Case Study, 38th Turbomachinery Symposium

Title:

Torsional – Lateral Coupled Vibration of Centrifugal Compressor System at Interharmonic Frequencies Related to Control Loop Frequencies in Voltage Source PWM Inverter

Abstract:

Centrifugal compressor train in a refinery experienced high vibration problem due to torsional resonance. Sidebands in the VFD output current based on VFD control loop frequencies were identified as the root cause. In this VFD, stator current was used for torque and speed control, hence control loop frequencies had a potential to generate such sidebands. Frequencies of this type of sidebands widely vary with the rotation speed (proportional to harmonics of the fundamental frequency), hence it is difficult to avoid resonance at the train torsional natural frequency. In addition, even if a compressor system is proven to have sufficient safety margin against high cycle fatigue failure due to the torque pulsation by this mechanism, such minute torque pulsation may have a potential to excite high lateral vibration at speed adjusting gear. If unpredicted or overlooked during design stage, such high vibration may disturb plant operation. This case study therefore proposes guidelines to predict such vibration levels by a simplified torsional-lateral coupled vibration analysis.

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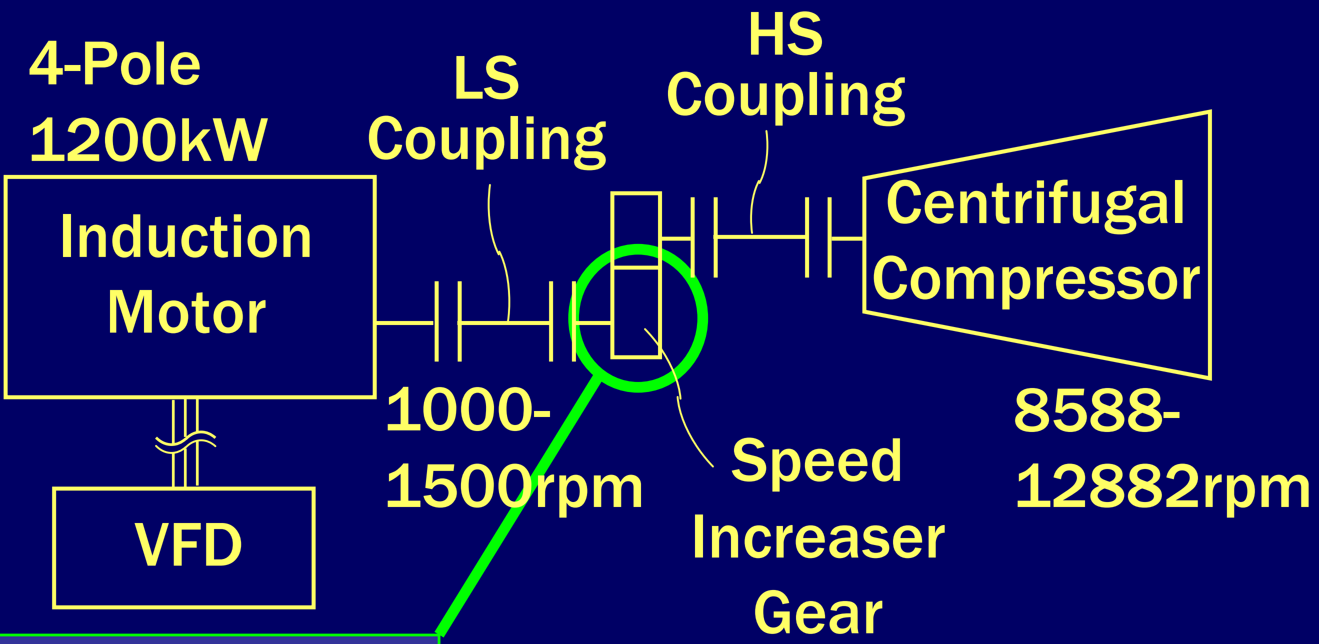
Introduction

Train Data

VFD Induction Motor + Gear + Centrifugal Compressor



4-Pole
1200kW

Induction Motor

VFD

LS Coupling

1000-1500rpm

HS Coupling

Speed Increaser Gear

Centrifugal Compressor

8588-12882rpm

High vibration was sometimes observed at gear LS shaft

Figure 1. Compressor Train

Onset of Problem

Lateral Vibration on Low Speed Gear Shaft

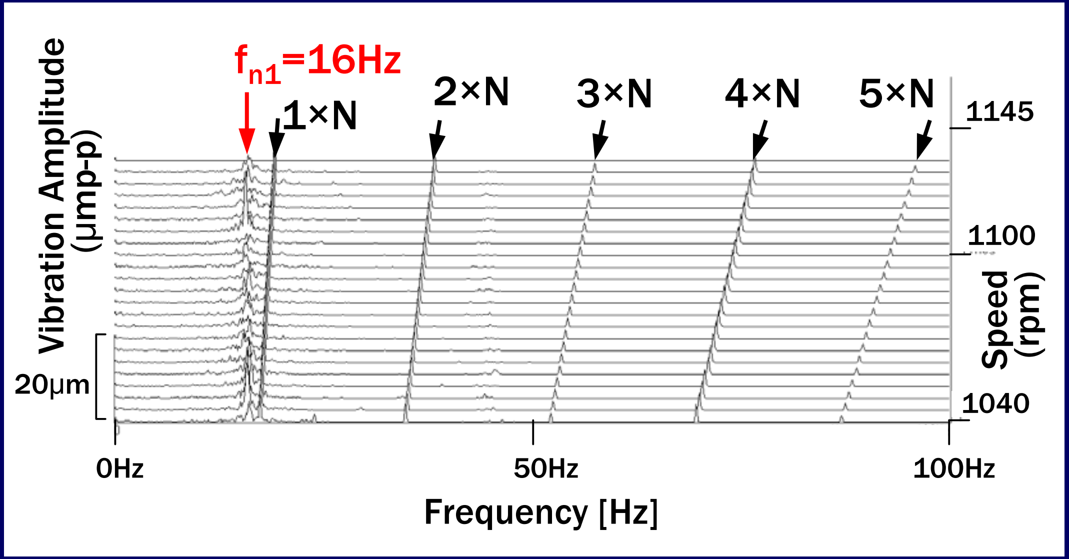


Figure 2. Cascade Plot of LS Gear Shaft Vibration

50μm (p-p) Vibration Detected on LS Gear Shaft around 1040-1140rpm (17.3-19.0rps), 570kW

Dominant Frequency Component: ca. 16Hz

Close to Calculated 1st Torsional Natural Freq. f_{n1} （ 15.71Hz ）

No Significant Vibration on Compressor Shaft or Motor Shaft

Onset of Problem

Lateral Vibration on High Speed Gear (Pinion) Shaft

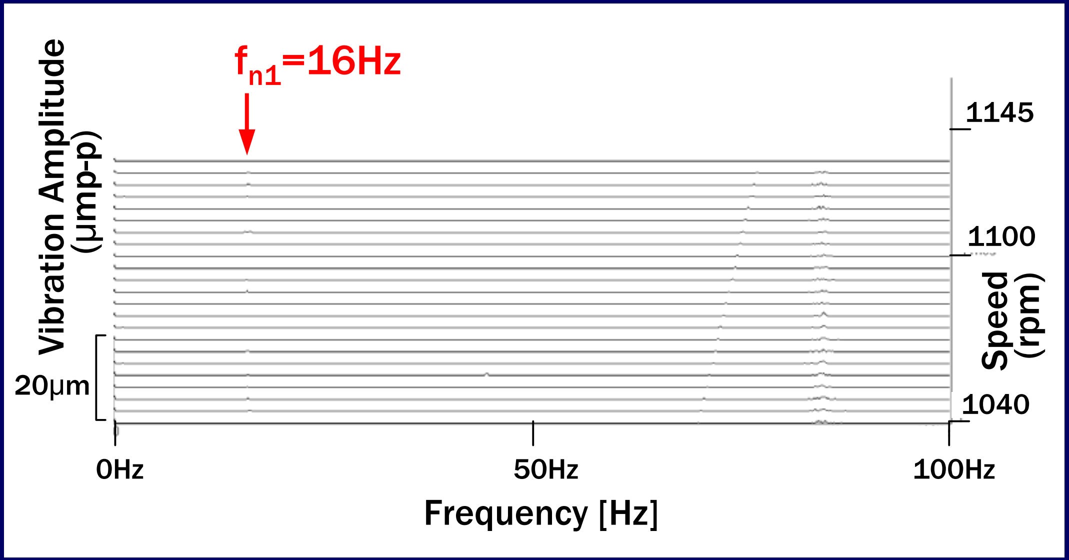


Figure 3. Cascade Plot of HS Gear Shaft Vibration

Max. 10µm (p-p) Vibration with 16Hz Detected on HS Gear Shaft

Lower Vibration on HS Gear Shaft

⬆

Stiffer Pinion Bearings Than Bull Gear Bearings at Part-Load Due to Uploading Bull Gear and Downloading Pinion

\+

Pinion Lighter Than Bull Gear

Concern: What is the Excitation Source?

Torsional Natural Frequencies

Analysis for Torsional Natural Frequencies (FEM)

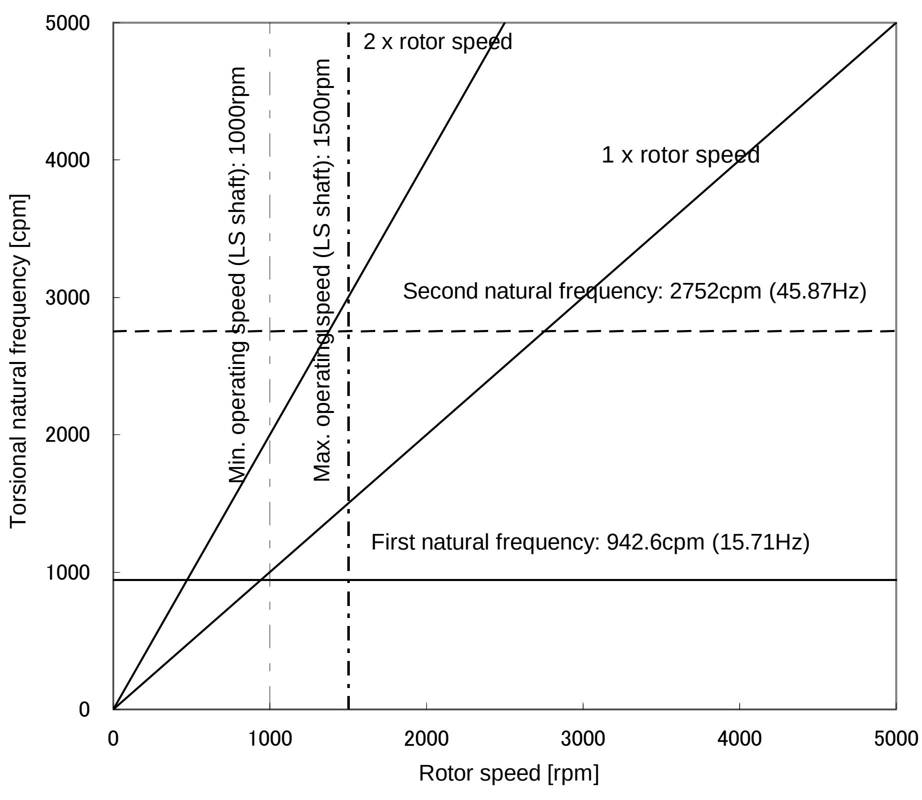


Figure 4. Campbell Diagram for Torsional Vibration

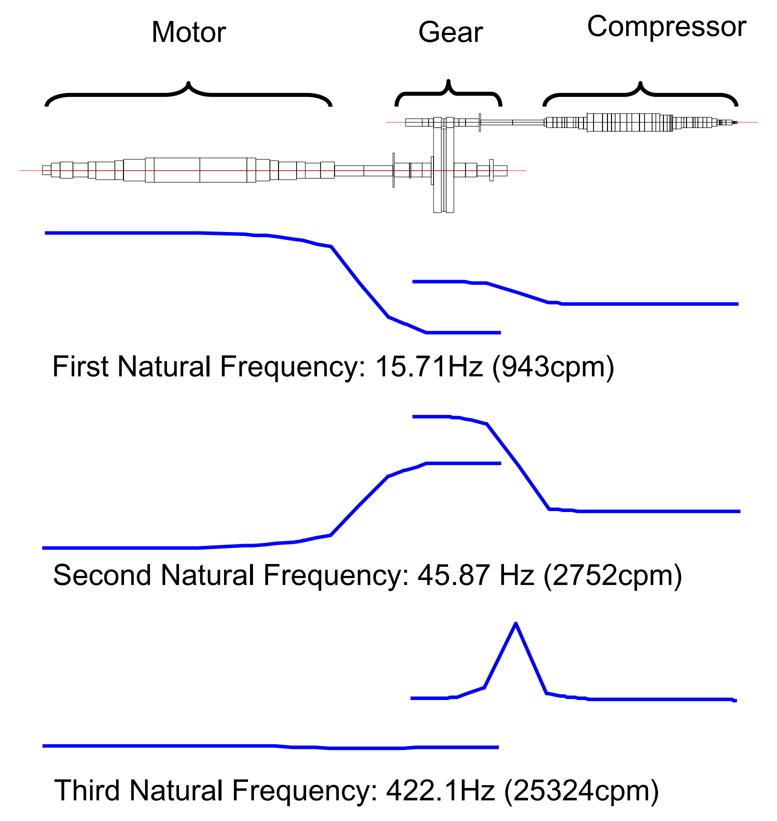


Figure 5. Torsional Vibration Mode Shapes

Critical Speeds Predicted by Rotor Analyses

Lateral & Torsional Vibration Calculation

Critical Speeds [rpm]

		First	Second	Operating Speed
Lateral	Compressor	5220	17700	8588-12882
	Pinion (HS Shaft)	21200-25600 Dependent on Load	-	8588-12882
	Bull Gear (LS Shaft)	3380-9450 Dependent on Load	-	1000-1500
	Motor	2078	-	1000-1500
Torsional		943	2752	

Shaft Synchronous Resonance is Excluded. Only Possibility = VFD?

Estimation of Shaft Torque and Motor Torque

Estimation of Shaft Torque Causing 50μm Shaft Vibration

Shaft Torque Deduced by One-Way Lateral-Torsional Analysis

Force Applied on Teeth Causing 50μm (p-p) Shaft Vibration

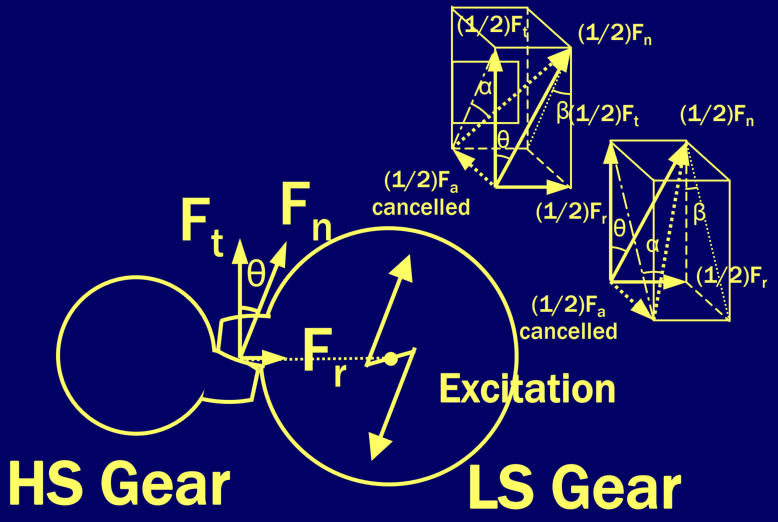


Figure 6. Force Applied
on Gear Teeth
(Double Helical)

Transverse Pressure Angle θ

$\theta = \tan^{-1}(\tan\alpha/\cos\beta)$

α= Normal Pressure Angle

β= Helix Angle

$$T_t = (PCD/2) \times F_t$$
$$= (PCD/2) \times F_n \times \cos\theta$$

Estimation of Shaft Torque and Motor Torque

Lateral Vibration Analysis of LS Gear Shaft

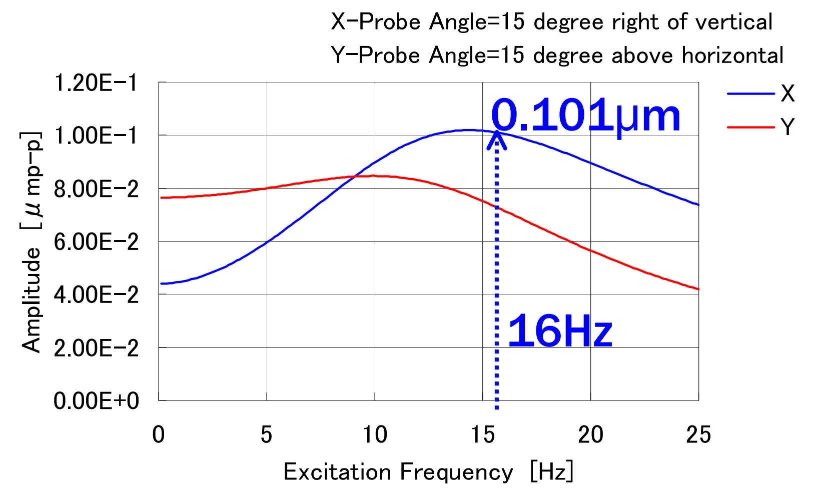


Figure 7. Frequency Response to Unit Excitation Force of Gear Shaft

(Bearing Stiffness and Damping Calculated @ 1140rpm, 570kW)

Unit Excitation on Tooth Surface

$F_{n\_p.u.}=9.8 \cdot \sin(2\pi f_{n1} t)$ [N]

LS Gear Shaft Vibration Amplitude at Probe @ 16Hz

=0.101μm (p-p) (Calculated)

$F_n=9.8\times(50/0.101)=4851$ [N]

$T_t = (PCD/2) \times F_n \times \cos\theta$

$= (0.806/2) \times 4851 \times \cos 21.9°$

$= 1815$ [N·m]

➡ 0.213 Times Rated Torque

Estimation of Shaft Torque and Motor Torque

Estimation of Excitation Torque at Motor Air Gap

Amplification Factor for Torsional System

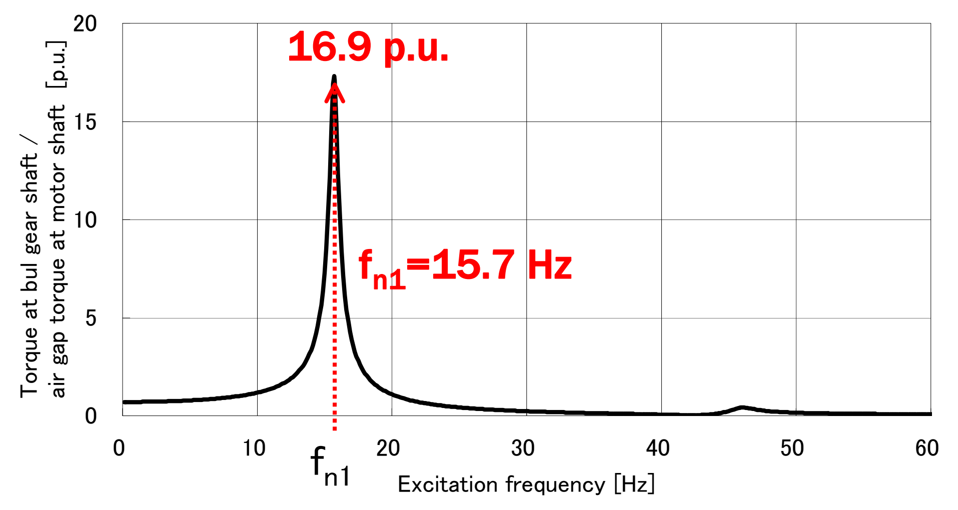


Figure 8. Frequency Response at LS Gear Shaft Assuming $\zeta = 0.02$

$$T_{AG} = 1815 / 16.9$$
$$= 107 \ [\mathrm{N \cdot m}]$$

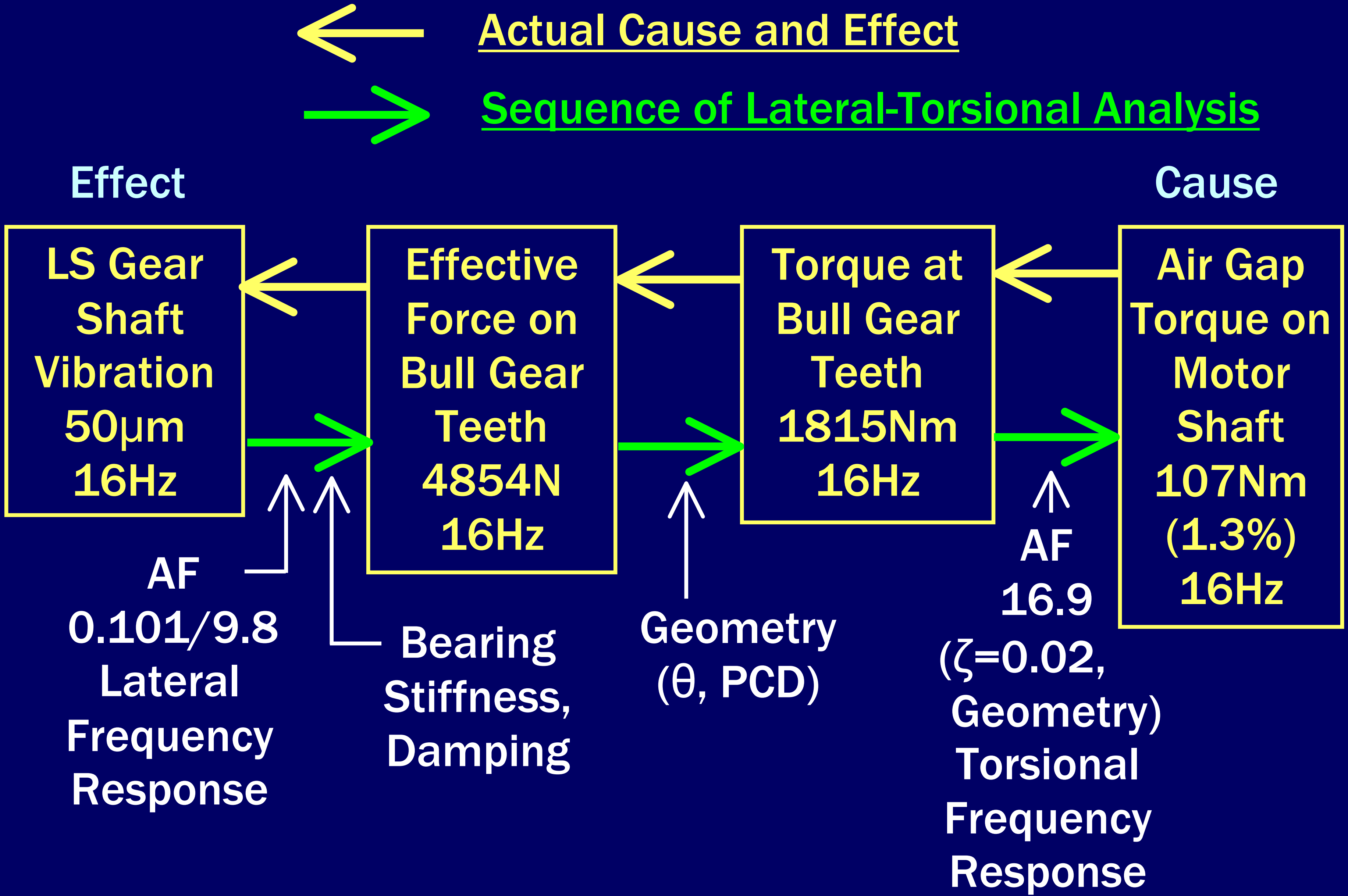
↓

1.3％Rated Torque at Motor Air Gap Suspected.

Close to Maximum Measured Data among Interharmonic Frequencies during Factory Test (1.5％Rated Torque)

Merely 1.3% of air gap torque fluctuation can cause 50 μm p-p lateral vibration!

Cause and Effect



← Actual Cause and Effect

→ Sequence of Lateral-Torsional Analysis

Effect

Cause

LS Gear Shaft Vibration 50μm 16Hz

Effective Force on Bull Gear Teeth 4854N 16Hz

Torque at Bull Gear Teeth 1815Nm 16Hz

Air Gap Torque on Motor Shaft 107Nm (1.3%) 16Hz

AF 0.101/9.8 Lateral Frequency Response

Bearing Stiffness, Damping

Geometry (θ, PCD)

AF 16.9 (ζ=0.02, Geometry) Torsional Frequency Response

Strength Evaluation

High Cycle Fatigue Evaluation

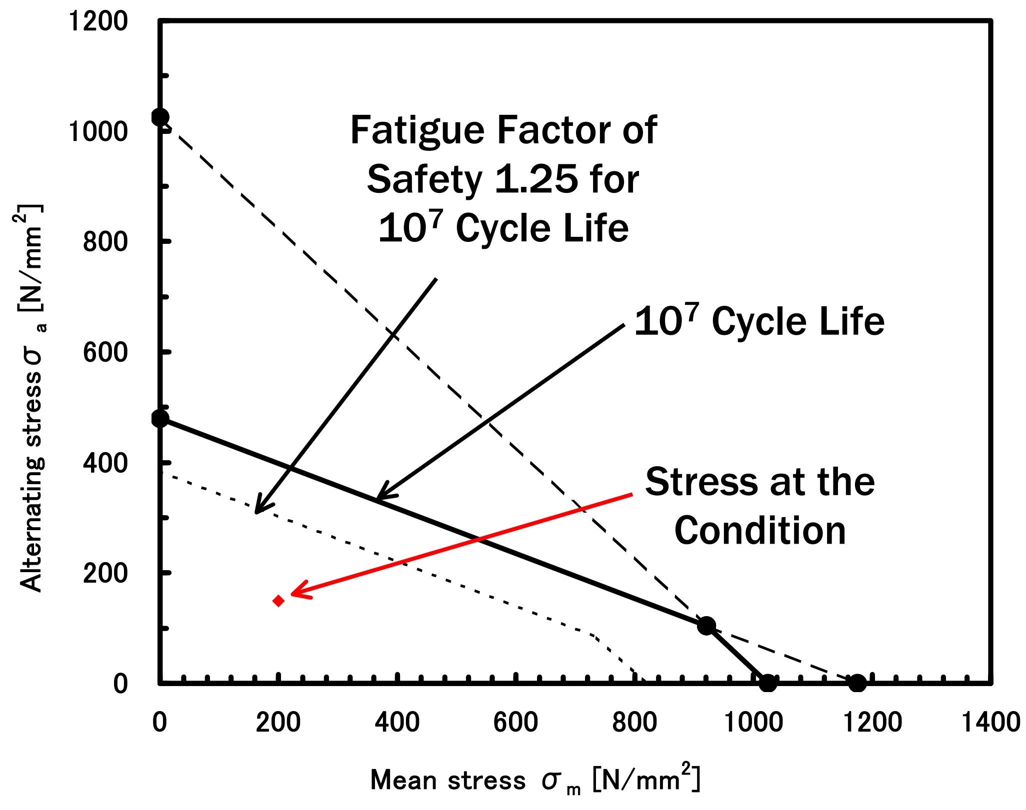


Figure 9. Modified Goodman Diagram

Mechanical Strength Verified

No Modification Made on Machinery or VFD

Investigation of Source of Excitation Torque

Detailed Measurement (LS Gear Shaft Vibration)

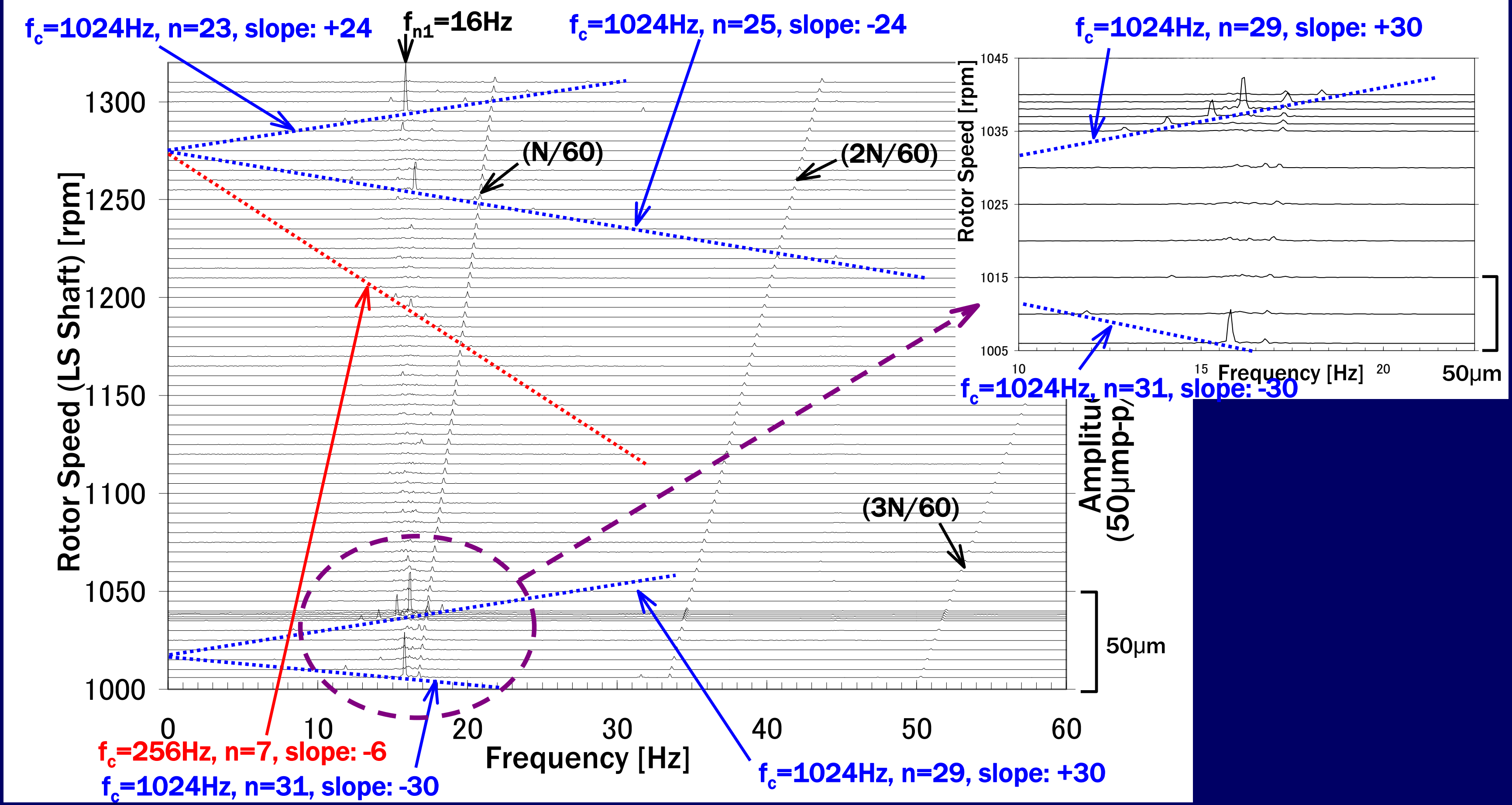


Figure 10. Cascade Plot of LS Gear Shaft Vibration

Investigation of Source of Excitation Torque

Detailed Measurement (VFD Output Current)

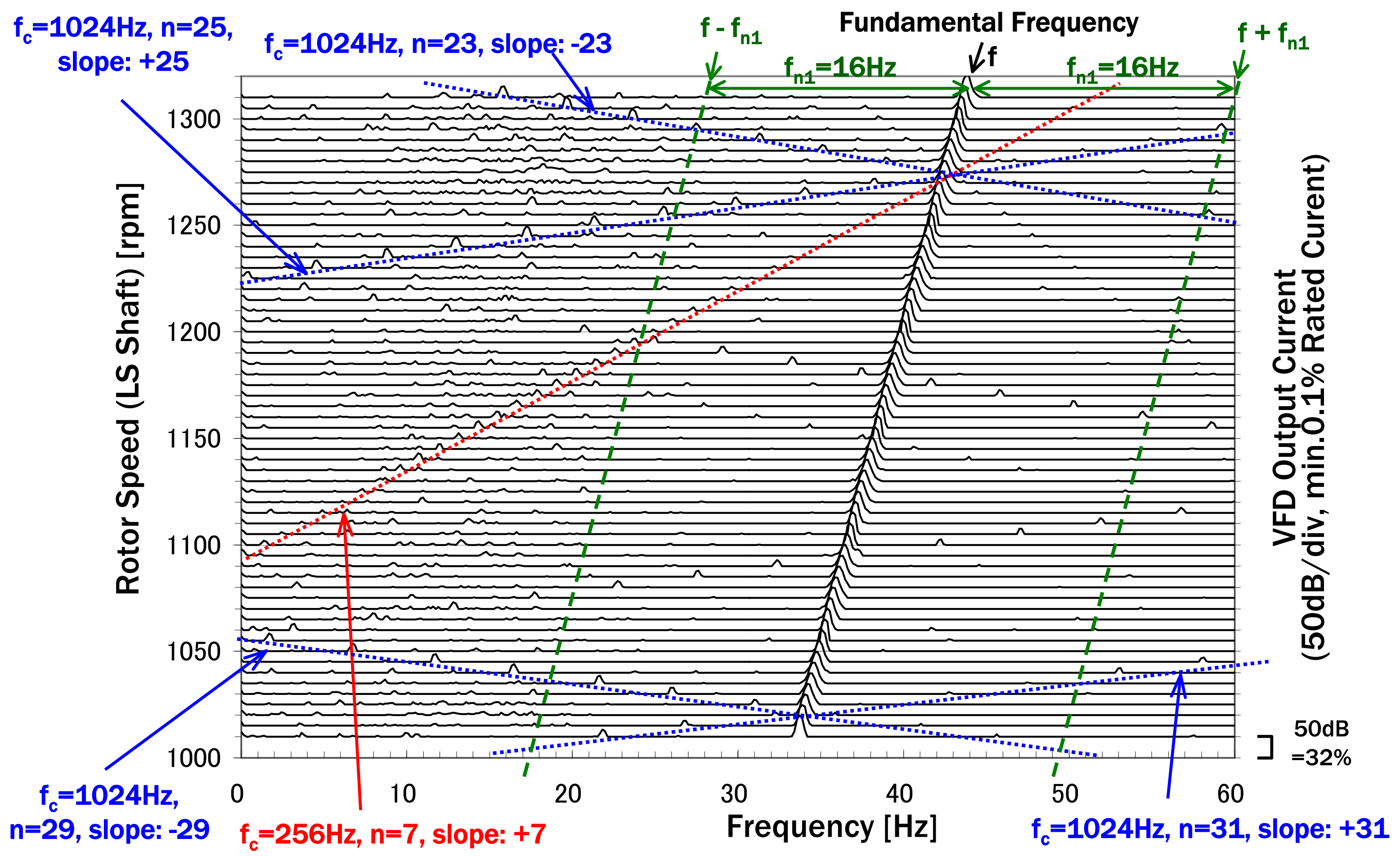


Figure 11. Cascade Plot of VFD Output Current

Pattern of Interharmonic Frequency Component

Inclined Streaks of Interharmonic Frequencies in Shaft Vibration Frequencies and VFD Output Frequencies

- **LS Shaft Vibration Frequency Content**

  Difference of Harmonics of Multiples of 6 and Sampling Frequencies of VFD (1024Hz, 256Hz)

- **VFD Output Current Frequency Content**

  Difference of Harmonics of Odd Numbers Other Than Multiples of 3 and Sampling Frequencies of VFD

  Inclination Opposite to That of Shaft Vibration

↓

Firm Correlation Between Shaft Vibration and VFD Output Current Suspected

Pattern of Interharmonic Frequency Component

Relation of Between Shaft Vibration Frequencies and VFD Output Frequencies

VFD Output Freq. [Hz]:

$f_{bi} = |f_c - nf|$ ← Sideband Frequencies

Shaft Vibration Freq. [Hz]:

$f_{bt} = |f_c - (n \pm 1)f|$

f : VFD Fundamental Freq. [Hz]

f_c : Arbitrarily Existing Constant Freq. [Hz]

n : Positive Odd Integer Other Than 3

Frequencies of Fluctuating Torque Generated by 3-Phase IM

$T_e = pM' I_{s\_a}' I_r' \cdot (9/4) \cdot \sin(2\pi(f_a - f)t + \gamma)$

If $f_a = f_{bi} = |f_c - nf|$

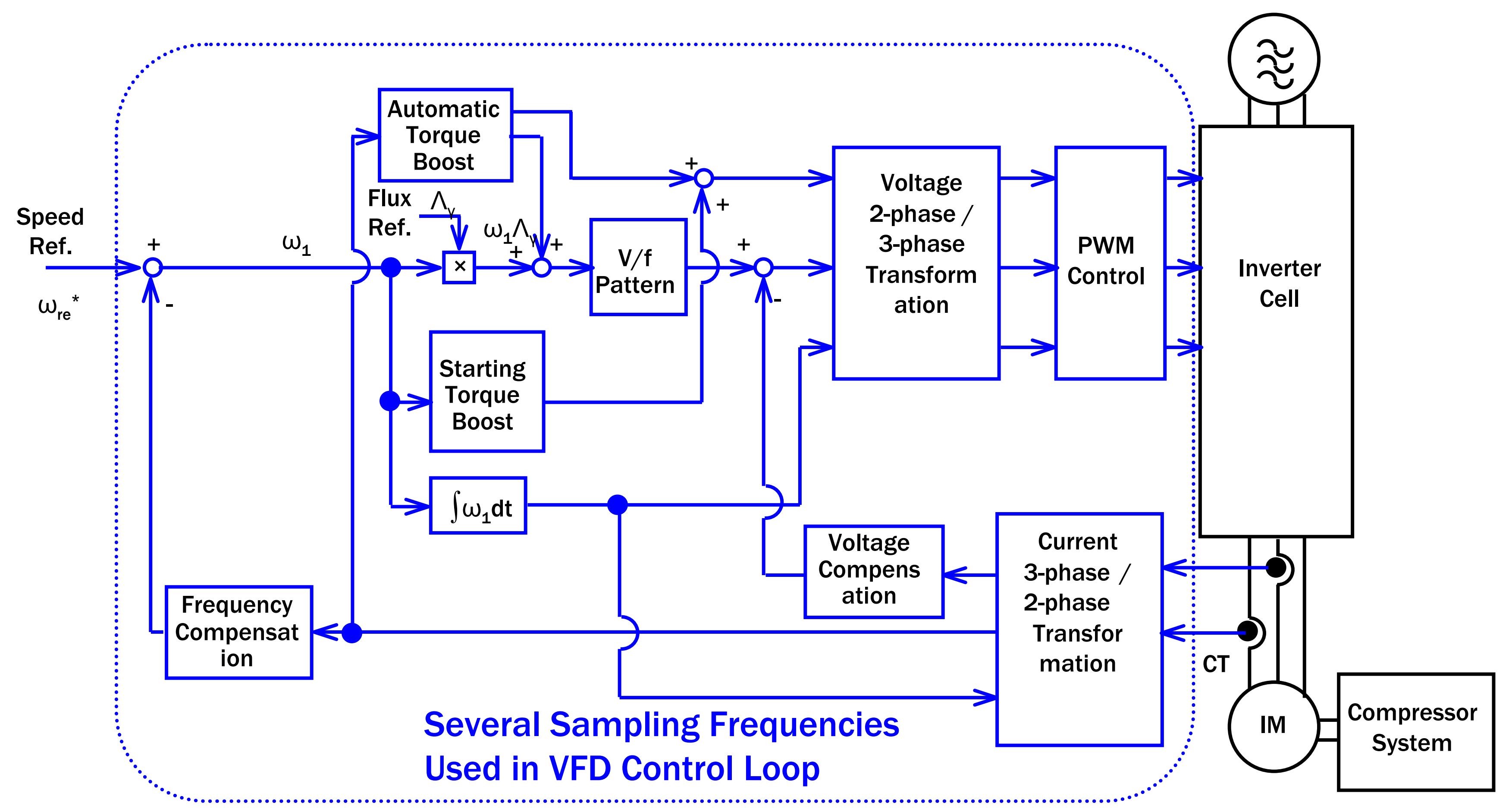
$T_e = pM' I_{s\_a}' I_r' \cdot (9/4) \cdot \sin(2\pi(\underline{|f_c - (n \pm 1)f|})t + \gamma)$

f_a : Arbitrarily Existing Current Freq. [Hz]

⇨ Shaft Vibration Caused by Excitation of Motor Torque

Sampling in VFD

VFD Control Loop



Several Sampling Frequencies Used in VFD Control Loop

Figure 12. Block Diagram of VFD Control System

Assumed Cause of Sideband

Assumed Cause of Sideband in VFD Output Current

Coarse Pulse of Fundamental Frequency Remained in Current (e.g. Improper Dead Time Compensation)

↓

Harmonics of Odd Numbers Produced by Pulse (Rectangular Wave) of Fundamental Frequency

↓

Harmonics of Multiple of 3 Eliminated in Balanced Three-Wire System

↓

Sideband Frequencies Raised by Modulation between Harmonic Frequencies and Sampling Frequencies Occurred in VFD Control Loop → Harmonics enhance sidebands.

Other Possible Cause of Sideband

Sideband Frequencies Due to PWM

Sum and Difference of Frequencies of Harmonics of Triangular Carrier Wave (4.8kHz) and Harmonics of Signal Wave (Fundamental Frequency)

Sideband Frequencies Due to PWM Not Observed in This VFD Output Current

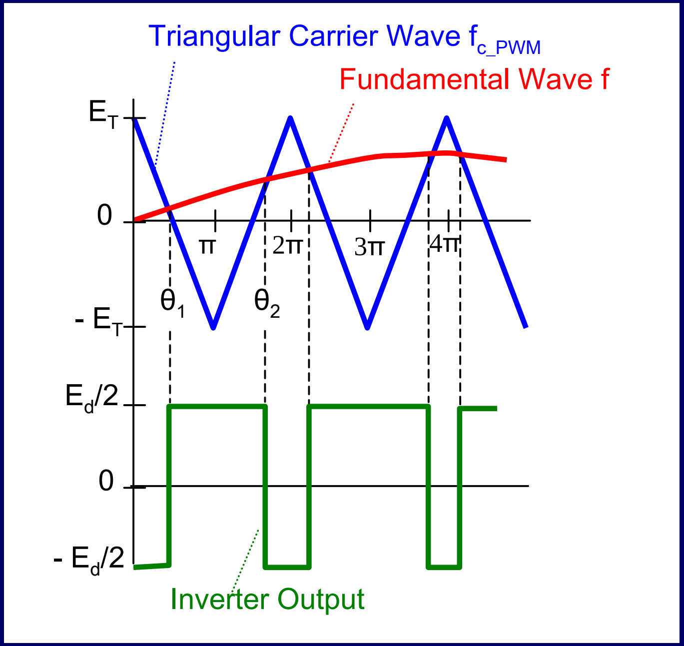


Figure 13. Mechanism of PWM

Concluding Remarks

- Measurement of torque & current in factory test is important in case VFD characteristics are unknown.
- Strength evaluation by lateral-torsional analysis is essential to determine mechanical soundness.
- Information of any possible frequencies used in VFD control and the resulting amplitude of torque pulsation should be disclosed in advance by VFD vendor.
- Reduction of amplitude of fundamental frequency harmonics would decrease amplitude of sideband frequencies.