Advanced Motor Monitoring and Diagnostics

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INTRODUCTION

Modern motor protection relays incorporate various protection elements that include thermal overload, over current, over voltage, under voltage, under frequency, ground fault, current unbalance and other protections. Two new proposed methods can detect incipient faults making the protection more efficient.

- STATOR TURN FAULT

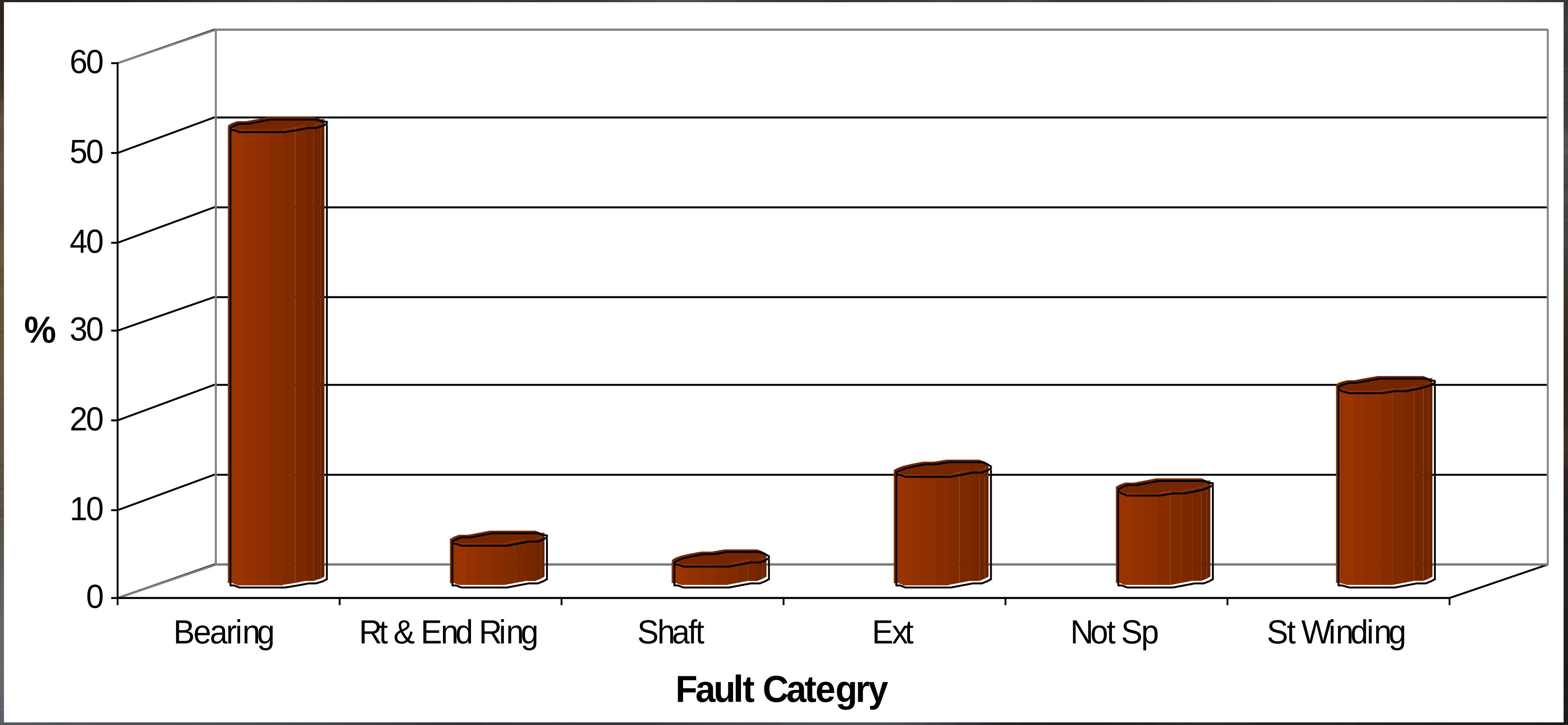
The proposed method is based on measuring the Cross Coupled Impedance of the motor.

- BROKEN ROTOR BAR

This paper discusses a diagnostic method using coherent demodulation in BRB detection, which utilizes one line or phase voltage and corresponding line current.

INTRODUCTION

Fault category of induction machine failure



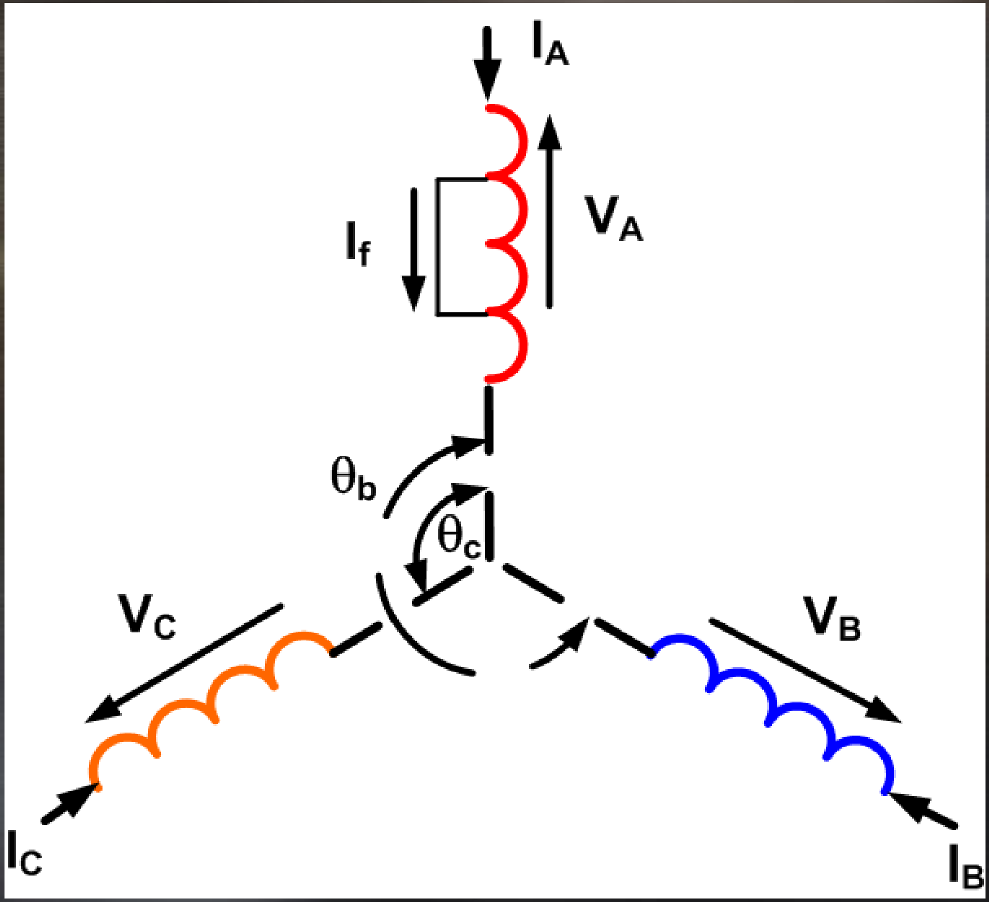
STATOR TURN FAILURE DETECTION

Cross Coupled Impedance as a Diagnostic Measure for Stator Turn Faults

N_s = total number of phase winding turns

N_f = number of faulted turns

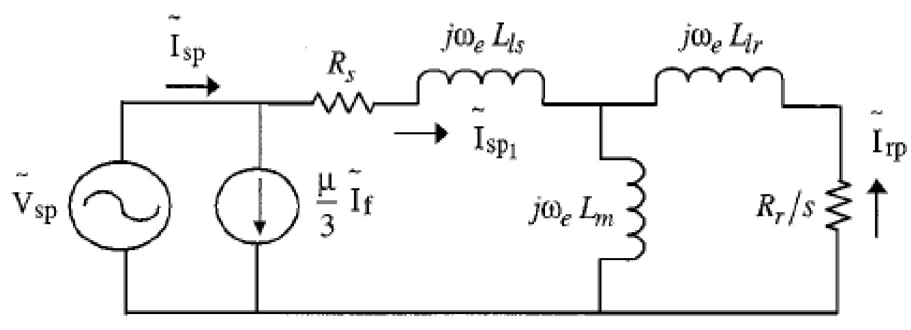
μ (severity of fault) = (N_f /N_s).



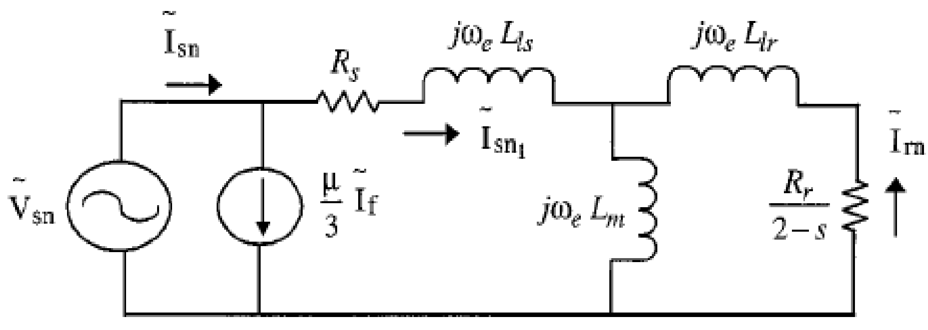
Stator winding with stator inter-turn fault on phase A

STATOR TURN FAILURE DETECTION

Cross Coupled Impedance as a Diagnostic Measure for Stator Turn Faults (continued)



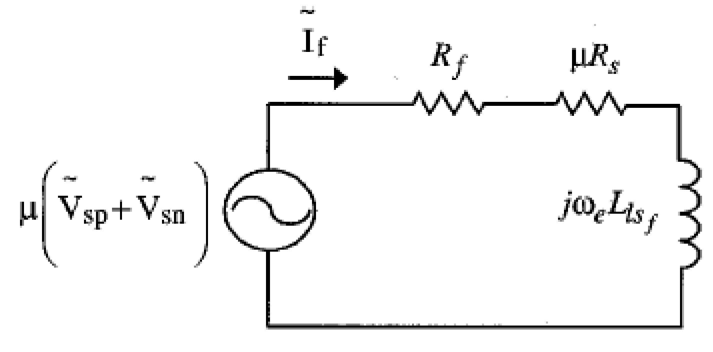
(a)



(b)

Equivalent circuits of a faulty motor (Based on Steinmetz model).

a) Positive-sequence line current component.
b) Negative-sequence line current component
c) Fault current



(c)

STATOR TURN FAILURE DETECTION

Detailed derivation for stator turn fault detection algorithm

$$V_{sp} = (R_s + jX_s)\left(I_{sp} - \frac{1}{3}\mu I_f\right) + jX_m I_{rp}$$

$$V_{sn} = (R_s + jX_s)\left(I_{sn} - \frac{1}{3}\mu I_f\right) + jX_m I_{rn}$$

$$0 = (R_r/s + jX_r)I_{rp} + jX_m\left(I_{sp} - \frac{1}{3}\mu I_f\right) \qquad \text{(A1)}$$

$$0 = (R_r/(2-s) + jX_r)I_{rn} + jX_m\left(I_{sn} - \frac{1}{3}\mu I_f\right)$$

$$\mu(V_{sp} + V_{sn}) = \mu(1 - 2\mu/3)(R_s + jX_{ls})I_f$$

Where R_s and R_r are the stator and rotor resistances respectively. X_s and X_r are the stator and rotor self-impedances respectively. $X_s = X_{ls} + X_m$ and $X_r = X_{lr} + X_m$. The leakage and magnetizing inductances are X_{ls}, X_{lr} and X_m respectively. I_f is the fault current.

$$\begin{bmatrix} V_+ \\ V_- \end{bmatrix} = \begin{bmatrix} Z_{pp} & Z_{pn} \\ Z_{np} & Z_{nn} \end{bmatrix} \begin{bmatrix} I_+ \\ I_- \end{bmatrix} \qquad \text{(A2)}$$

Where V_-, I_-, V_+, I_+ are negative and positive sequence voltages and currents, Z_{xx} are cross-coupling impedances. Further on:

$$\begin{bmatrix} Z_{pp} & Z_{pn} \\ Z_{np} & Z_{nn} \end{bmatrix} = \begin{bmatrix} Y_{pp} & Y_{pn} \\ Y_{np} & Y_{nn} \end{bmatrix}^{-1}$$

STATOR TURN FAILURE DETECTION

Detailed derivation for stator turn fault detection algorithm (cont.)

Equation A2 can be simplified with a valid approximation that, $Z_{pn} << Z_{pp}$.

$$\begin{aligned} V_+ &= Z_{pp} I_+ + Z_{pn} I_- \approx Z_{pp} I_+ \\ V_- &= Z_{np} I_+ + Z_{nn} I_- \end{aligned} \qquad \text{(A3)}$$

Using equation A3, the ratio of Z_{np} to Z_{pp} is computed as shown below.

$$\frac{Z_{np}}{Z_{pp}} = \frac{\dfrac{V_- - Z_{nn} I_-}{I_+}}{\dfrac{V_+}{I_+}} = \frac{V_- - Z_{nn} I_-}{V_+} \qquad \text{(A4)}$$

- For a perfectly symmetrical machine Z_{pn} and Z_{np} in A2 are zero.
- In practice the values are small non-zero quantities.
- When a fault occurs, cross-coupling terms values will increase.
- The normalized cross-coupled impedance (ratio of Z_{np} to Z_{pp}) is the key operating signal expressed in A4.

STATOR TURN FAILURE DETECTION

Stator Turn Fault Detection Algorithm

Method properties:

1. Load independence
2. Robustness to system imbalance
3. Machine independence

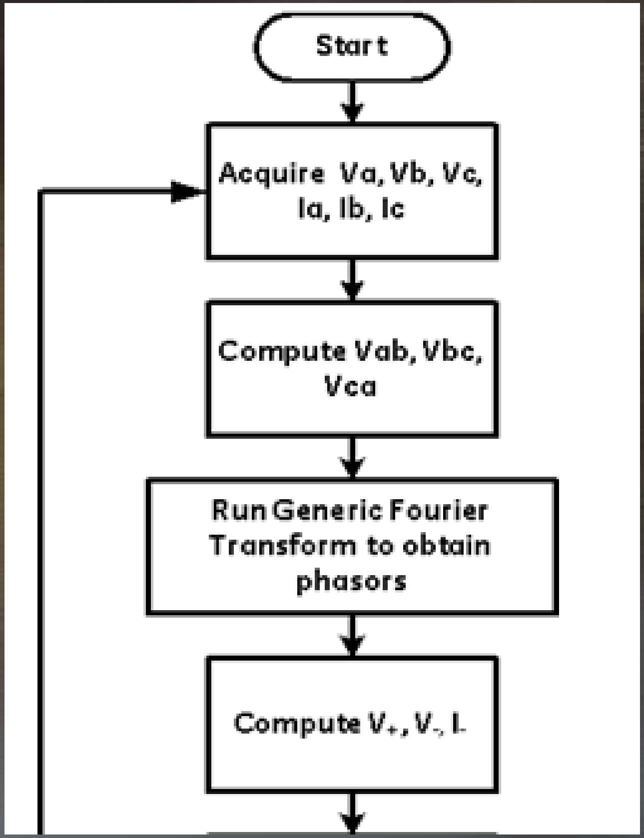
The following inputs are required to run the algorithm:

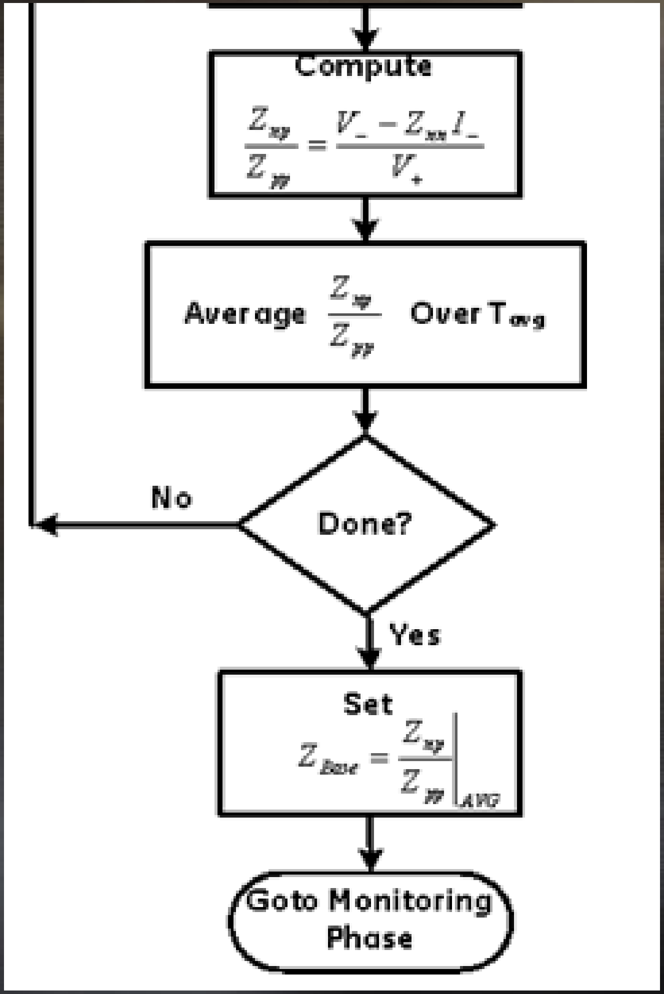
1. Negative sequence impedance (Znn).
   a. Directly from supplier
   b. Obtained from test during commissioning
   c. From heuristic method
2. Machine ratings – Line-to-line RMS voltage (VLL), Power (HP) and number of poles.
3. Averaging window (T_{avg}) – 2.5 sec / 5 sec / 10 sec / 20 sec.
4. User defined threshold limits – TH1 and TH2.

The algorithm has two sections Learning Phase and Monitoring Phase:

STATOR TURN FAILURE DETECTION

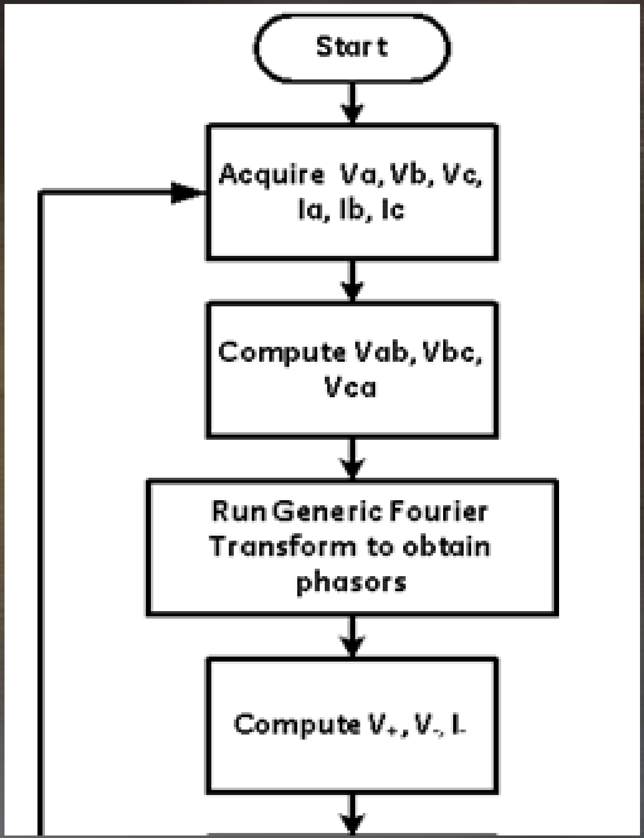
Learning Phase Algorithm Flowchart

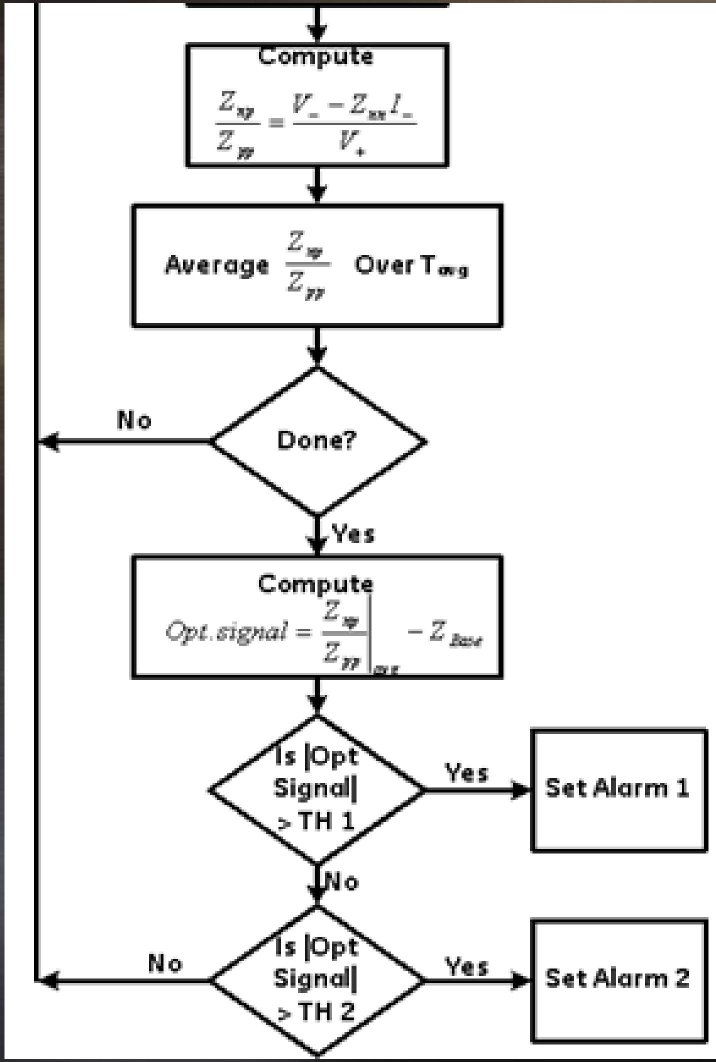




STATOR TURN FAILURE DETECTION

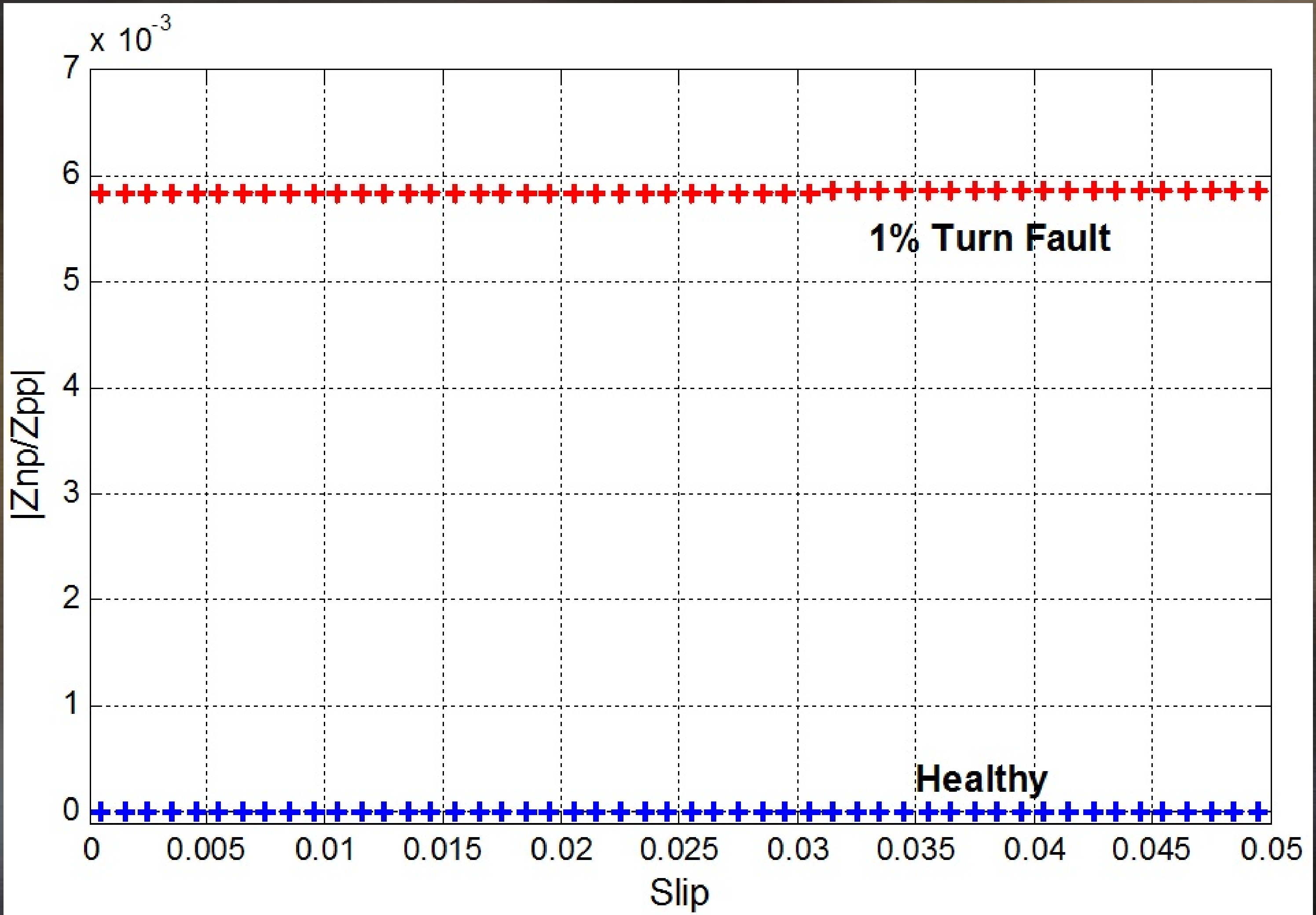
Monitoring Phase Algorithm Flowchart





STATOR TURN FAILURE DETECTION

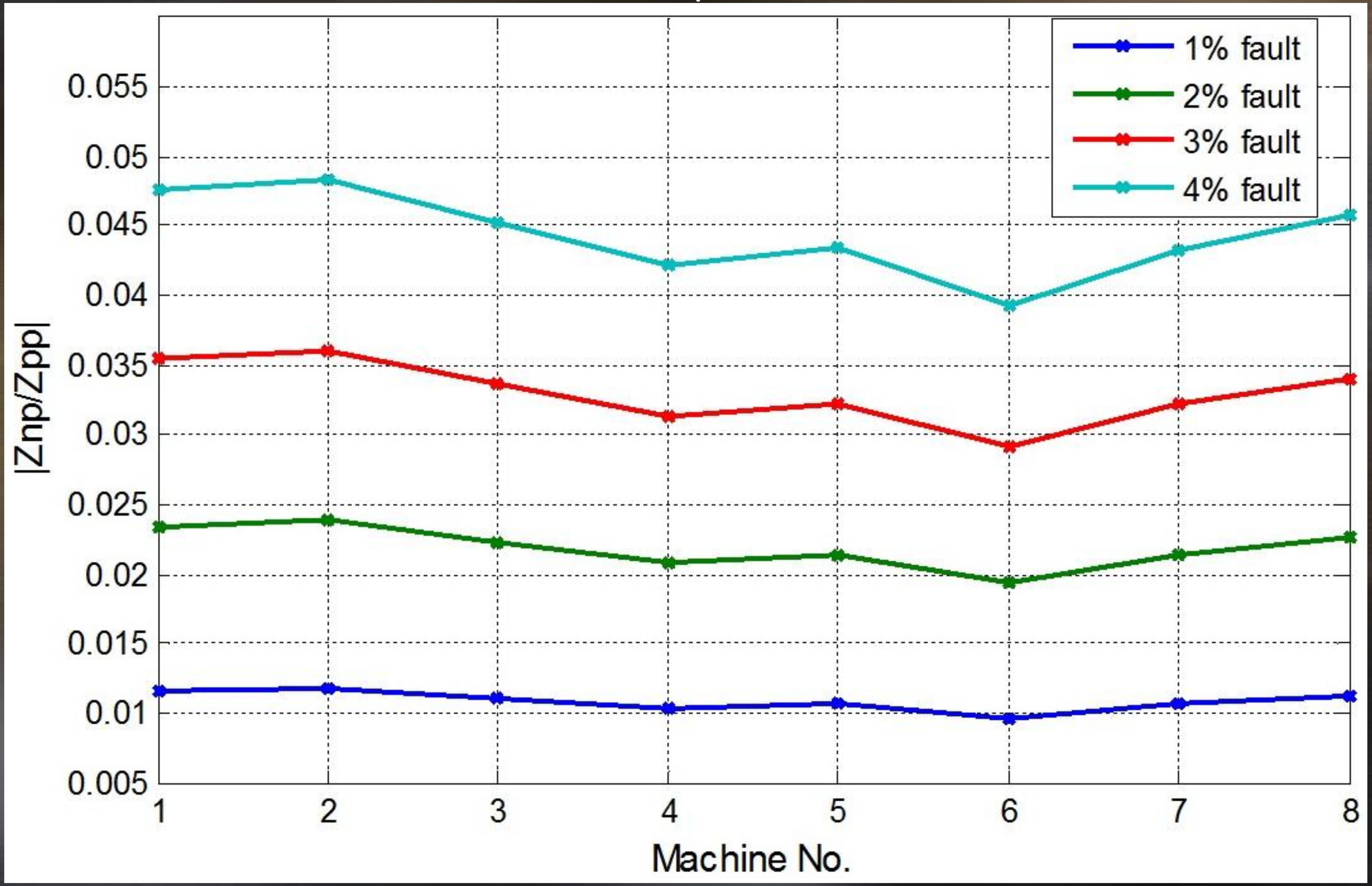
Simulation and Experimental Results



Simulation results of load independency of algorithm

STATOR TURN FAILURE DETECTION

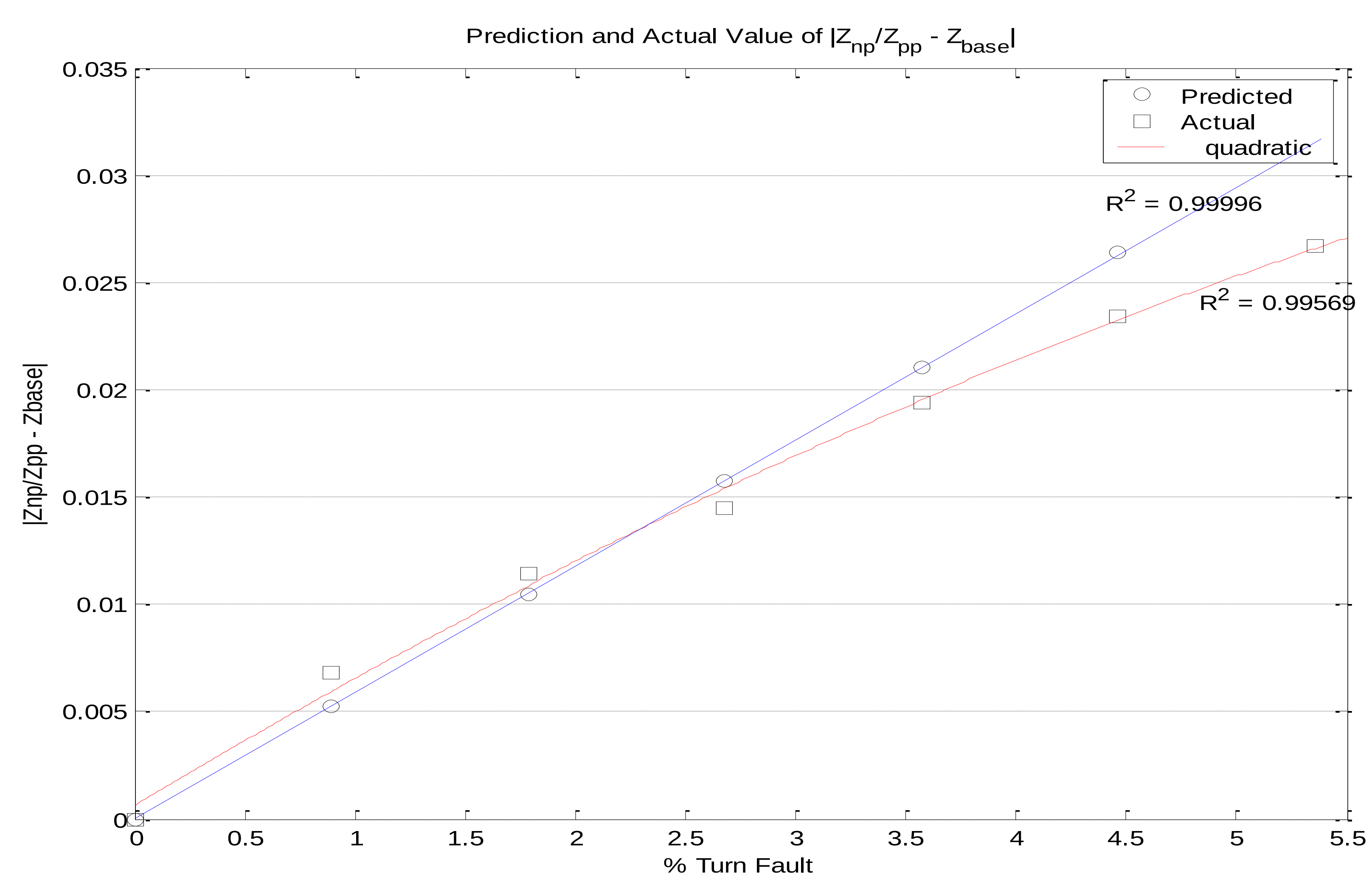
Simulation and Experimental Results



Simulation results of machine independency of algorithm

STATOR TURN FAILURE DETECTION

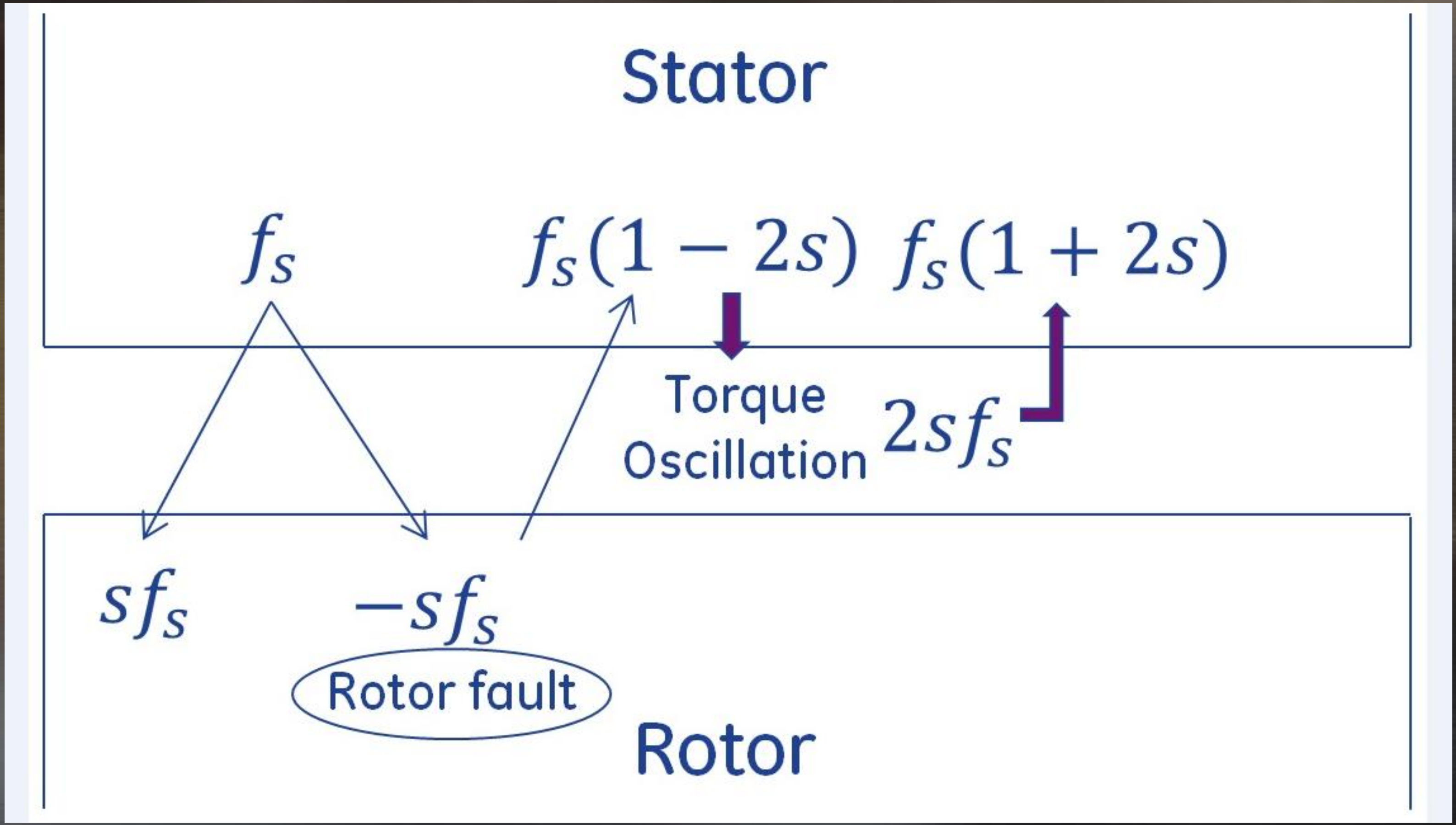
Simulation and Experimental Results



Comparison of predicted and actual operating signal

BROKEN ROTOR BAR DETECTION

Double Slip Frequency Component as a Measure of the Broken Rotor Bar Fault



Theoretical representation of induced rotor bar fault signature in stator currents

BROKEN ROTOR BAR DETECTION

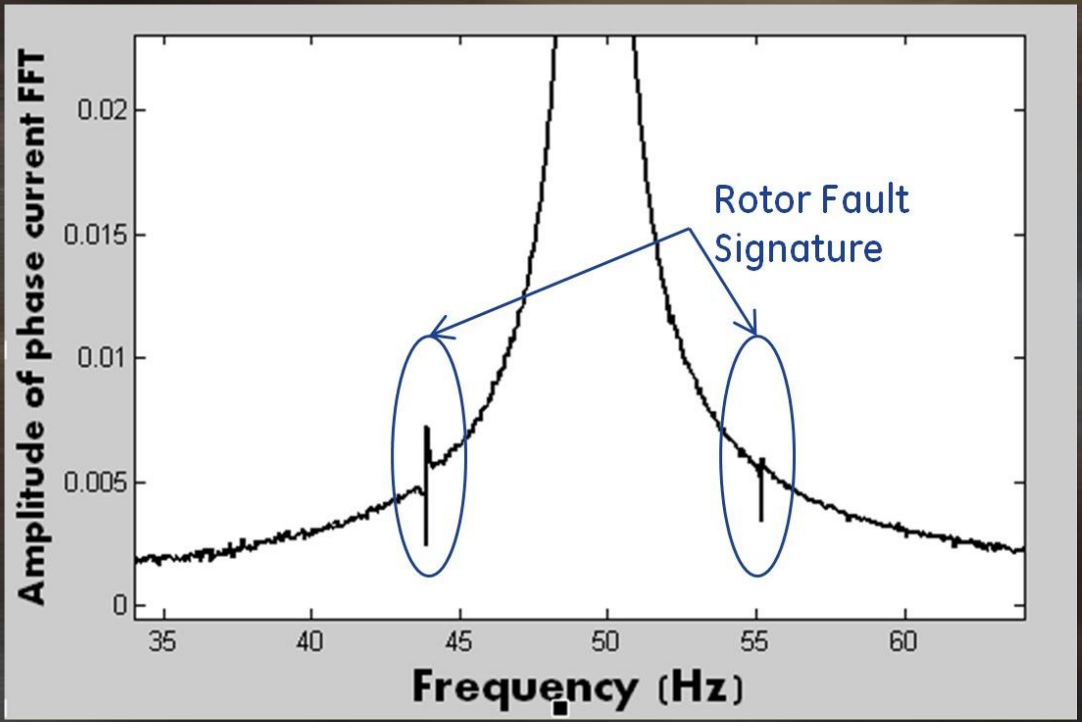
Double Slip Frequency Component as a Measure of the Broken Rotor Bar Fault

- Healthy rotor current frequency is (sf_s).
- BRB creates an asymmetry forming a negative rotating magnetic field at slip frequency ($-sf_s$) in the rotor.
- This creates current at $f_s(1-2s)$ frequency in the stator.
- This causes electromagnetic torque and speed oscillation at twice the slip frequency and $f_s(1+2s)$ component in the stator.
- This sequence repeats resulting in stator current at $f_s(1\pm2ns)$, where n is an integer and s is the slip.
- The strongest fault signature is at frequency $f_s(1\pm2s)$.

BROKEN ROTOR BAR DETECTION

Conventional Approach to Rotor Broken Bar Detection

Fast Fourier Transformation (FFT) of stator current of induction machine with rotor bar fault



- The rotor fault signature component $f_{signature}=f_s(1\pm 2s)$ is very close to the supply frequency in the spectrum.
- The frequency spectrum provides weak contrast to detect the fault signature component due to the proximity of $f_{signature}$ and f_s.

BROKEN ROTOR BAR DETECTION

Modified Method for Rotor Broken Bar Detection

- Coherent Demodulation Approach.
- Increased contrast between fault signature and supply frequency achieved by multiplying two signals.

Consider the line voltage and current as

$$v_{ab} = V_m \cos \omega t$$

$$i_a = I_m \cos(\omega t - \theta) + I_{f1} \cos(\omega_1 t - \theta_1) + I_{f2} \cos(\omega_2 t - \theta_2)$$

Where,

$$\omega_1 = \omega - \omega_f$$

$$\omega_2 = \omega + \omega_f$$

$\omega =$ Supply frequency

$\omega_f = 2sf_s =$ Twice the slip frequency

BROKEN ROTOR BAR DETECTION

Modified Method for Rotor Broken Bar Detection

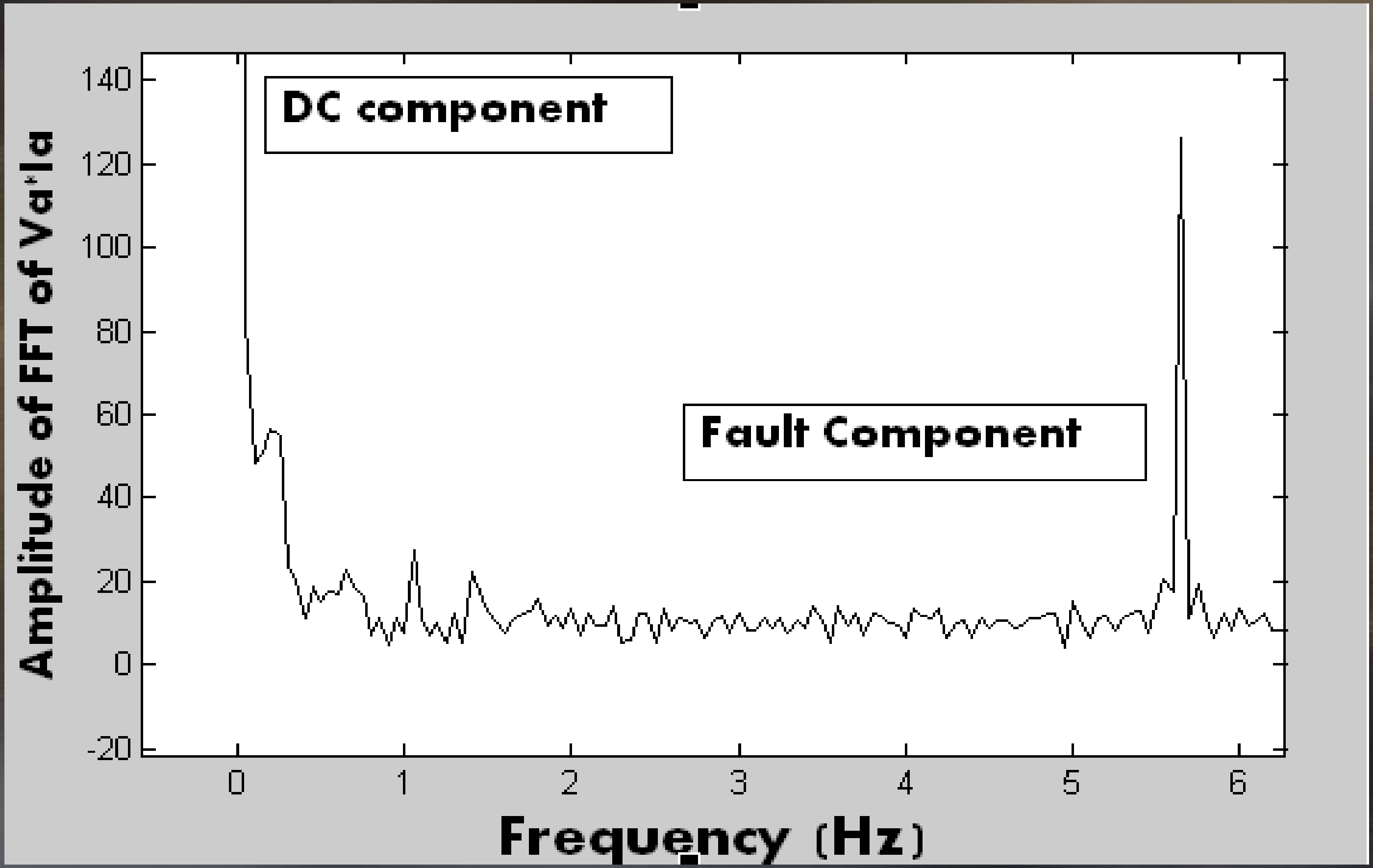
$$v_{ab}i_a = V_m \cos \omega t \ (I_m \cos(\omega t - \theta) + I_{f1} \cos(\omega_1 t - \theta_1) + I_{f2} \cos(\omega_2 t - \theta_2)) \quad \text{(A5)}$$

$$v_{ab}i_a = \frac{V_m I_m}{2} \cos \theta + \frac{V_m I_{f1}}{2} \cos(\omega_f t + \theta_1) + \frac{V_m I_{f2}}{2} \cos(\omega_f t - \theta_2) - \frac{V_m I_{f2}}{2} \cos(2\omega t - \omega_f t + \theta_2) - \frac{V_m I_m}{2} \cos(2\omega t + \theta) - \frac{V_m I_{f1}}{2} \cos(2\omega t + \omega_f t + \theta_1) \quad \text{(A8)}$$

- Applying standard mathematical transformations, initial equation A5 is rearranged to equation A8.
- The first term of the equation A8 shows the magnitude of the DC component.
- Similarly, the second and third components represent the fault frequency.
- Other components are around twice the supply frequency.

BROKEN ROTOR BAR DETECTION

Modified Method for Rotor Broken Bar Detection

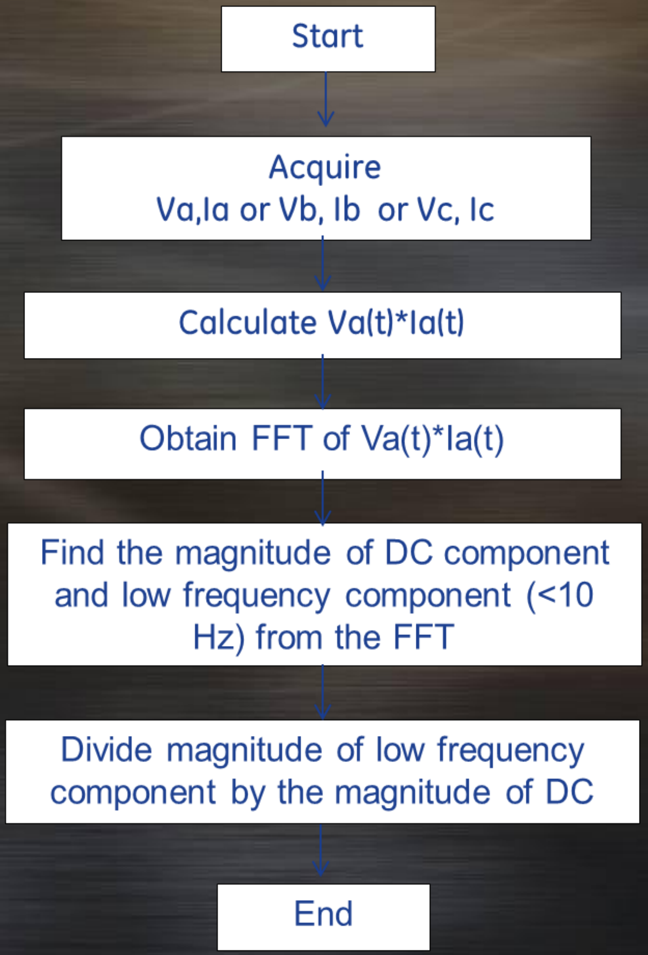


FFT of demodulated stator current of induction machine with rotor bar fault

BROKEN ROTOR BAR DETECTION

Algorithm for Broken Rotor Bar Detection

- Only one line voltage and one line current required.
- No motor parameters information needed.
- Measured low frequency fault component is divided by the DC component.
- This normalization reduces the slip or load dependency of the fault signature.



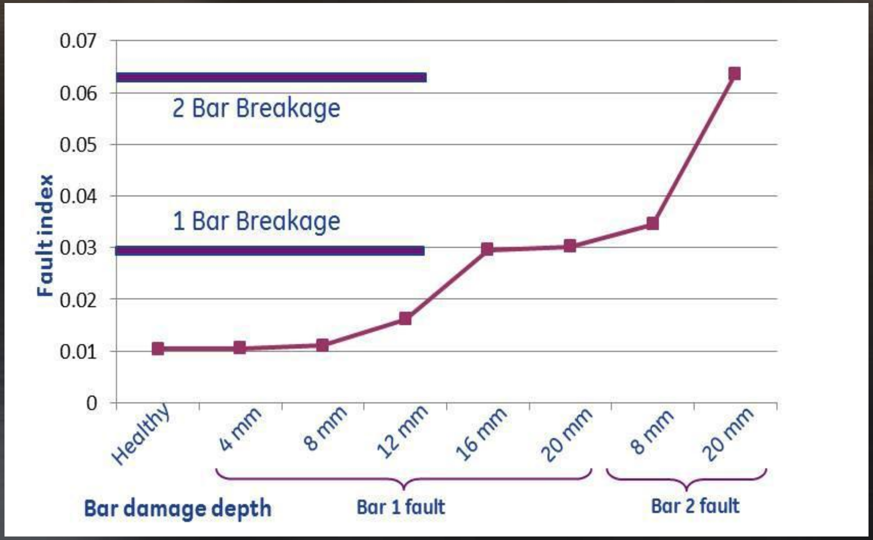
Flowchart of coherent demodulation with FFT for rotor fault detection

BROKEN ROTOR BAR DETECTION

Partial breakage of the rotor bar

- Test motor has 22 bars. Bar diameter is 18mm.
- The depth of drilled hole was increased: 4, 8, 12, 16 and 20mm.

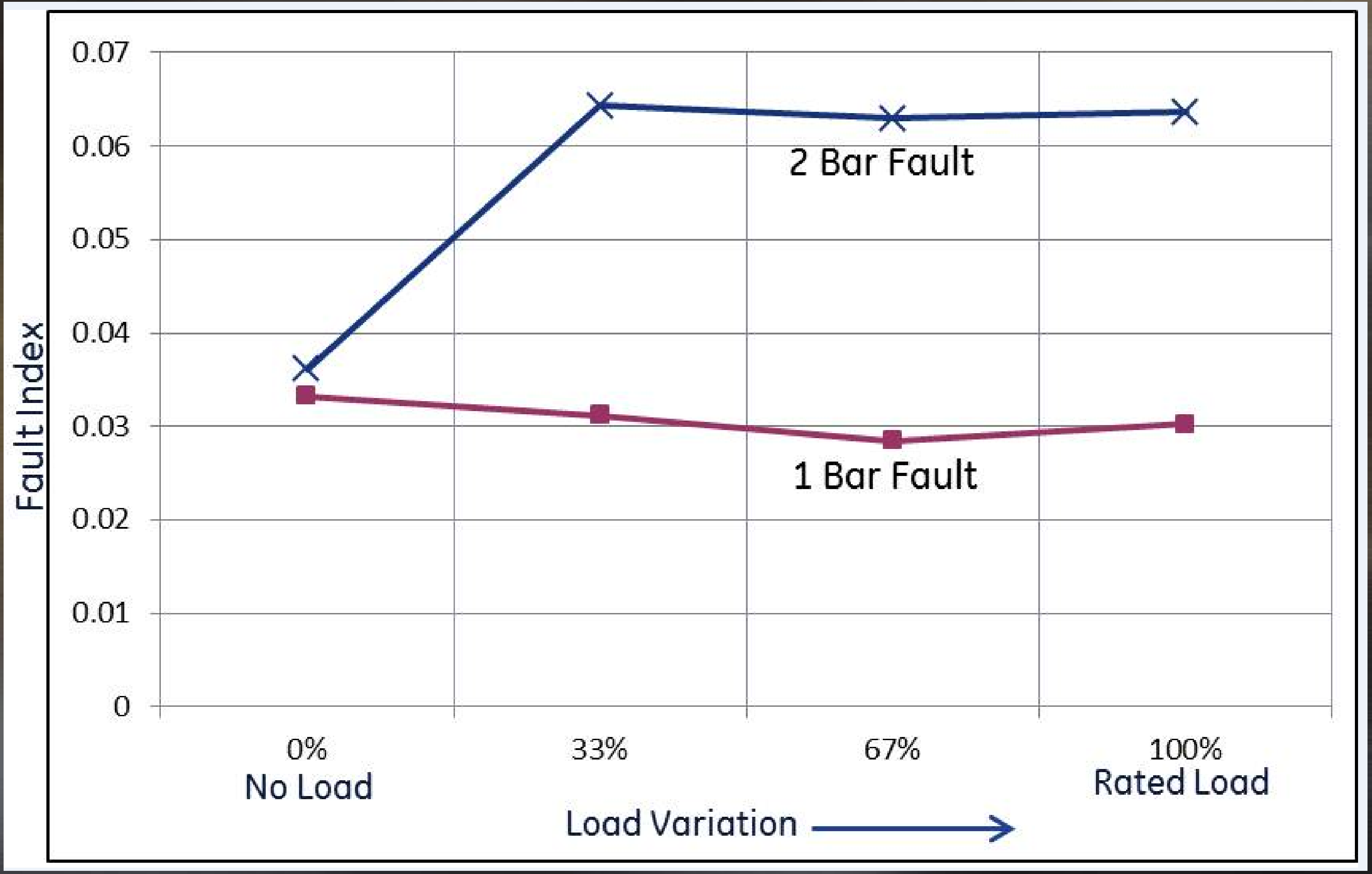
- Clear difference between one bar and two bar breakages.
- 12 mm hole on one bar is clearly detectable.
- A healthy condition does not have a fault index of zero due to asymmetry.



Experimental results of partial breakage detection

BROKEN ROTOR BAR DETECTION

Slip independence in the working region of the motor



Experimental results for slip independent feature of algorithm

CONCLUSIONS

- A novel method of detection of stator-turn failure in induction motors based on normalized cross coupled impedance calculations is proposed. The algorithm is simple to implement, accurate, robust and free from user involvement. It is designed for running on microprocessor based relays.
- A novel algorithm for broken rotor bar detection using coherent demodulation is also discussed which provides better detection compared to the conventional method. The unique fault signature is capable of detecting partial rotor bar damage and it is practically independent of the operating condition of the motor.

Thank You

Questions?