December 2015 Final Evaluation

Timothy Mitchell Thompkins

Diagnosis of Rolling Mill Cycloconverters Using Time-Frequency Signature Analysis

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Overview

01 Introduction

- Project goals and motivation
- Current Techniques

02 Theory Overview

- Cycloconverter Operation
- Time-Frequency Analysis
- Feature Identification
- Modeling

03 Operating Status Decision Boundary

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- Loaded Motor Error Statistical Analysis
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- Error Decision Boundary Thresholds

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- Closing Remarks

Introduction

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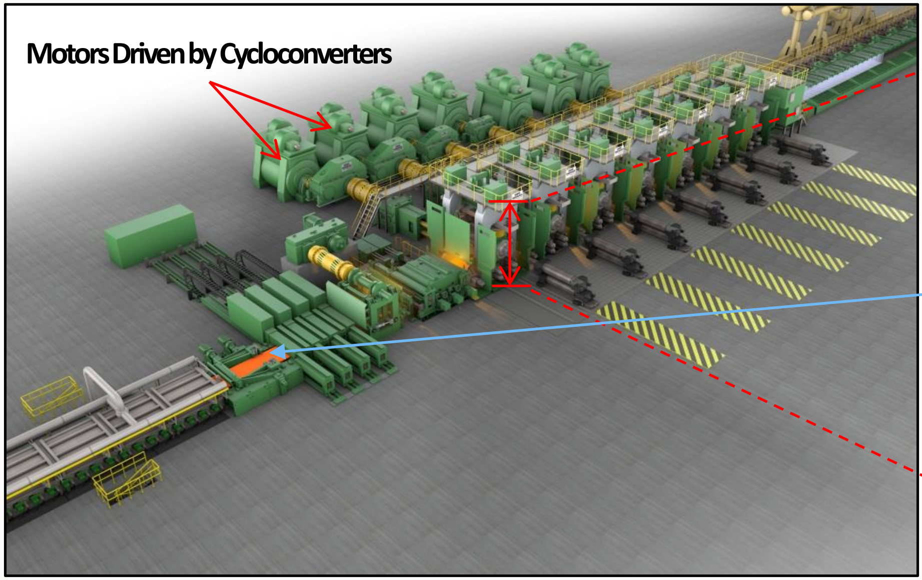
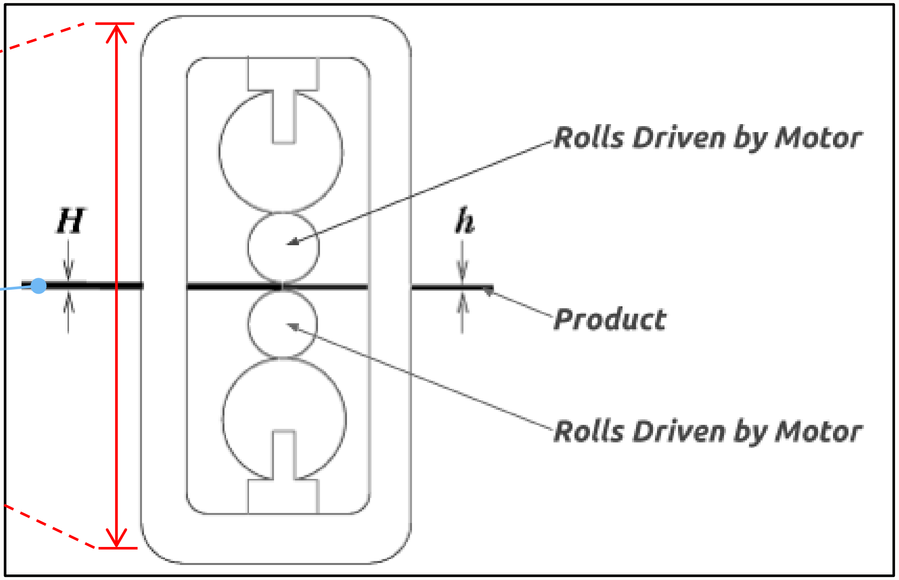
Introduction

Project Goals and Motivation





Typical Rolling Mill Setup *

Roll Stack **

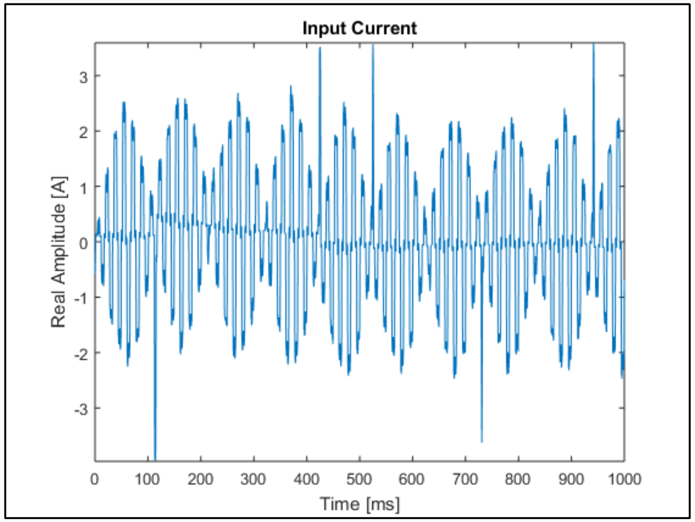
- Reduce gauge of steel in a controlled and reliable manner
  - Minimize damage to equipment and time down
- Confirm or call into question failure status of cycloconverter

* [Rendering by SMS Group] <https://www.sms-group.com/pressedetail.php?id=1229>

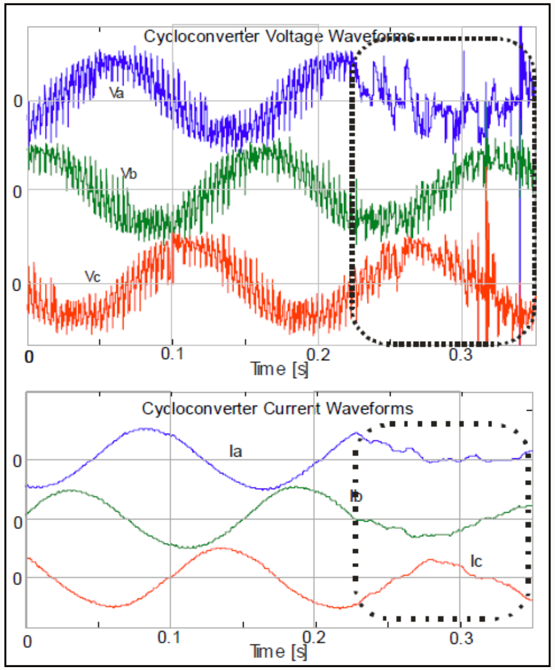
** [Open source Wikimedia file] <https://www.cds.caltech.edu/~murray/amwiki/index.php/Exercise:_Exploring_the_dynamics_of_rolling_mill>

Current Techniques

Benchmarking – Time Domain Analysis

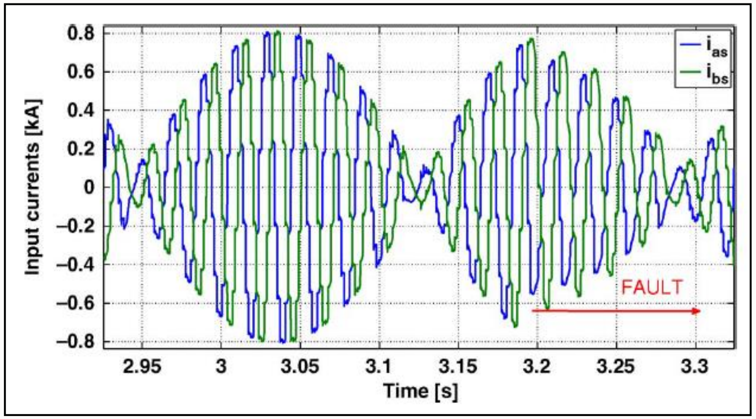


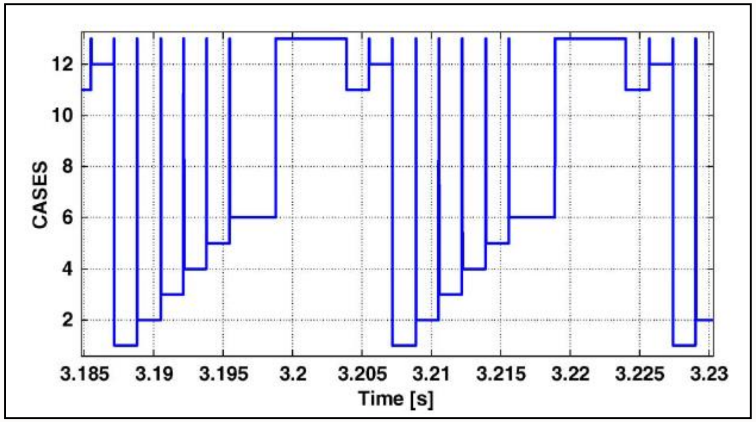
Damaged cycloconverter input current of concern



Loss of blocking capability in specific SCR [2]

Attempt to identify faults in time domain [1]

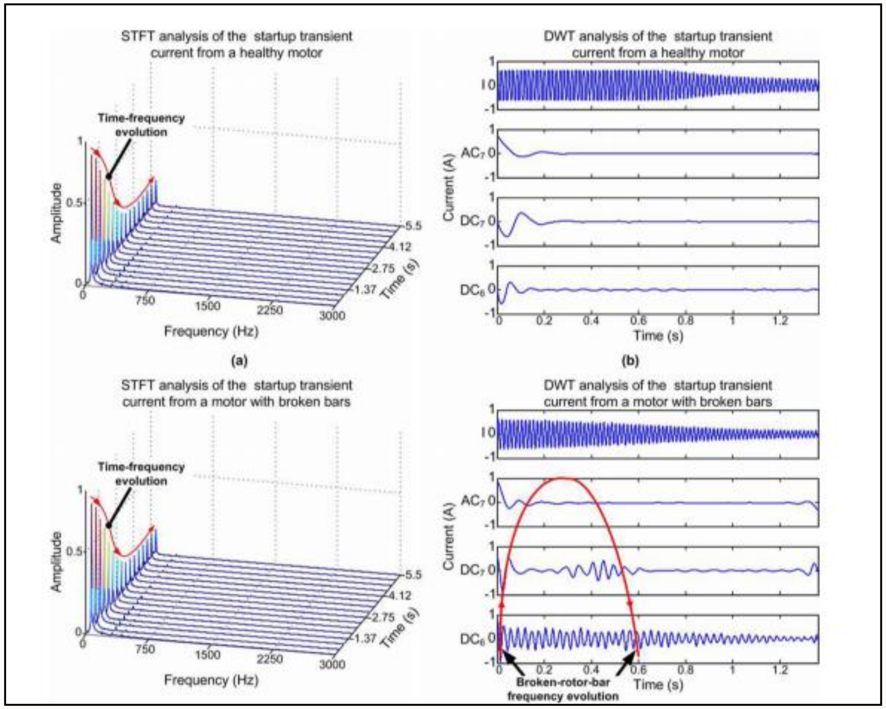




[1] V. Guerrero, J. Pontt, J. Dixon, and J. Rebolledo, "A novel noninvasive failure-detection system for high-power converters based on SCRs," *IEEE Trans. Ind. Electron.,* vol. 60, no. 2, pp. 450 - 458, Feb. 2013.
[2] J. Pontt, J. Rodríguez, E. Cáceres, I. Illanes and J. Rebolledo, "Cycloconverter behavior for a grinding mill drive under firing pulses fault conditions," in *Industry Applications Conf., Hong Kong,* 2005, pp. 645-649

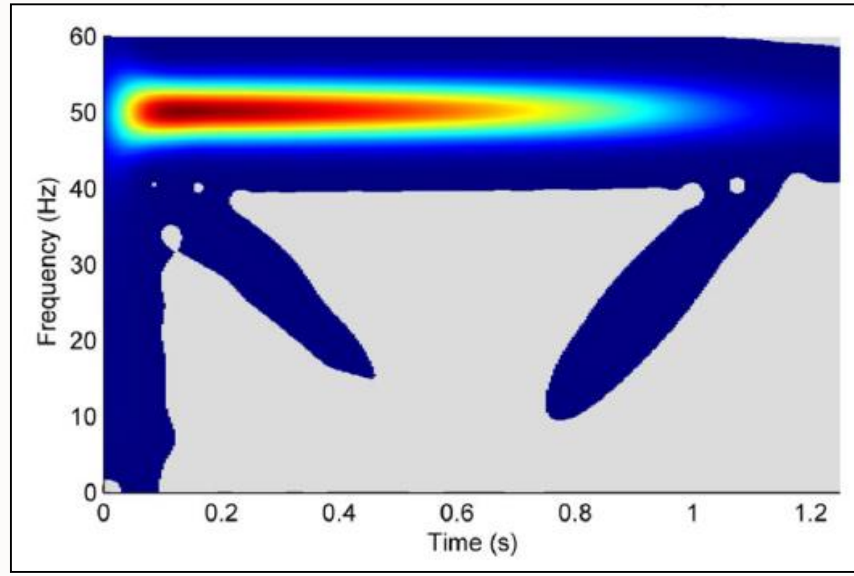
Current Techniques

Benchmarking – TF Domain Analysis

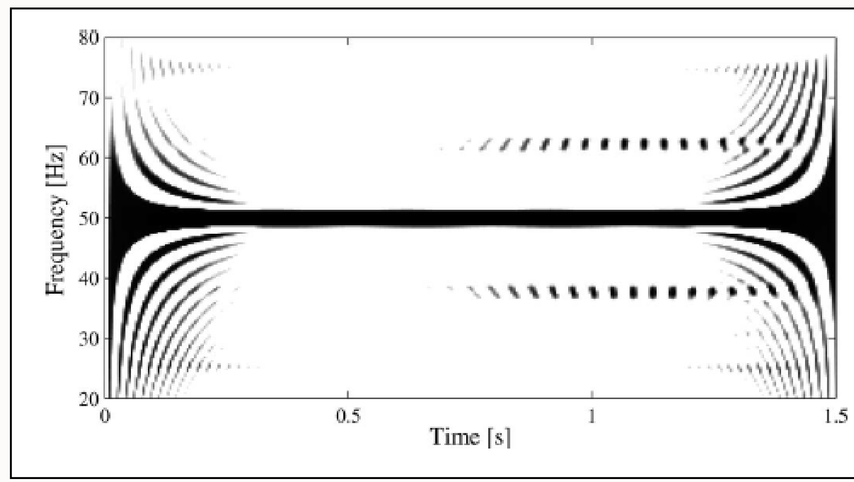


Attempt to characterize the motor in the time-frequency domain [3]

Gabor transform to quickly identify motor faults [4]



Acoustic analysis of motor [5]



[3] Eduardo Cabal-Yepez, Armando G. Garcia-Ramirez, Rened J. Romero-Tronosco, Artuo Garcia-Perez, and Roque A. Osornio-Rios, "Reconfigurable Monitoring System for Time-Frequency Analysis on Industrial Equipment Through STFT and DWT," *IEEE Trans. Ind. Informat.,* vol. 9, no. 2, pp. 760-771, May 2013.

[4] M. Riera-Guasp, M. Pineda-Sanchez, J. Perez-Cruz, R. Puche-Panadero, J. Roger-Folch, and J. A. Antonino-Daviu, "Diagnosis of induction motor faults via gabor analysis of the current in transient regime," IEEE Trans. Instrum. Meas., vol. 61, no. 6, pp. 1583-1596, Jun. 2012.

[5] M. Blödt, M. Chabert, J. Regnier and J. Faucher, "Mechanical load fault detection in induction motors by stator current time-frequency analysis," IEEE Trans. Ind. Appl., vol. 42, no. 6, pp. 1454-1463, Nov./Dec. 2006.

Theory Overview

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01 Cycloconverter Operation
02 Time-Frequency Analysis
03 Feature Identification
04 Modeling

Theory Overview

Cycloconverter Operation – General

$$\alpha = f(\theta_o) = \sin^{-1} r \sin\theta_o$$

$$\alpha = Firing\ Angle$$

$$r = DC\ Voltage\ Ratio$$

$$\theta_o = 2\pi f_o t$$

$$f_o = output\ frequency$$

Phase Modulation Term

$$i_A = \hat{I}_o \sin(\theta_o + \phi_o) \cdot F_1\left(\theta_i - \frac{\pi}{2} + f(\theta_0)\right) \cdot F_P(\theta_o)$$

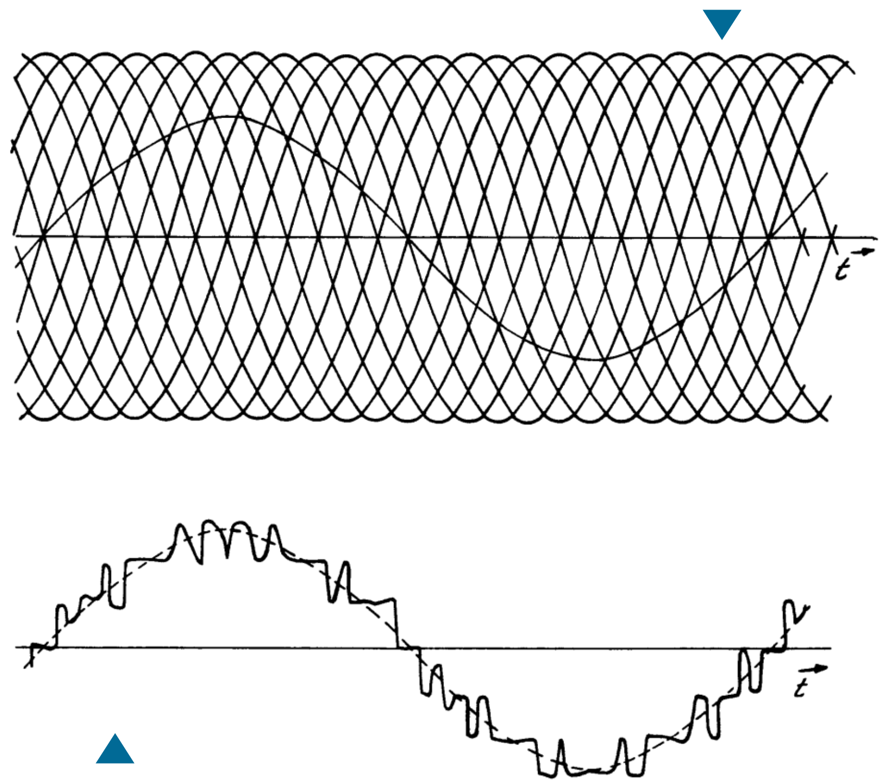
$$+\hat{I}_o \sin(\theta_o + \phi_o) \cdot F_1\left(\theta_i + \frac{\pi}{2} - f(\theta_0)\right) \cdot F_N(\theta_o)$$

$$\alpha = Firing\ Angle$$

$$F_1 = Thyristor\ Switching\ Function$$

$$F_{N\ or\ P}(\theta_o) = Negative\ and\ Postive\ Converter$$

Input Phases and Reference Waveform



Reference Waveform and Voltage Output

Relevant Voltage Waveforms

Theory Overview

Cycloconverter Operation – Input Current Harmonics

$$f_H = |[kq \pm 1]f_i \pm 6nf_o|$$

$$f_H = Harmonic\ Freq$$

$$f_i = Input\ Freq$$

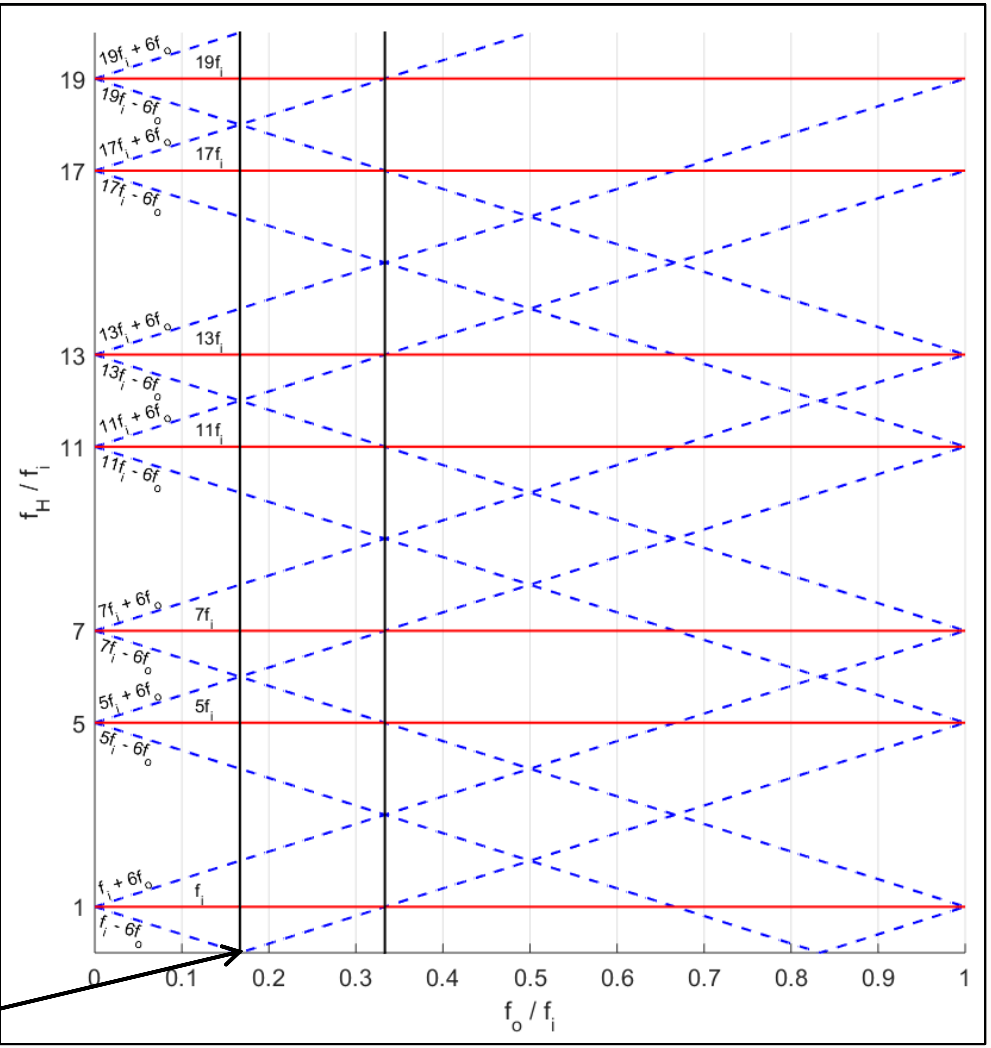
$$f_o = Output\ Freq$$

$$q = drive\ pulse\ number$$

$$k = any\ int\ from\ 1\ to\ \infty$$

$$n = any\ int\ from\ 0\ to\ \infty$$

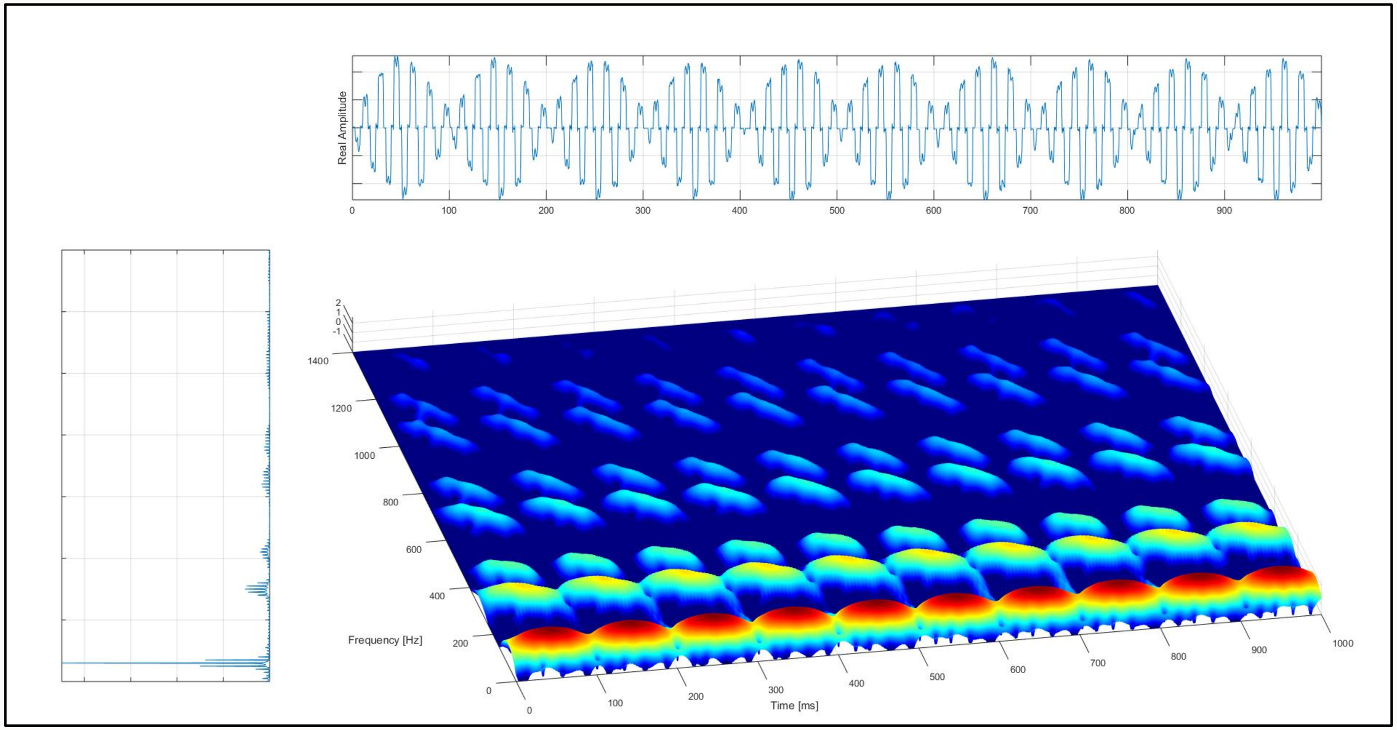
$$\frac{f_o}{f_i} = \frac{1}{6}$$



Predominant harmonic frequencies present in the input current for a 6-pulse cycloconverter

Theory Overview

Time-Frequency Analysis – General



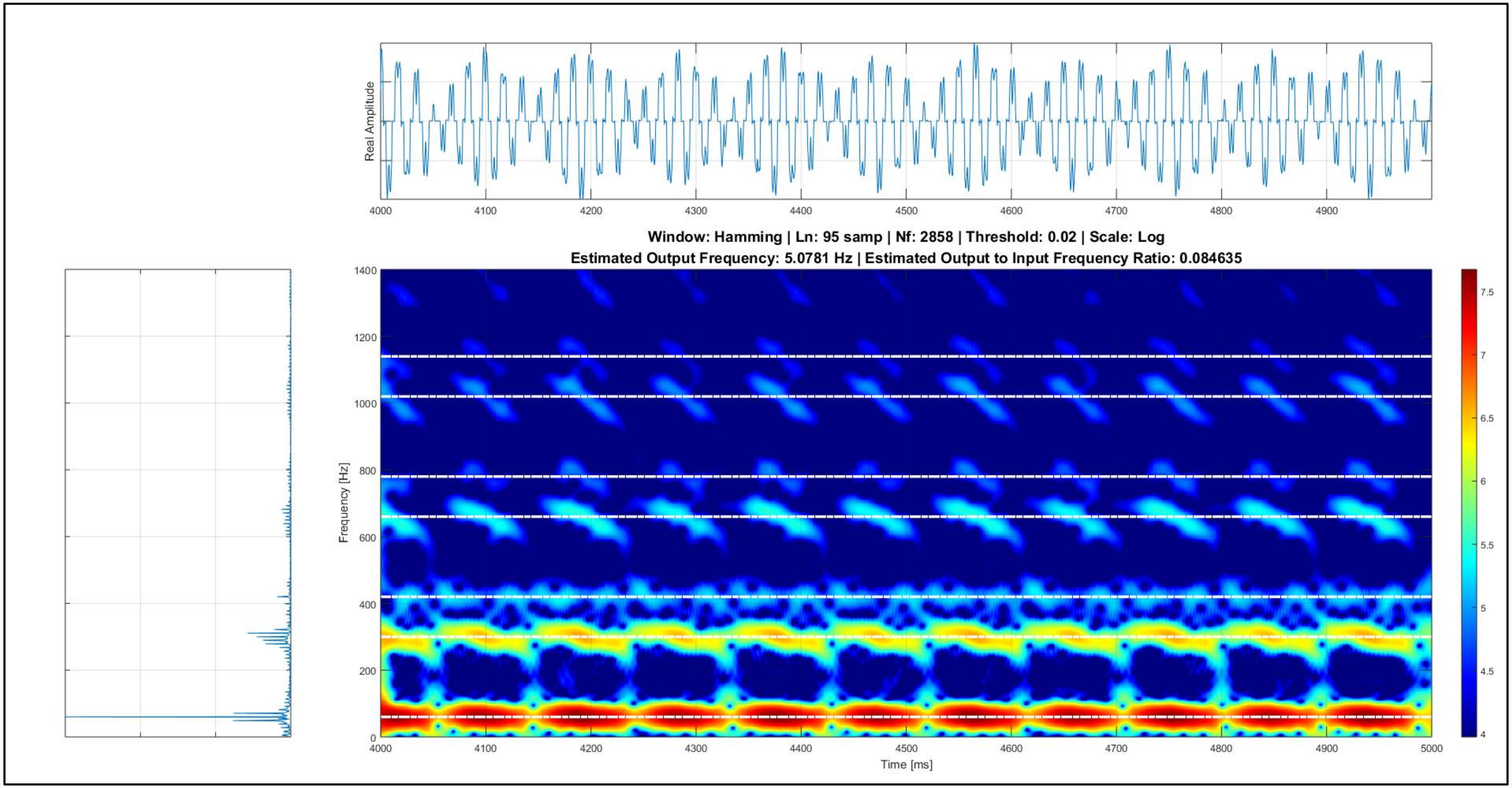
Spectrogram Sample

- Features of Interest
  - Frequency Centers of Chirps
  - Harmonic Slopes in the Time-Frequency Domain

$$C(t,\omega) = \left| \frac{1}{\sqrt{2\pi}} \int e^{-j\omega t} s(\tau) h(\tau - t) d\tau \right|^2$$

Theory Overview

Feature Identification – Frequency Centers

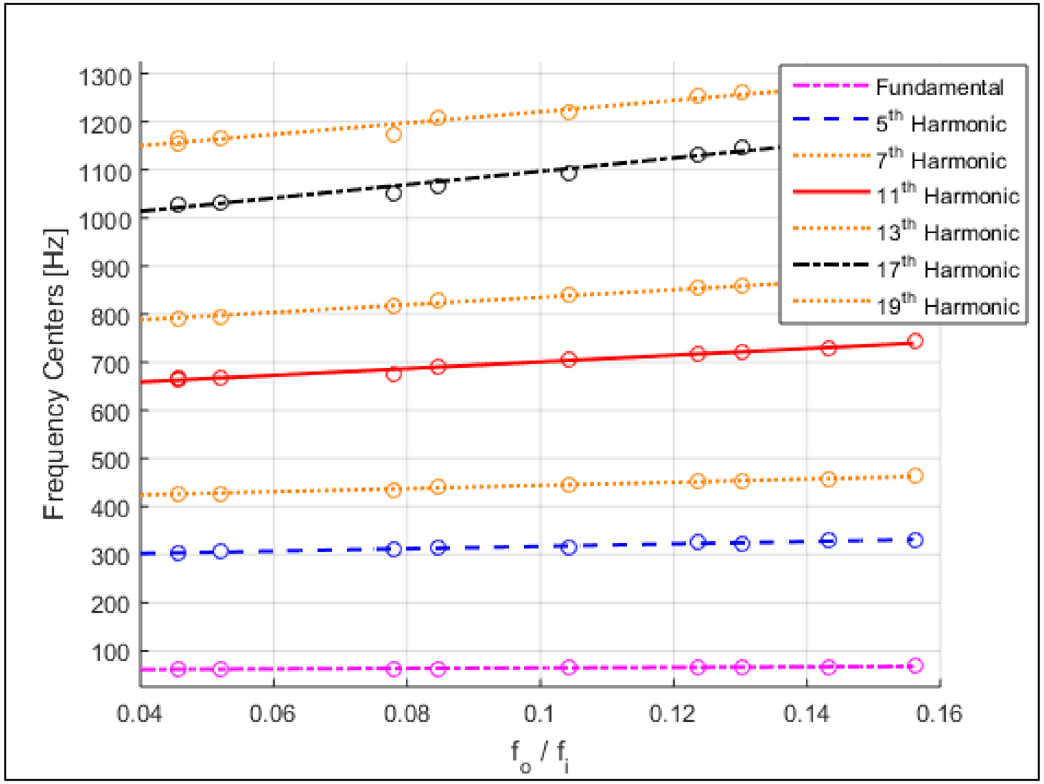


- White Lines = Frequency Centers of Chirps

$$\langle \omega \rangle = \int \omega |S(\omega)|^2 d\omega$$

Theory Overview

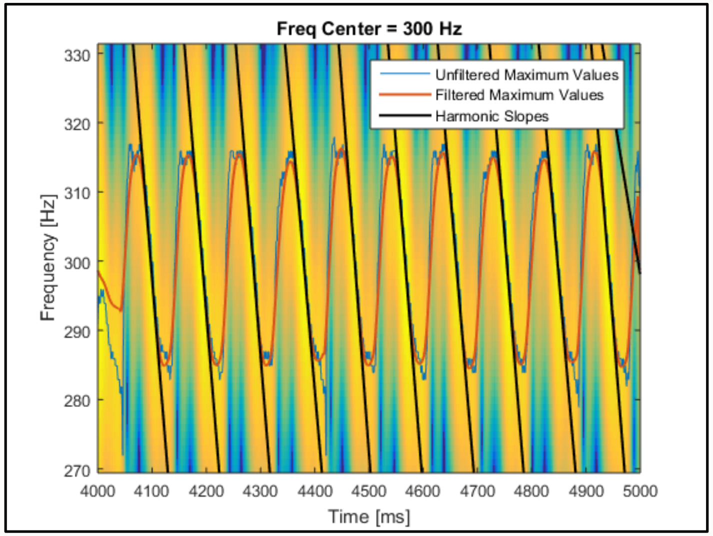
Feature Identification – Frequency Centers

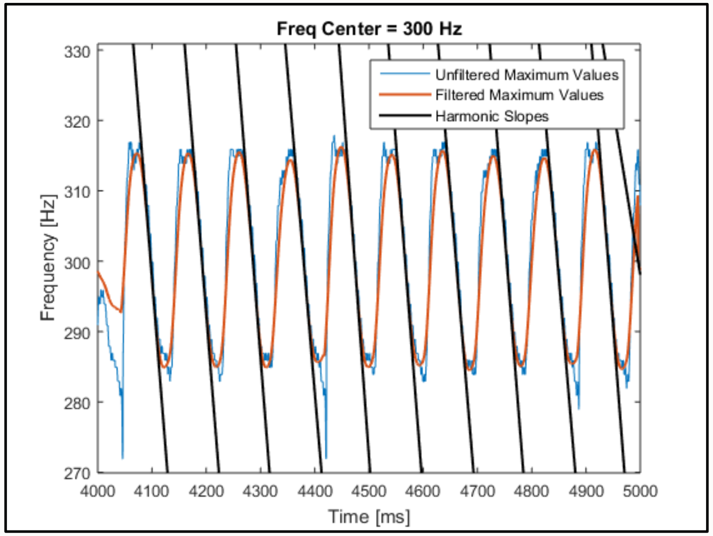


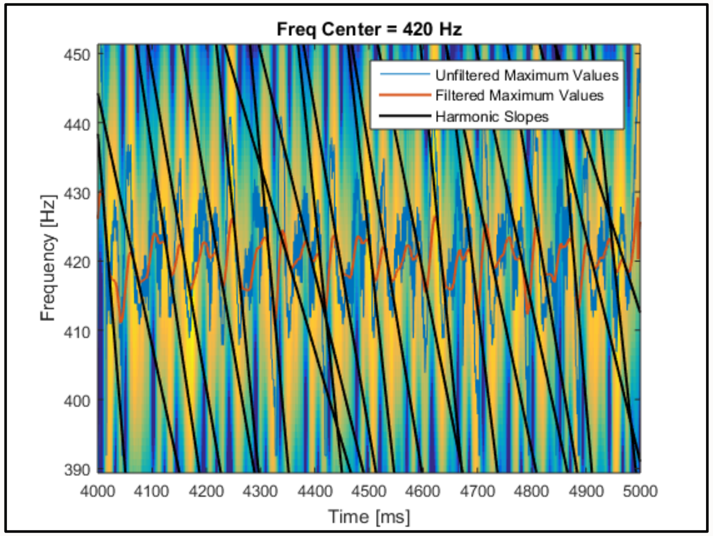
- Unloaded motor frequency centers rise linearly
- Loaded motor frequency centers do not change

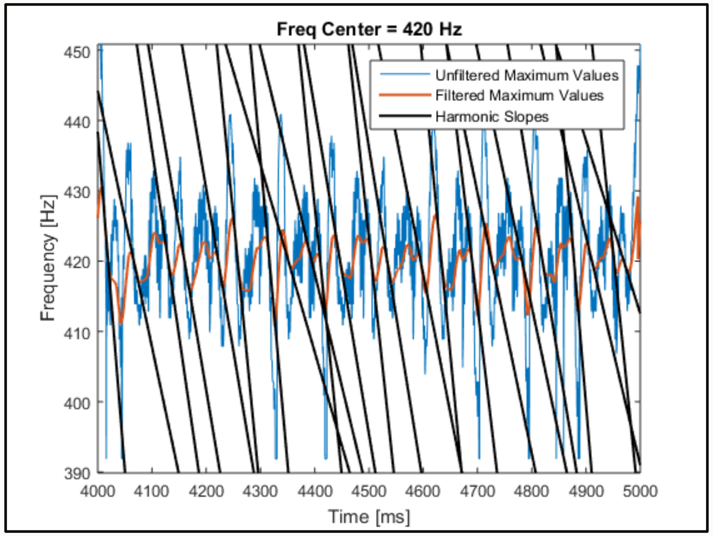
Theory Overview

Feature Identification – Harmonic Slopes



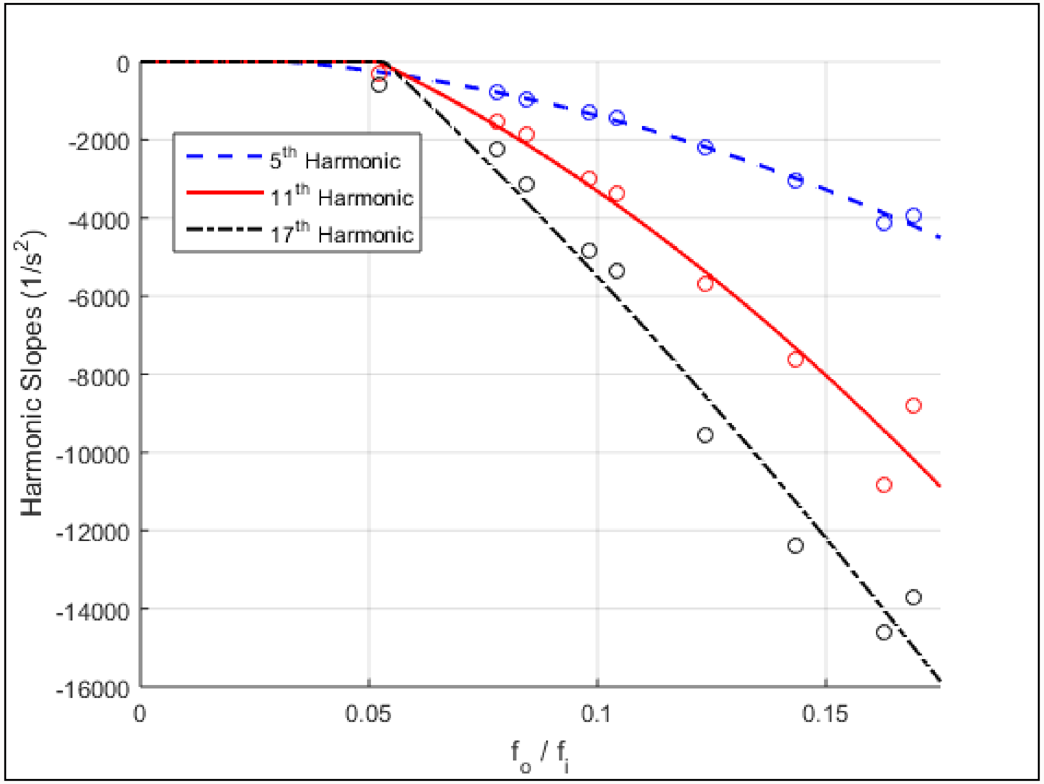






Theory Overview

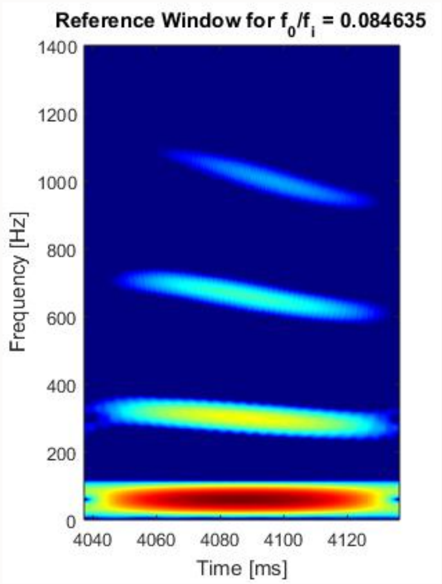
Feature Identification – Harmonic Slopes



- 2nd order polynomial fit to harmonic slope data for 5th, 11th, and 17th harmonics
  - Unknown behavior for higher ratios
  - Represented by $\beta\left(\gamma\left(\frac{f_0}{f_i}\right)\right)$ in modeling equation

Theory Overview

Modeling – Modeling Equation



$$\overbrace{\sin(2\pi f_o t)}^{\textbf{Amplitude Modulation}} \underbrace{\sum_{n=0}^{3} \left|\frac{1}{6n-1}\right| \sin\Bigg(\Bigg(}_{\textbf{Frequency Modulation}} \overbrace{\left(|6n-1|\left(f_i + \left(\alpha_h\left(\frac{f_o}{f_i}\right) - f_i|6n-1|\right)\right)\right)}^{\textbf{Fund, 5th, 11th, and 17th}} 2\pi t\Bigg)$$

Empirical Slopes

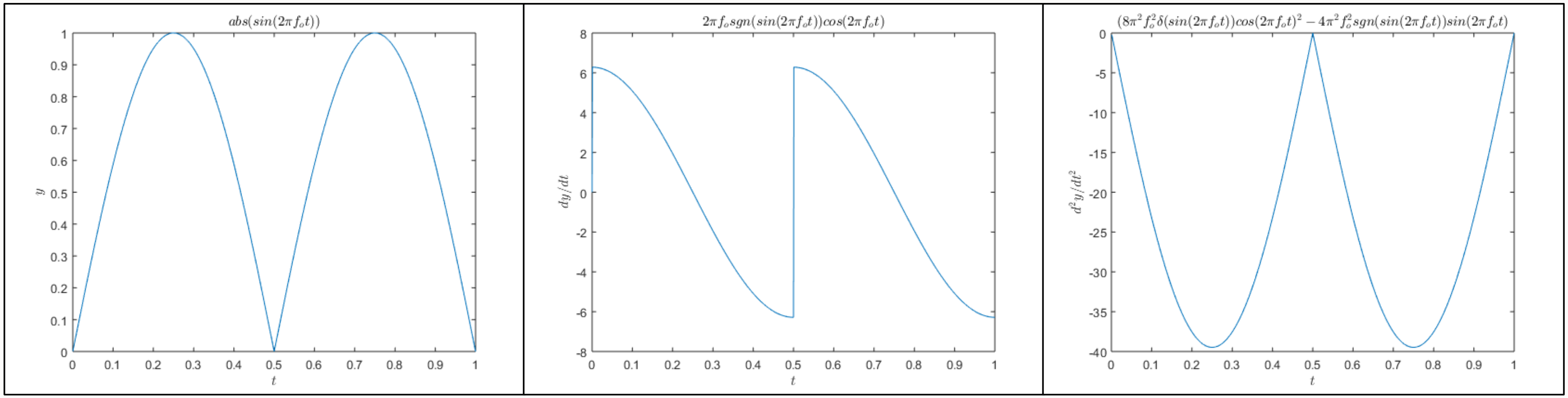
Empirical Unloaded Frequency Centers

$f_i = input\ freq.$

$f_o = output\ freq.$

Theory Overview

Modeling - Frequency Modulation Term



Frequency Modulation Function

$$\phi(t) = \beta\left(\gamma_h\left(\frac{f_o}{f_i}\right)\right)|\sin(2\pi f_o t)|$$

Empirical Slopes

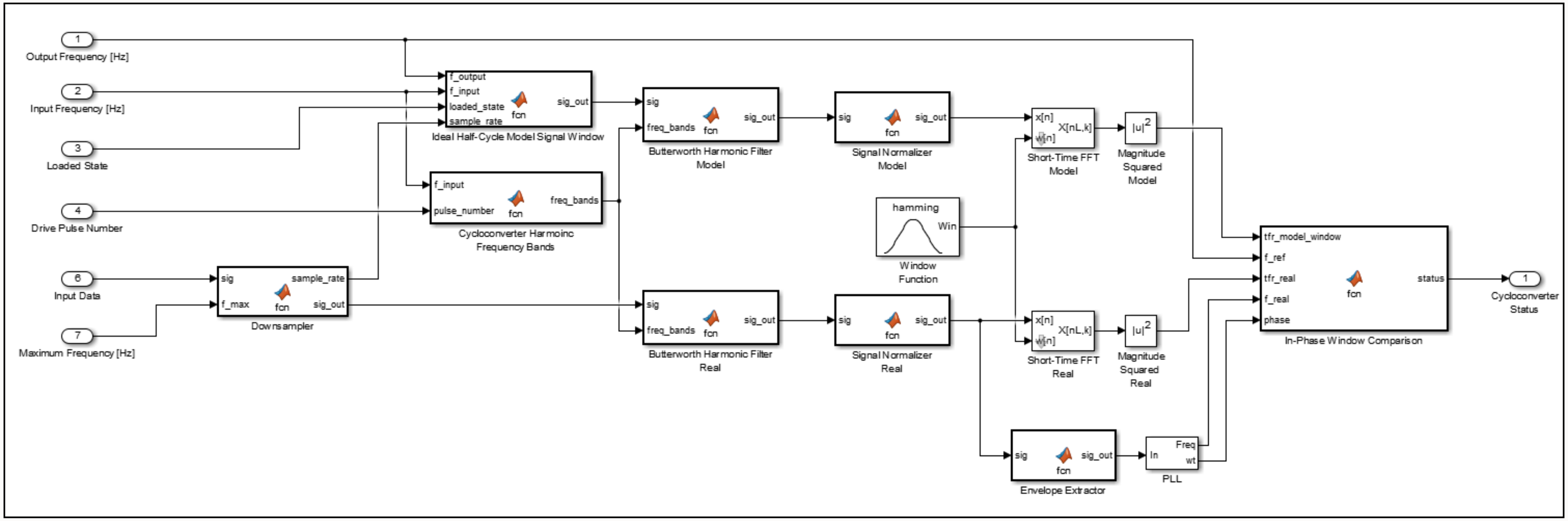
$$\beta\left(\gamma_h\left(\frac{f_o}{f_i}\right)\right) = \frac{\gamma_h\left(\frac{f_o}{f_i}\right)}{4\,\pi^2 f_o\left(2\delta\left(\sin\left(\frac{\pi}{2}\right)\right)\cos\left(\frac{\pi}{2}\right)^2 - \operatorname{sgn}\left(\sin\left(\frac{\pi}{2}\right)\sin\left(\frac{\pi}{2}\right)\right)\right)}$$

f_i $= input\ freq.$

f_o $= output\ freq.$

Theory Overview

Modeling – Model Block Diagram



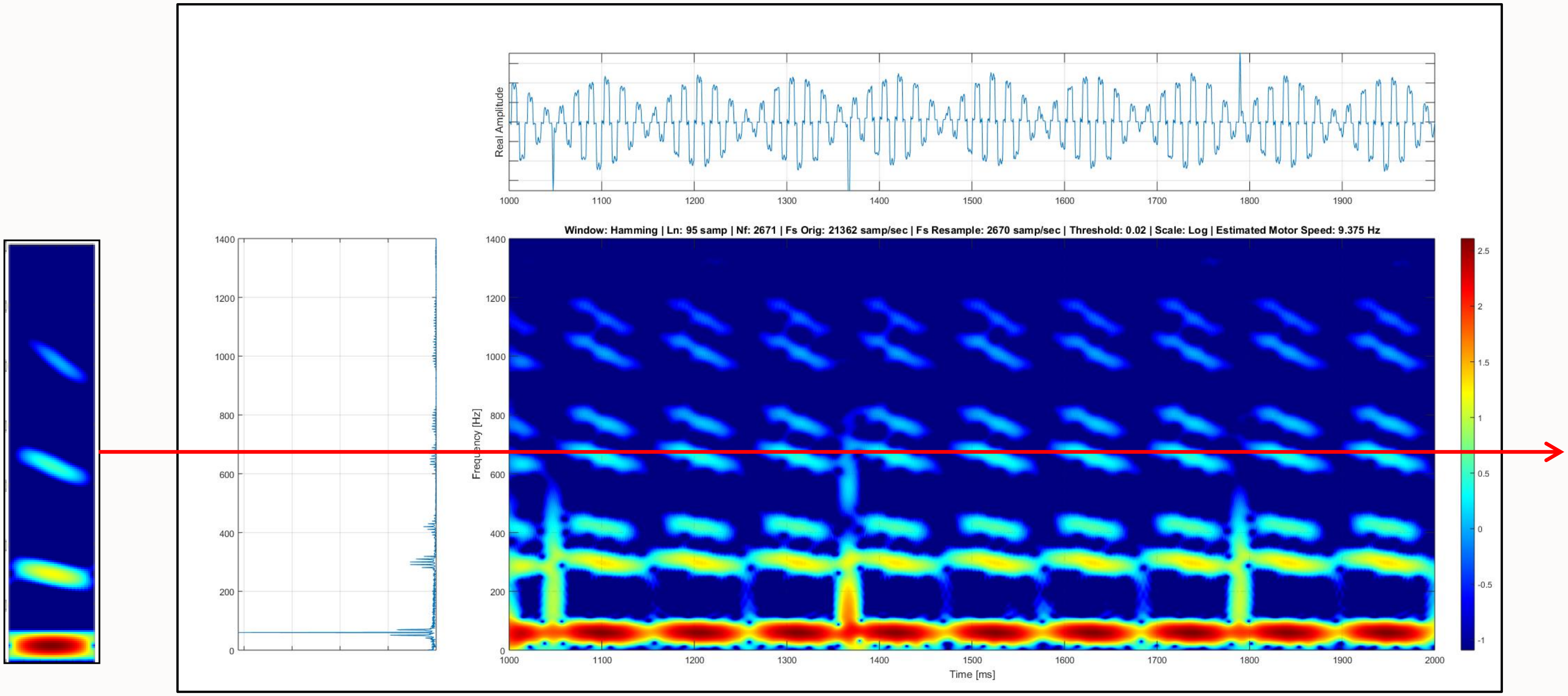
- 1. Given inputs develop a model in the time domain and convert to time-frequency domain
- 2. Filter real input current data and time domain model
    - a. Normalize both signals
- 3. Convert to time-frequency domain with spectrogram
- 4. Compare reference window in phase to real data
    - a. Characterize cycloconverter as in normal or abnormal operation

Operating Status Decision Boundary

3

Operating Status Decision Boundary

Error Analysis Technique

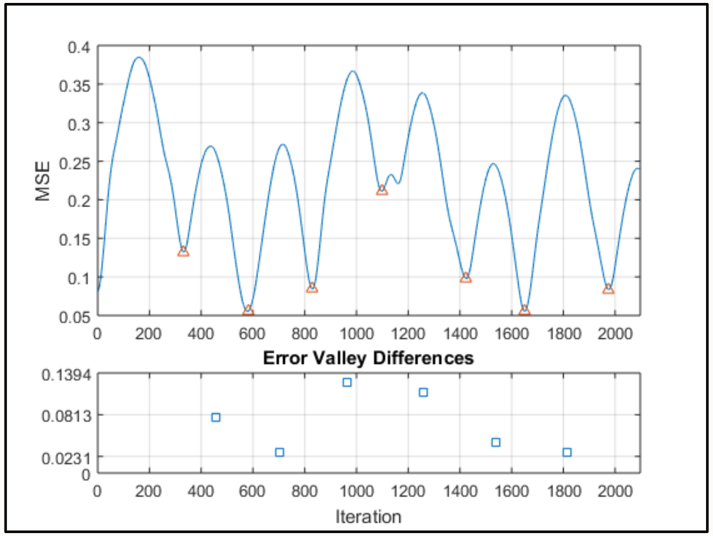


- Slide reference window through spectrogram
- Find error for each iteration, calculate MSE

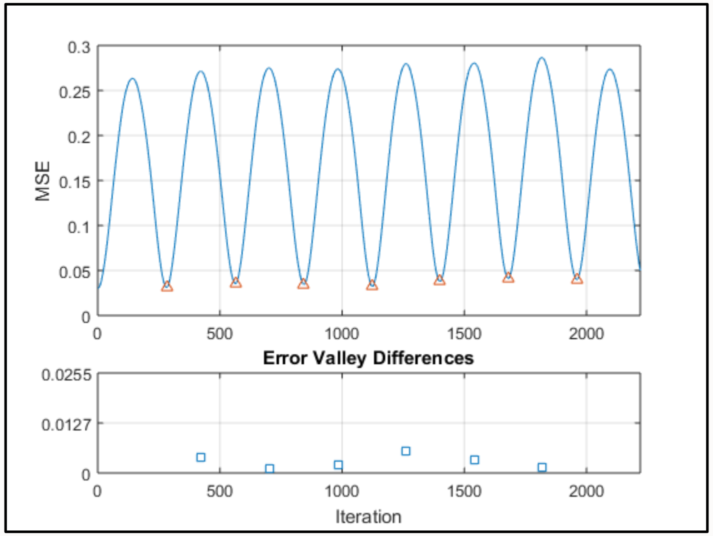
$$MSE = \frac{1}{N \cdot M} \sum_{n=1}^{N} \sum_{m=1}^{M} \left| C_{reference}[n,m] - C_{real}[n,m] \right|^2$$

Operating Status Decision Boundary

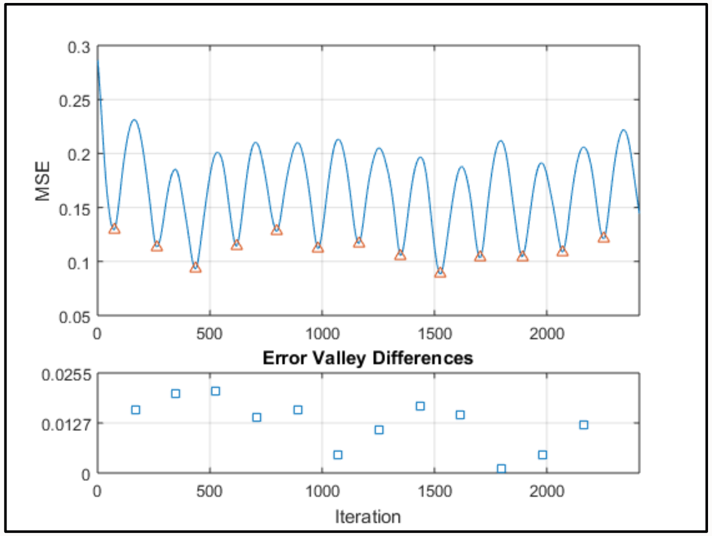
Error Analysis Technique



Damaged Loaded



Undamaged Loaded

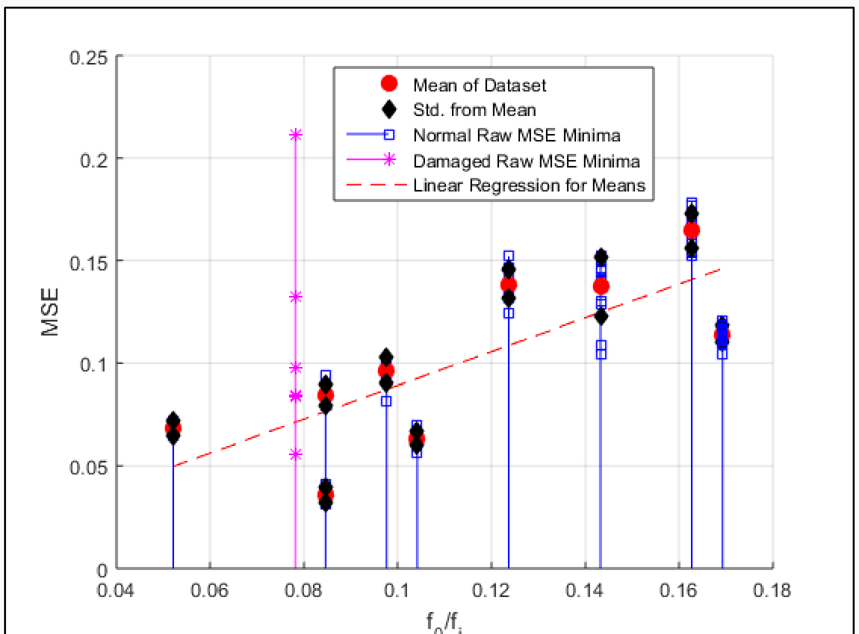


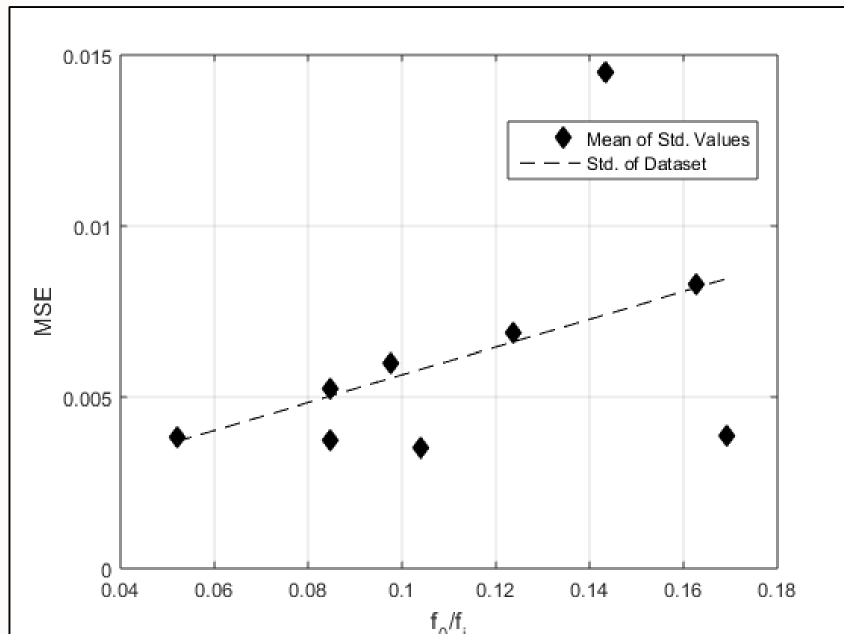
Undamaged Unloaded

Operating Status Decision Boundary

Loaded Motor Error Statistical Analysis – MSE

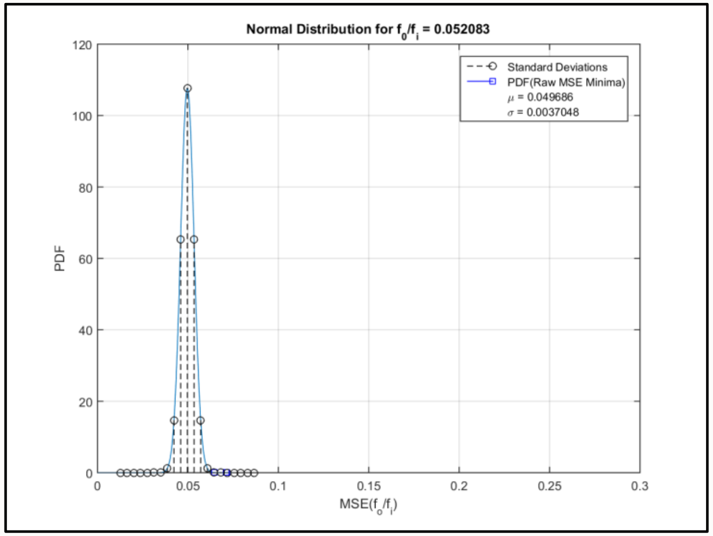
Fund. Freq (Hz)	60																					
Output Frequency (Hz)	***Notes***	***f_o/f_i***	***Mean***	***Std.***	***Loaded Motor Local Minima MSE***																	
3.1250	**F6**	**0.0521**	**0.0681**	**0.0033**	0.065	0.071	0.065	0.072														
4.6875	**Damaged F1**	**0.0781**	**0.1029**	**0.0505**	0.132	0.055	0.084	0.211	0.098	0.056	0.084											
5.0781	**F6**	**0.0846**	**0.0836**	**0.0048**	0.085	0.079	0.08	0.083	0.088	0.079	0.082	0.094										
5.0781	**F1**	**0.0846**	**0.0360**	**0.0035**	0.031	0.035	0.034	0.032	0.038	0.041	0.04											
5.8594	**F1**	**0.0977**	**0.0966**	**0.0057**	0.098	0.081	0.1	0.1	0.092	0.098	0.098	0.101	0.096	0.101								
6.2500	**F6**	**0.1042**	**0.0634**	**0.0033**	0.066	0.066	0.065	0.062	0.069	0.065	0.061	0.063	0.061	0.056								
7.4219	**F6**	**0.1237**	**0.1385**	**0.0066**	0.124	0.132	0.138	0.138	0.134	0.139	0.137	0.137	0.146	0.152	0.145	0.141	0.137					
8.5938	**F6**	**0.1432**	**0.1373**	**0.0140**	0.137	0.138	0.15	0.146	0.149	0.142	0.152	0.145	0.152	0.139	0.137	0.13	0.129	0.109	0.104			
9.7656	**F2**	**0.1628**	**0.1651**	**0.0081**	0.16	0.161	0.17	0.154	0.156	0.172	0.163	0.168	0.172	0.173	0.152	0.154	0.177	0.178	0.169	0.159	0.16	0.174
10.1563	**F2**	**0.1693**	**0.1141**	**0.0037**	0.119	0.113	0.104	0.111	0.113	0.118	0.121	0.117	0.115	0.113	0.116	0.112	0.11	0.113	0.115	0.117	0.115	0.112

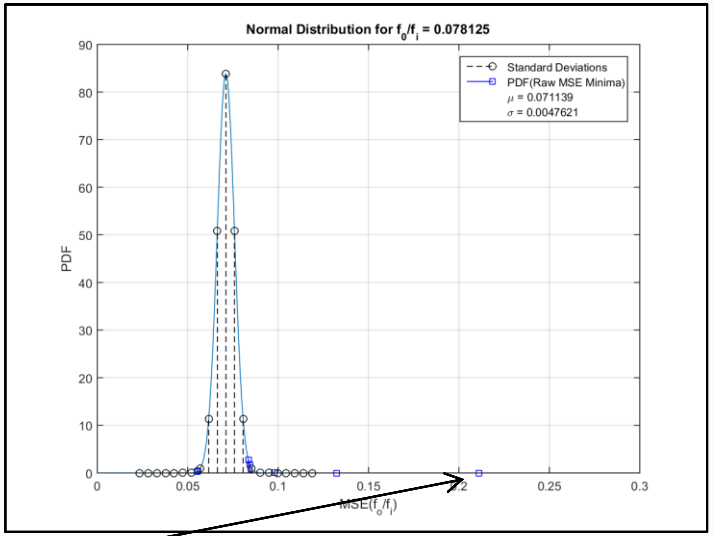


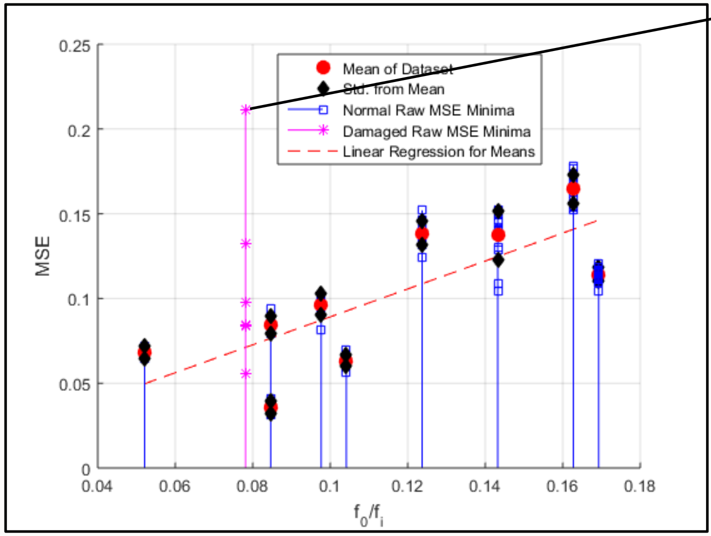


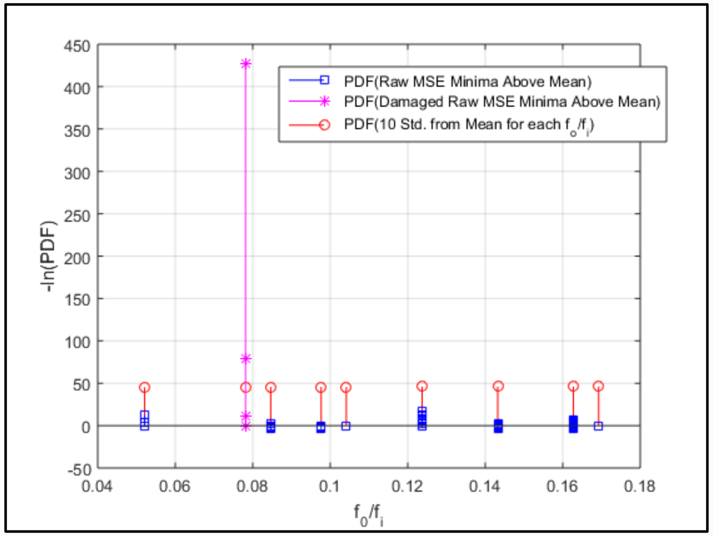
Operating Status Decision Boundary

Loaded Motor Error Statistical Analysis – MSE



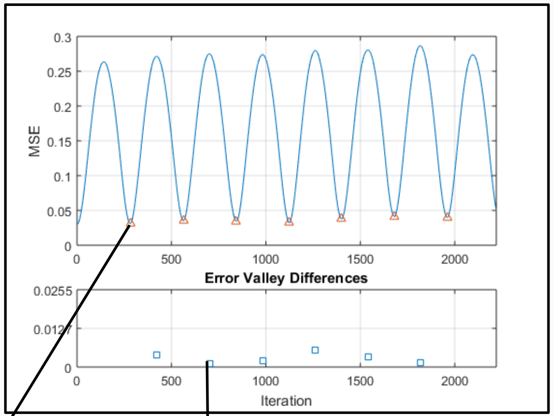






Operating Status Decision Boundary

Loaded Motor Error Statistical Analysis – MSE Differences



Fund. Freq (Hz)	60																					
Output Frequency (Hz)	***Notes***	***f_o/f_i***	***Mean***	***Std.***	***Loaded Motor Local Minima MSE***																	
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4.6875	Damaged F1	0.0781	0.1029	0.0505	0.132	0.055	0.084	0.211	0.098	0.056	0.084											
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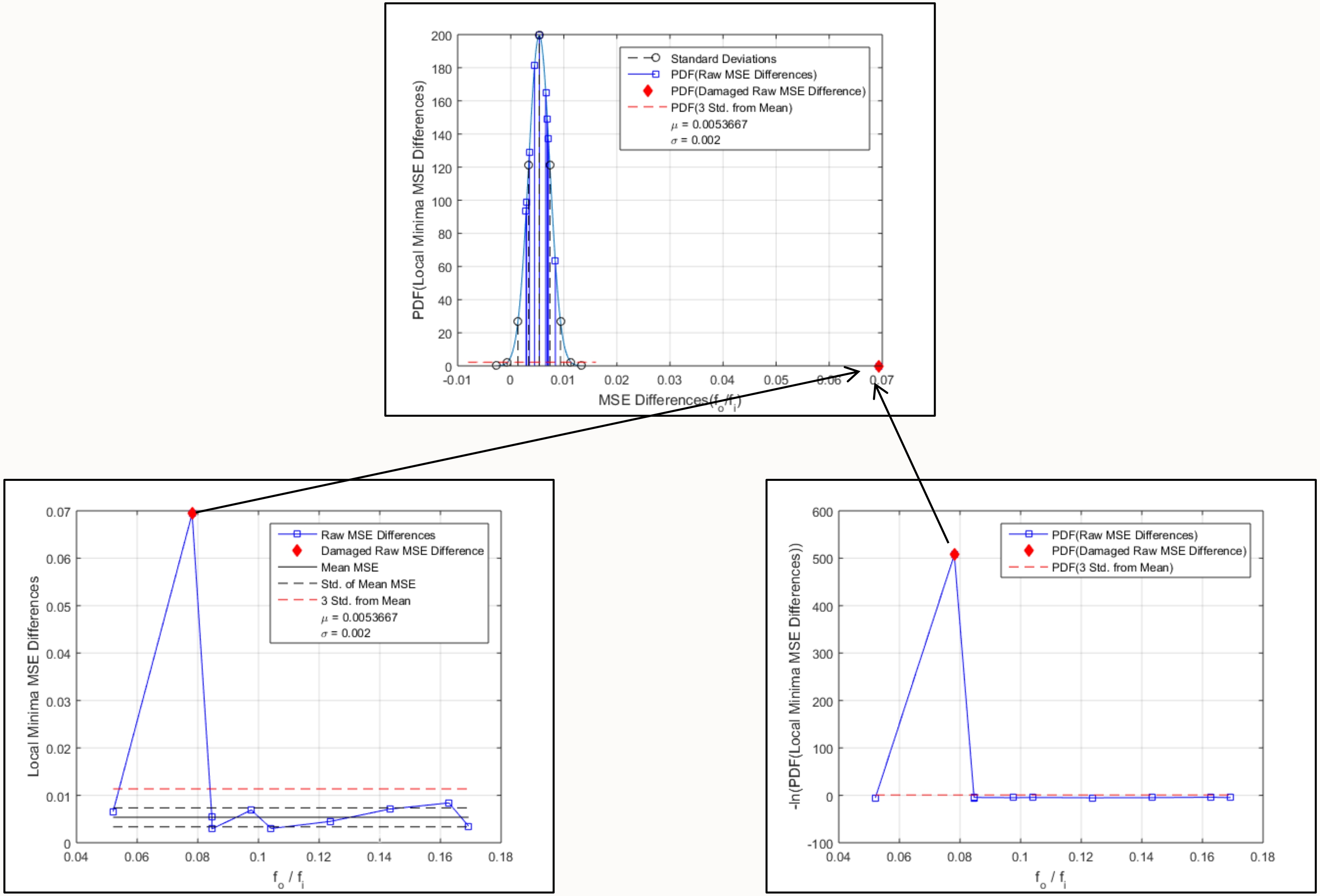
6.2500	F6	0.1042	0.0634	0.0033	0.066	0.066	0.065	0.062	0.069	0.065	0.061	0.063	0.061	0.056								
7.4219	F6	0.1237	0.1385	0.0066	0.124	0.132	0.138	0.138	0.134	0.139	0.137	0.137	0.146	0.152	0.145	0.141	0.137					
8.5938	F6	0.1432	0.1373	0.0140	0.137	0.138	0.15	0.146	0.149	0.142	0.152	0.145	0.152	0.139	0.137	0.13	0.129	0.109	0.104			
9.7656	F2	0.1628	0.1651	0.0081	0.16	0.161	0.17	0.154	0.156	0.172	0.163	0.168	0.172	0.173	0.152	0.154	0.177	0.178	0.169	0.159	0.16	0.174
10.1563	F2	0.1693	0.1141	0.0037	0.119	0.113	0.104	0.111	0.113	0.118	0.121	0.117	0.115	0.113	0.116	0.112	0.11	0.113	0.115	0.117	0.115	0.112

Fund. Freq (Hz)	60																				
Output Frequency (Hz)	***Notes***	***f_o/f_i***	***Mean***	***Std.***	***Loaded Motor Local Minima MSE Differences***																
3.1250	F6	0.0521	0.0066	0.0002	0.006	0.006	0.007														
4.6875	Damaged F1	0.0781	0.0694	0.0394	0.077	0.029	0.127	0.113	0.042	0.028											
5.0781	F6	0.0846	0.0054	0.0038	0.006	8E-04	0.003	0.005	0.009	0.002	0.013										
5.0781	F1	0.0846	0.0029	0.0016	0.004	0.001	0.002	0.006	0.003	0.002											
5.8594	F1	0.0977	0.0069	0.0063	0.017	0.019	3E-04	0.008	0.006	9E-05	0.003	0.005	0.005								
6.2500	F6	0.1042	0.0030	0.0022	3E-04	0.001	0.003	0.007	0.005	0.003	0.001	0.001	0.005								
7.4219	F6	0.1237	0.0045	0.0026	0.007	0.006	3E-04	0.004	0.005	0.002	3E-04	0.009	0.006	0.007	0.005	0.003					
8.5938	F6	0.1432	0.0071	0.0051	4E-04	0.012	0.005	0.004	0.007	0.01	0.007	0.007	0.012	0.003	0.007	1E-03	0.02	0.004			
9.7656	F2	0.1628	0.0084	0.0069	1E-03	0.009	0.015	0.002	0.016	0.009	0.005	0.004	0.001	0.021	0.002	0.022	0.001	0.009	0.01	9E-04	0.013
10.1563	F2	0.1693	0.0035	0.0021	0.005	0.009	0.007	0.001	0.006	0.003	0.004	0.003	0.001	0.003	0.004	0.002	0.004	0.001	0.002	0.002	0.003

Operating Status Decision Boundary

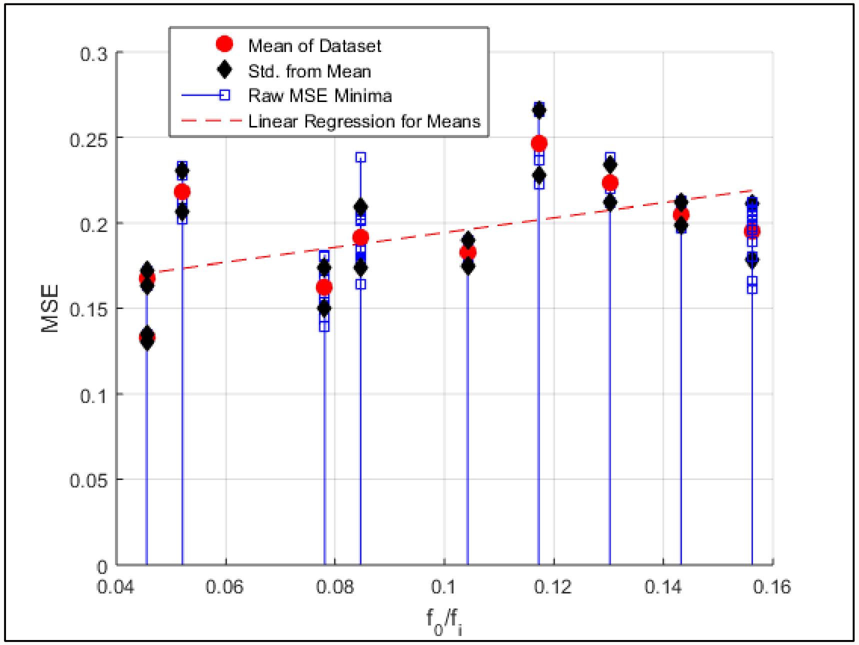
Loaded Motor Error Statistical Analysis – MSE Differences

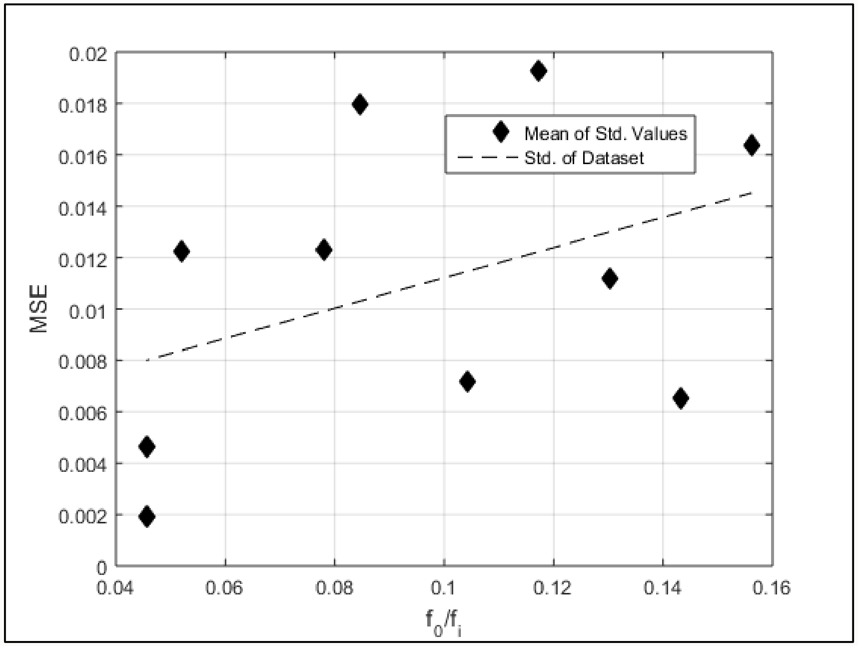


Operating Status Decision Boundary

Unloaded Motor Error Statistical Analysis – MSE

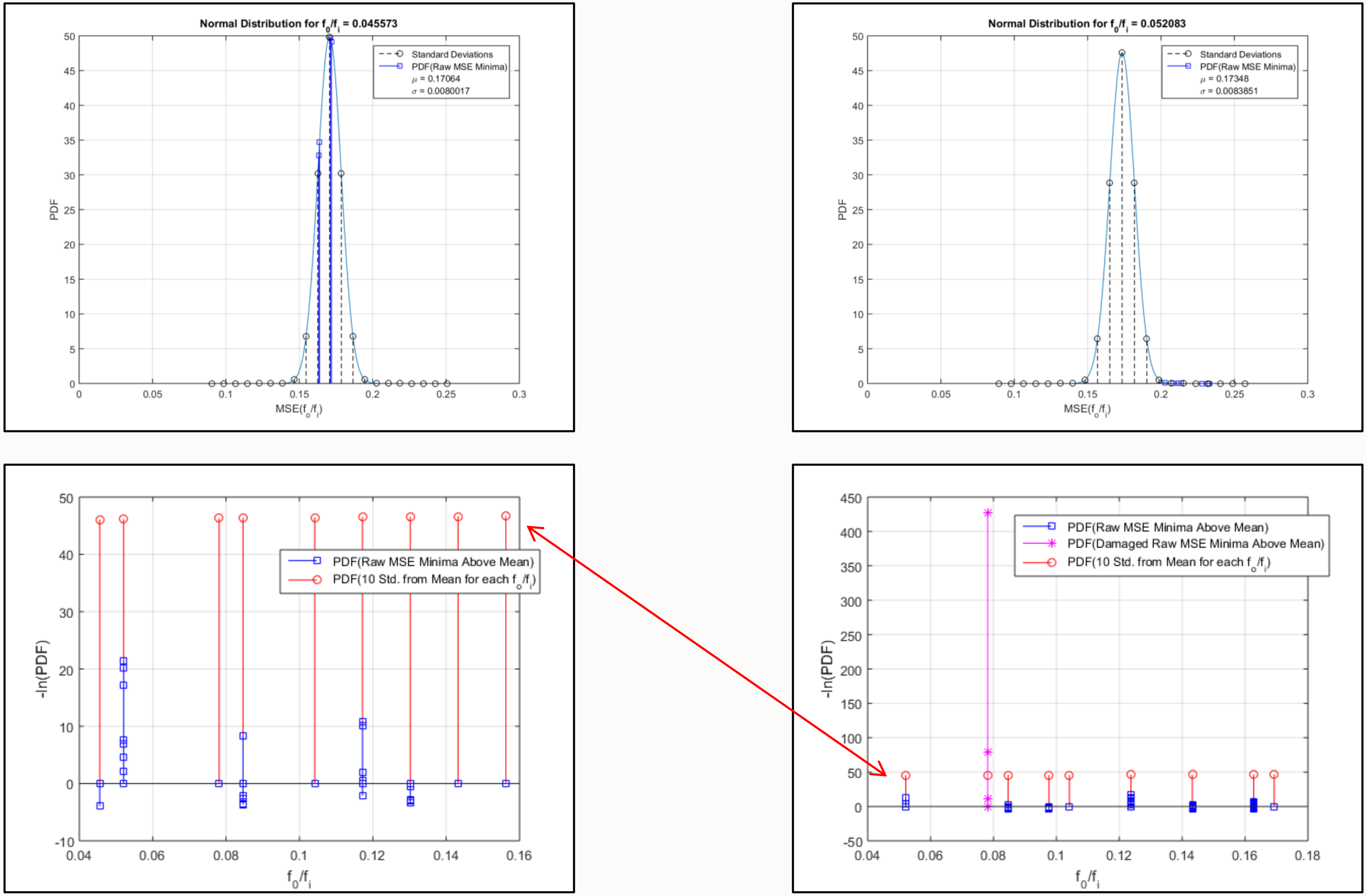
Fund. Freq (Hz)	***60***																			
Output Frequency (Hz)	***Notes***	***f_o/f_i***	***Mean***	***Std.***	***Unloaded Motor Local Minima MSE***														
2.7344	**F1**	**0.0456**	**0.1676**	**0.0040**	0.171	0.164	0.172	0.163											
2.7344	**F2**	**0.0456**	**0.1328**	**0.0015**	0.132	0.135	0.131												
3.1250	**F6**	**0.0521**	**0.1824**	**0.0059**	0.175	0.19	0.182												
4.6875	**F1**	**0.0781**	**0.2185**	**0.0113**	0.232	0.228	0.214	0.233	0.212	0.203	0.208								
5.0781	**F6**	**0.0846**	**0.2468**	**0.0172**	0.242	0.222	0.237	0.265	0.267										
6.2500	**F6**	**0.1042**	**0.2233**	**0.0097**	0.223	0.22	0.239	0.212											
7.0313	**F6**	**0.1172**	**0.2051**	**0.0058**	0.203	0.202	0.21	0.197	0.213										
7.8125	**F2**	**0.1302**	**0.1620**	**0.0118**	0.18	0.167	0.145	0.167	0.181	0.163	0.167	0.154	0.139	0.157	0.156	0.158	0.172		
8.5938	**F6**	**0.1432**	**0.1904**	**0.0172**	0.178	0.164	0.192	0.179	0.202	0.184	0.238	0.19	0.202	0.205	0.203	0.184	0.185	0.176	0.176
9.375	**F6**	**0.1563**	**0.1947**	**0.0157**	0.196	0.18	0.161	0.166	0.212	0.207	0.206	0.204	0.208	0.189	0.205	0.198	0.201		





Operating Status Decision Boundary

Unloaded Motor Error Statistical Analysis – MSE

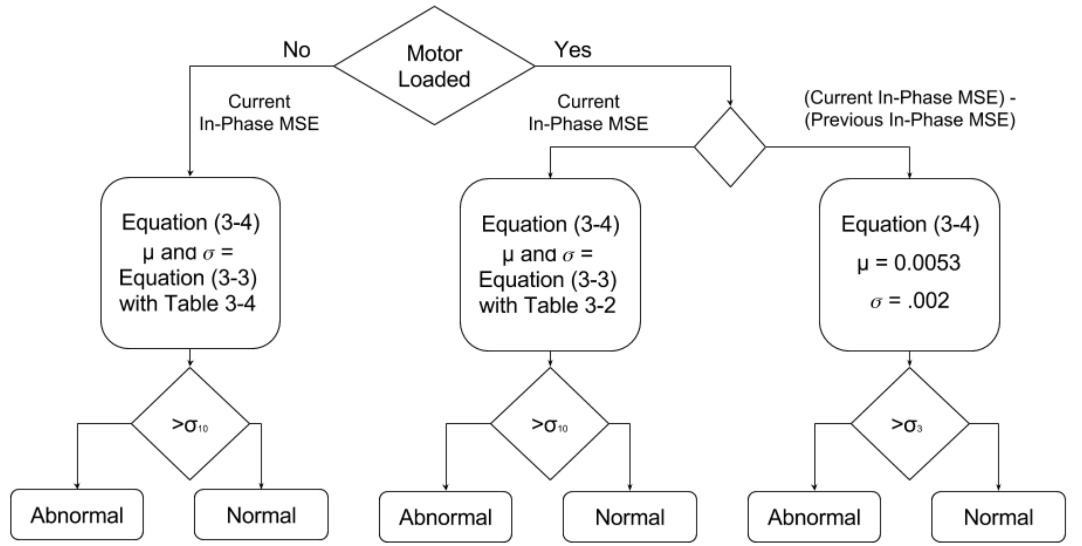


Loaded Data for Comparison

Operating Status Decision Boundary

Error Decision Boundary Thresholds

Error Type	State	PDF μ	PDF σ	Standard Deviatinon Threshold
In-Phase MSE	Loaded	Equation (3-3) with Table 3-2	Equation (3-3) with Table 3-2	10
	Unloaded	Equation (3-3) with Table 3-4	Equation (3-3) with Table 3-4	10
In-Phase MSE Differences	Loaded	0.0053	0.002	3
	Unloaded	N/A	N/A	N/A



Equation (3-3) $MSE_{\mu\ or\ \sigma}\left(\frac{f_o}{f_i}\right) = m\left(\frac{f_o}{f_i}\right) + b$

Equation (3-4) $PDF\left(MSE\left(\frac{f_o}{f_i}\right)\middle|\mu,\sigma\right) = \frac{1}{\sigma\sqrt{2\pi}}e^{\frac{-\left(MSE\left(\frac{f_o}{f_i}\right)-\mu\right)^2}{2\sigma^2}}$

Table 3-2

	Coefficient	
	m	b
μ	0.8238	0.0068
σ	0.0406	0.0016

Table 3-4

	Coefficient	
	m	b
μ	0.4354	0.1508
σ	0.0589	0.0053

Conclusion and Continued Research

4

Conclusion and Continued Research

Next Steps

- Summary of work
  - Identified characteristics used to diagnosis cycloconverter status
  - Developed model that uses these characteristics to find an error value
  - Defined decision boundaries based on said error
  - Strong foundation on which further research can evolve
- Improvements
  - Consider other frequency modulation terms
  - Improved harmonic slope estimator
  - Improved output frequency estimator
- Next Steps
  - Modify current algorithms for real time system

THANK YOU