data doesn't show a serious problem, going through the time -domain data gives more insights for this case. Amplitude modulation is very clear in the waveform, and this is a serious indication that should be considered in our analysis, after all, that's why we see the sidebands.

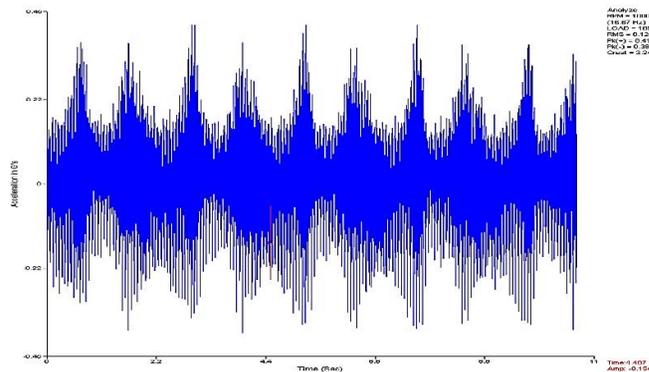


Fig 3- Motor Time-Domain Data

**3.1.4 Re-taking Vibration Spectra:**

I asked for a high-resolution spectrum with a lower Fmax to be taken as this was not normally collected as part of the route. This spectrum has a Fmax of 100 Hz and with 6400 lines. You can now see that those peaks of 1X, and harmonics we saw are not simple peaks – they are broad because of the sidebands surrounding each of the peaks. With limited resolution,

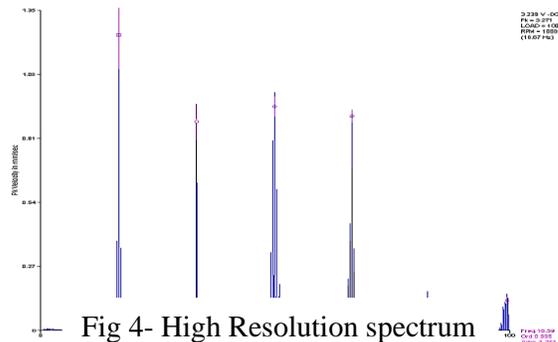


Fig 4- High Resolution spectrum

there is no way to tell that those sidebands are present.

Zooming in at one of these 1xs', then you can obviously see the sidebands, and consequently detect the frequency of these sidebands. This is definitely the core part of the analysis that led you to the rotor bar problems.

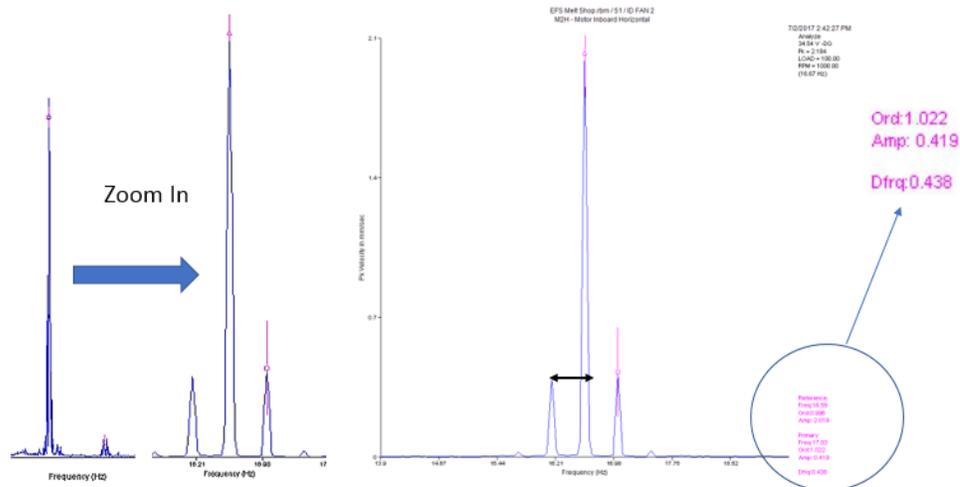


Fig 5- High Resolution spectrum

### 3.1.5 Spectral Data Interpretation:

Now the clue comes from the sideband frequency, as we see in the spectrum, the difference between the fundamental frequency and the left sideband is 0.438 Hz. This small value will lead us to introduce the terminology of “Pole Pass Frequency”. Until further illustration for this term in the following pages, I will introduce the following terms, and calculations:

Slip frequency (S):

Difference in speed between the rotating field and the rotor bars.

$S = N_s - N_r / 60$ , Where:

$N_s$ : Synchronous Speed

$N_r$ : Rotor Speed

Calculating Motor No. of Poles (P)

$P = 120 \times LF / N_s$ ,

LF=50 Hz in Egypt

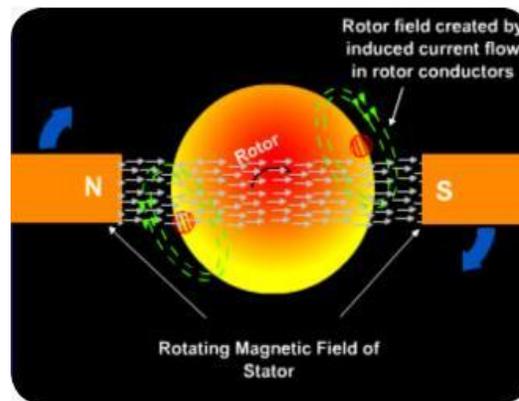


Fig 6- Rotor & Stator Construction

Calculating  $F_{pp}$ :

$F_{pp} = \text{Slip Frequency (S)} \times \text{No. of Poles (P)}$

In our Case

Motor Data:

RPM: 1000 (Name Plate RPM =  $N_s$ ) , RPM: 995.6 (Rotor Actual RPM by Tachometer)

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$$F_{pp} = [(N_s - N_r) / 60] \times [(120 \times XLF / N_s)] = [1000 - 995.62 / 60] \times [120 \times 50 / 1000]$$

$$F_{pp} = 0.438 \text{ Hz}$$

### 3.1.5 Time-Domain Data Interpretation:

Again, the difference in the time-Domain between any two peaks gives the same  $F_{pp}$ , which is 0.438 Hz, this means that the running speed (1X) is modulated by the pole pass frequency.

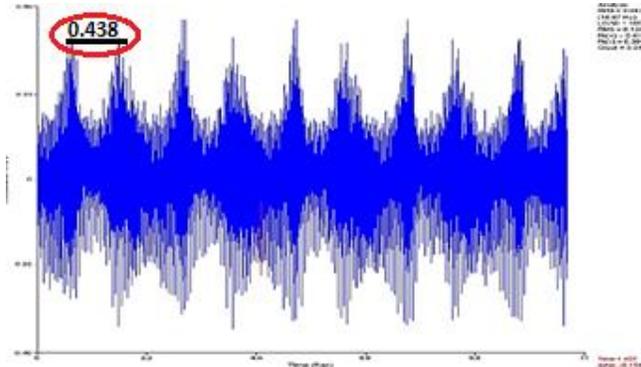


Fig 7 – 1X is Modulated by  $F_{pp}$

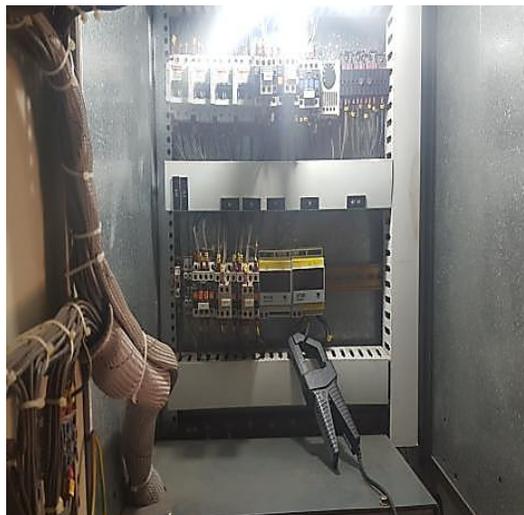
## 3.2 Fault Mechanism and Motor Current Signature Analysis

### 3.2.1 Data Collection:

In this case we used: CSI analyzer with CSI Ac Current Probe Model 341B  
 Input: 600 A AC Max & Output: 0.005 V/A



It can be in any one of the three phases, because the rotating flux waves produced by the different faults cut all three stator phase windings, and corresponding currents are induced in each of the three phases. The Motor was running and loaded at least 75%. To get reliable data from current signature the motor must be under load. The motor was running at 995 RPM measured by the Tachometer. As long as we need to see the line frequency (50Hz) and the sidebands, we selected the  $F_{max} = 150\text{Hz}$



3.2.2 Data Interpretation – First Snapshot: Fig 8- Collecting Current Signature Using  
CSI Ampere Clamp & CSI Analyzer.

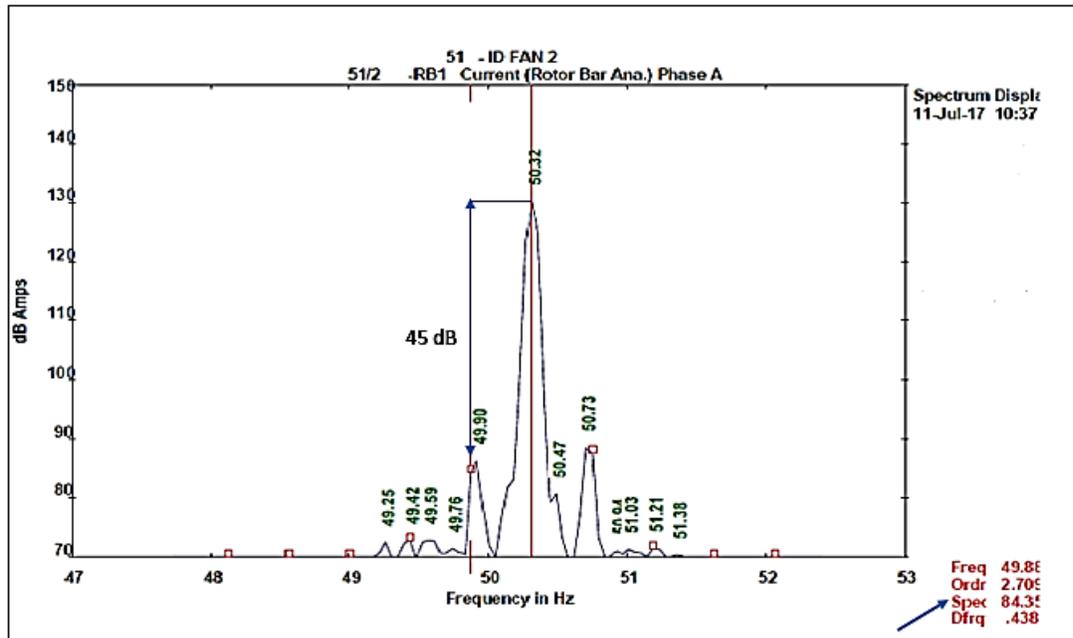


Fig 9- Current Signature frequency domain on 11-July 2017 Shows 45dB difference between line frequency Amplitude and Left sideband Amplitude.

In Fig 9, we can see the line frequency (50Hz) recorded an amplitude 130 dB approx., and two obvious sidebands which reflect the existence and the severity of the rotor bar defect. The amplitude of the left sideband as shown in red data recorded 84.35 dB, this value increase as the defect becomes more severe. In this signature which had been taken on 11-July -2017, the difference between the height of the line frequency 50Hz, and the height of the left first sideband was 45dB, this value is our indicator of rotor bar deterioration.

<b>dB</b>	<b>Rotor Condition Assessment</b>	<b>Recommendations</b>
> 60	Excellent	None
54 - 60	Good	None
48 - 54	Moderate	Trend Condition
42 - 48	High Resistance Connection or cracked rotor Bars	Increase Test Frequency And Trend
36 - 42	Broken Rotor bars will show In Vibration	Confirm With Vibration , Plan Repair , Replace
30 - 36	Multiple Cracked/ Broken Rotor Bars	Repair / Replace ASAP
< 30	Severe Rotor Fault	Repair /Replace Immediately

Fig 10- CAT III, Mobius Institute Manual, dB value, Rotor Condition, and Recommendations.

According to the previous table, the condition of the rotor bars of this motor is at a stage which needs a very close monitoring, the suspicion of cracked rotor bars exists. As a result, the frequency of the measurements has been increased to be twice per week and we introduced thermography activity to detect any expected overheat.

When a broken bar is present within the rotor, current cannot flow through it, and therefore, it can no longer add its share of torque to the rotors load burden. As the broken bar passes under the pole it will effectively reduce the torque of the rotor for the period of time it is under the field pole, in its torque producing position. Since the torque of the rotor is reduced slip is again introduced. As the rotor slows and the slip is increased, the voltage induced into the rotor is also increased, and therefore, the current in the good rotor bars will have to increase to produce the needed torque. This continues until the torque of the motor is restored to equal the torque of the load. When the broken bar is in a position where its contribution is not relied upon (traveling parallel to the lines of flux), the torque of the motor will go up and the opposite effect will be true. This beating is very clear in the time waveform. This analysis method is referred to in several ways - lower side band analysis, pole pass frequency sideband analysis, rotor bar

signature analysis, as well as a few others, [4]. Regardless of the name, the current spectrum surrounding the fundamental frequency is closely examined for the relative amplitude difference between the fundamental and what is referred to as the rotor bar sideband frequency (Frotorbar). The amplitude increase at the Frotorbar is due to the added current drawn in the rotor and also from the stator as the good bars attempt to make up for the one defective bar. As the amplitude increases at the rotor sideband frequency, the amplitude difference between the fundamental frequency, and the rotor bar frequency will go down. As the rotor bars break, and the health of the rotor continues to decline, this difference will also decline over time as the sideband frequency becomes more and more dominant in the signal, [4].

### 3.2.3 Data Interpretation – Second Snapshot:

After few days, we captured a new current signature to figure out the status of the dB value, the measurement conditions were the same and surprisingly the dB values dropped from 45dB to 42dB. This was a serious alarm for the bars condition and the deterioration rate. Moreover, the height of the lower sideband on the left side of the line frequency increased from 84.2 Hz to 90Hz, this indicates the rotor bar defect frequency and how the severity increases by the time. At 42dB, we can expect one rotor bar breakage. At this stage we issued our recommendation to stop the motor and pull it out to the workshop for immediate inspection, but unfortunately due to some production due dates we could not stop this motor. We increased the frequency of measurement either vibration or current signature to be on a daily-basis. We could notice the drop of dB value week by week.

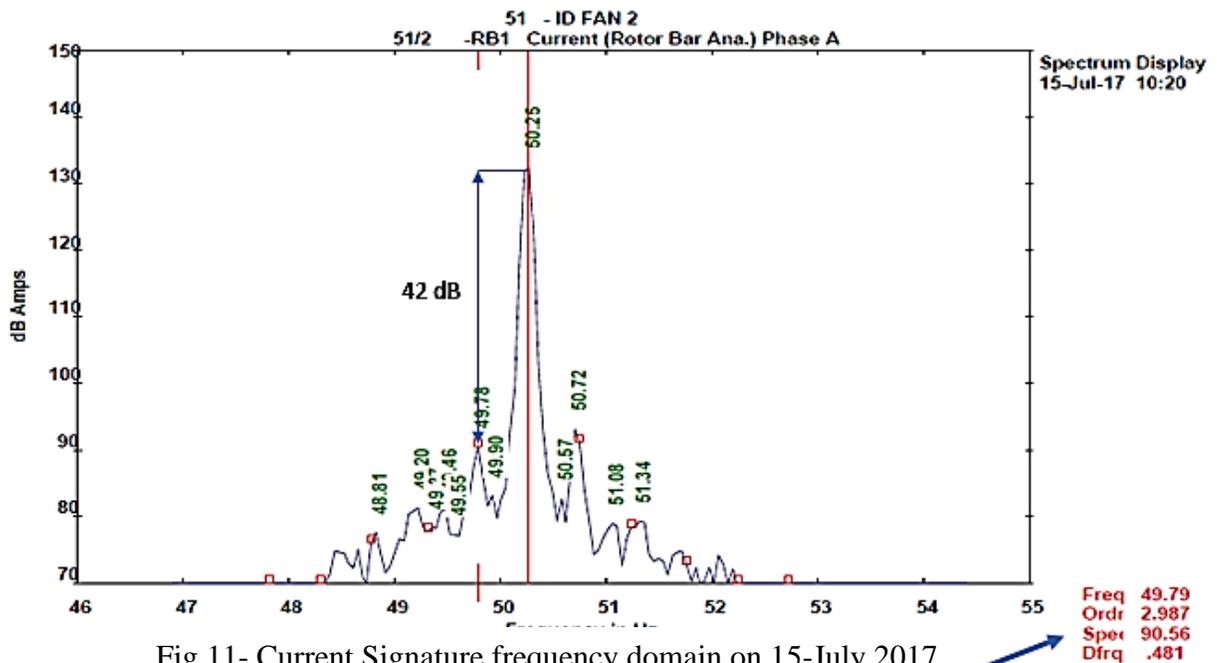


Fig 11- Current Signature frequency domain on 15-July 2017 Shows 42dB difference between line frequency Amplitude and Left sideband Amplitude.

### 3.2.4 Data Interpretation – Third Snapshot:

On 26<sup>th</sup> July-2017, the dB value dropped significantly to 34.3dB. At this stage -even its too late-, we decided to stop the motor and pull it out from the operation and send it to the workshop for inspection. You can clearly hear the humming sound close to motor area, and feel the beating you already see in the waveform.

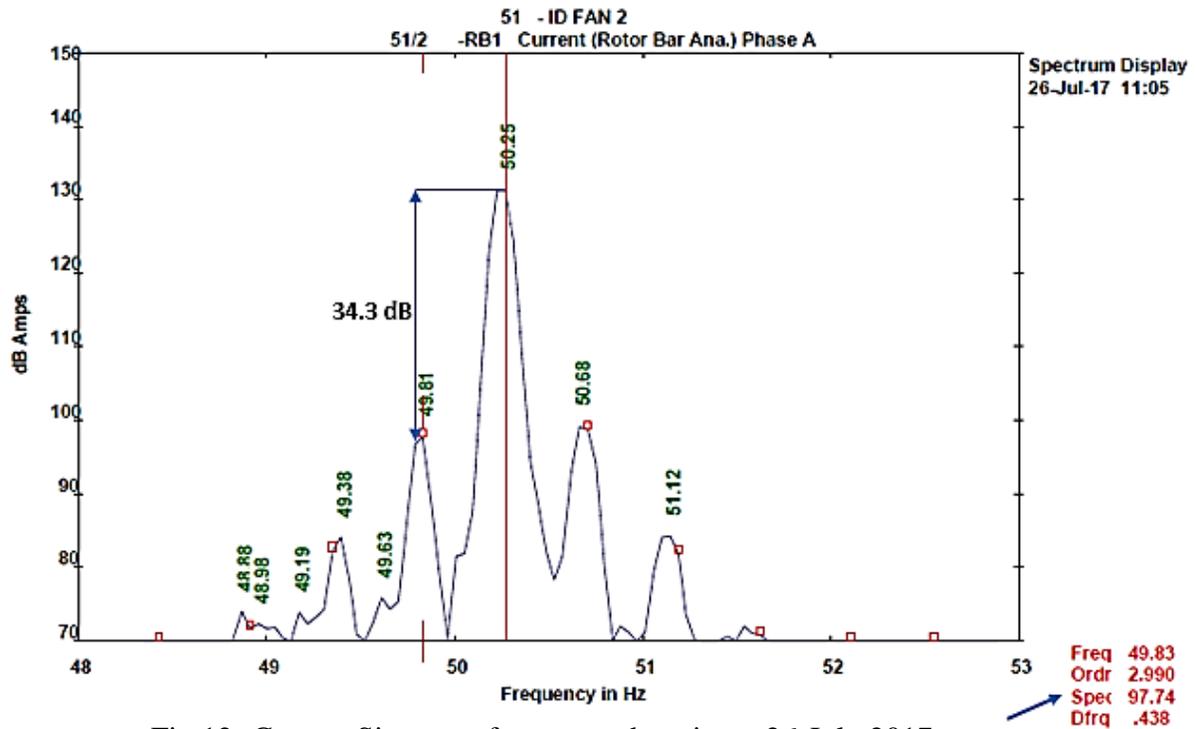


Fig 12- Current Signature frequency domain on 26-July 2017  
Shows 34dB difference between line frequency Amplitude and  
Lower Left sideband Amplitude.

### 3.2.5 Motor Visual Inspection in The Workshop:

By Pulling the motor out to the workshop and inspect it we found a completely broken bar fallen from its position on the rotor, three cracked bars, and parts of melted lamination.



Fig 13- One completely Broken Rotor Bar in The Motor

### 3.2.5 Estimating The Number Of Broken Rotor Bar:

$$N = \frac{2R}{(10^{n/20} + 3)}$$

(Thomson and Rankin 1987, [2])

N: Estimate of Number of Broken Bars

R: Number of Motor Slots

n: Average dB difference between upper and lower sidebands and supply component.

P: Pole Pairs

### 3.2.6 Applying the Equation:

$$N = \frac{2R}{(10^{n/20} + 3)} = \frac{2 \times 58}{(10^{39/20} + 3)}$$

$$N = 1.24 \text{ Bars}$$

It was therefore predicted that there was definitely one bar completely broken. There was also a risk of the broken bar lifting out of the slot with consequential mechanical damage to the stator winding.



Fig 14- The Equation validates the one broken bar existence.

## 4.CASE HISTORY 2

Fume Treatment Plant – ID Fan Motor # 4, EzzSteel, Suez, Egypt  
Case Information:

<b>Case Date</b>	Nov -2019
<b>Location</b>	EzzSteel Plant, Suez City, Egypt
<b>Division</b>	Melt Shop, Fume Treatment Plant
<b>Motor Brand</b>	WEG
<b>Duty</b>	Special
<b>Motor Power</b>	1.2 MW
<b>Supply Current</b>	50 HZ
<b>HP</b>	1630
<b>Volt</b>	11000
<b>Amp</b>	77.2
<b>RPM</b>	1000
<b>No. of Poles</b>	6
<b>No. of Slots</b>	58

### 4.1.1 Data Interpretation – First Snapshot:

In this case the dB value was 44dB, but we decided at this stage to pull out the motor to workshop to mitigate any further risk, and to avoid any damage as we experienced in the Case 1.

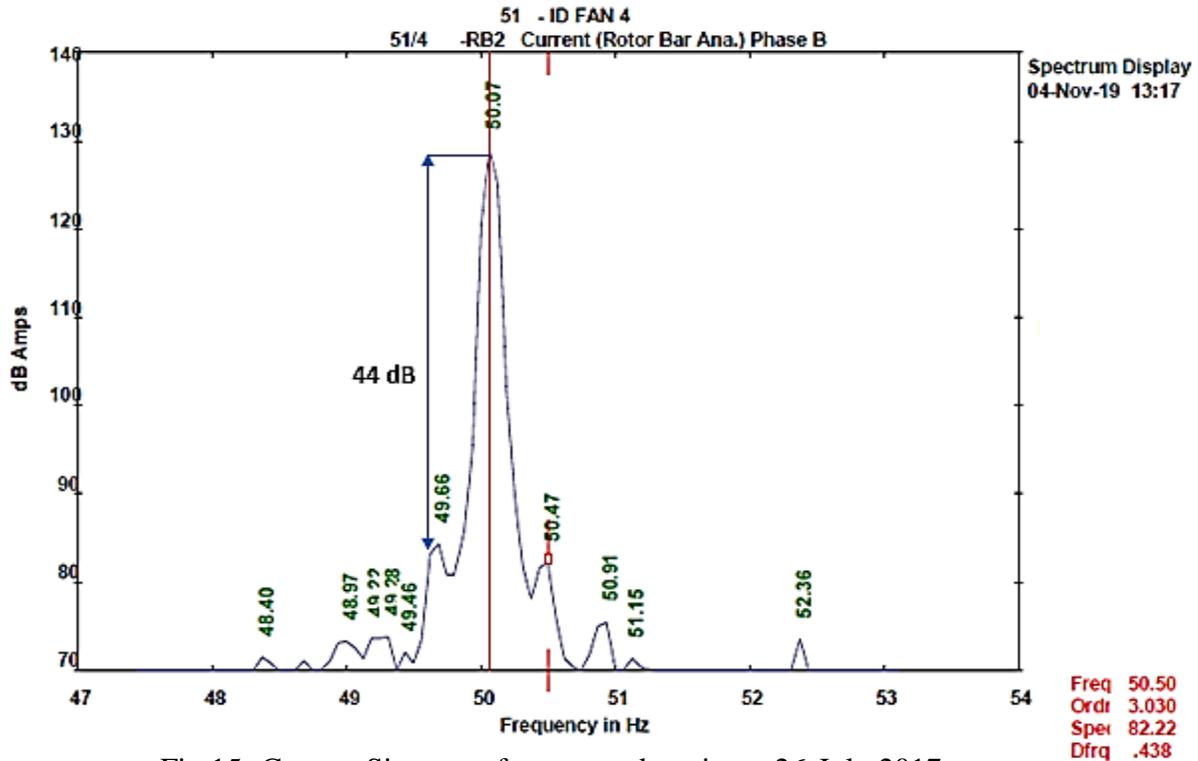


Fig 15- Current Signature frequency domain on 26-July 2017 Shows 44dB difference between line frequency Amplitude and Lower Left sideband Amplitude.

**4.1.2 Estimating the Number of Broken Rotor Bar:**

$$N = \frac{2 R}{(10^{n/20} + 3)} = \frac{2 \times 58}{(10^{44/20} + 3)}$$

N= 0.7 Bars

In this case, we could catch the severity level very early and the equation again proves the prediction of the existence of only cracked rotor bars, an no broken bars.



Fig 16- Two Cracked Rotor Bars

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