ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

CONDITION MONITORING AND FAULT DIAGNOSIS OF VFD-FED INDUCTION MOTORS

M.Sc. THESIS

Alper SENEM

Department of Mechatronics Engineering

Mechatronics Engineering Programme

JUNE 2021

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Thesis Advisor: Prof. Dr. Şeniz ERTUĞRUL

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

DEĞİŞKEN FREKANSLI SÜRÜCÜ İLE BESLENEN ASENKRON MOTORLARDA DURUM İZLEME VE ARIZA TANILAMA

YüKSEK LİSANS TEZİ

Alper SENEM
(518181003)

Mekatronik Mühendisliği Anabilim Dalı

Mekatronik Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Şeniz ERTUĞRUL

HAZİRAN 2021

Alper SENEM, a M.Sc. student of ITU Graduate School student ID 518181003, successfully defended the thesis entitled "CONDITION MONITORING AND FAULT DIAGNOSIS OF VFD-FED INDUCTION MOTORS", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Prof. Dr. Şeniz ERTUĞRUL** Istanbul Technical University	....
Jury Members :	**Prof. Dr. Name SURNAME** Middle East Technical University	....
	Prof. Dr. Name SURNAME Boğaziçi University	....
	Prof. Dr. Name SURNAME Bilkent University	....
	Prof. Dr. Name SURNAME Sabancı University	....
	Prof. Dr. Name SURNAME Koç University	....

Date of Submission : 11 June 2021
Date of Defense : 11 June 2021

To my family,

FOREWORD

For the foreword, 1 line spacing must be set. The foreword, written as a first page of the thesis must not exceed 2 pages.

The acknowledgments must be given in this section.

After the foreword text, name of the author (right-aligned), and the date (as month and year) must be written (left-aligned). These two expressions must be in the same line.

The foreword is written with 1 line spacing.

June 2021 Alper SENEM
(Mechanical Engineer)

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ABBREVIATIONS

AIC	: Akaike Information Criteria
ANN	: Artificial Neural Network
App	: Appendix
BP	: Backpropagation
CGI	: Common Gateway Interface
ESS	: Error sum-of-squares
GARCH	: Generalized Autoregressive Conditional Heteroskedasticity
GIS	: Geographic Information Systems
HCA	: Hierarchical Cluster Analysis
Mbps	: Megabits per second
St	: Station
SWAT	: Soil and Water Assessment Tool
UMN	: University of Minnesota

SYMBOLS

C	: Capacitance
H	: The amount of heat
M_x, M_y	: Torque Components
N_x, N_y, N_z	: Normal Power Components
q	: Phase load
t	: Time
u, v	: Displacement Vector Components
w	: Angular velocity
XC	: Capacitive reactance
XL	: Inductive reactance
α	: Angle of deviation from the direction of the principal stresses
ρ	: Density
σ_x, σ_y, σ_{xy}	: Shell internal stresses

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CONDITION MONITORING AND FAULT DIAGNOSIS OF VFD-FED INDUCTION MOTORS

SUMMARY

1 line spacing must be set for summaries. For theses in Turkish, the summary in Turkish must have 300 words minimum and span 1 to 3 pages, whereas the extended summary in English must span 3-5 pages.

For theses in English, the summary in English must have 300 words minimum and span 1-3 pages, whereas the extended summary in Turkish must span 3-5 pages.

A summary must briefly mention the subject of the thesis, the method(s) used and the conclusions derived. References, figures and tables must not be given in Summary.

Above the Summary, the thesis title in first level title format (i.e., 72 pt before and 18 pt after paragraph spacing, and 1 line spacing) must be placed. Below the title, the expression **ÖZET** (for summary in Turkish) and **SUMMARY** (for summary in English) must be written horizontally centered.

It is recommended that the summary in English is placed before the summary in Turkish.

DEĞİŞKEN FREKANSLI SÜRÜCÜ
İLE BESLENEN ASENKRON MOTORLARDA
DURUM İZLEME VE ARIZA TANILAMA

ÖZET

Özet hazırlanırken 1 satır boşluk bırakılır. Türkçe tezlerde, Türkçe özet 300 kelimeden az olmamak kaydıyla 1-3 sayfa, İngilizce genişletilmiş özet de 3-5 sayfa arasında olmalıdır.

İngilizce tezlerde ise, İngilizce özet 300 kelimeden az olmamak kaydıyla 1-3 sayfa, Türkçe genişletilmiş özet de 3-5 sayfa arasında olmalıdır.

Özetlerde tezde ele alınan konu kısaca tanıtılarak, kullanılan yöntemler ve ulaşılan sonuçlar belirtilir. Özetlerde kaynak, şekil, çizelge verilmez.

Özetlerin başında, birinci dereceden başlık formatında tezin adı (önce 72, sonra 18 punto aralık bırakılarak ve 1 satır aralıklı olarak) yazılacaktır. Başlığın altına büyük harflerle sayfa ortalanarak (Türkçe özet için) **ÖZET** ve (İngilizce özet için) SUMMARY yazılmalıdır.

Türkçe tezlerde Türkçe özetin İngilizce özetten önce olması önerilir.

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1. INTRODUCTION

1.1 Overview

Electric motors extensively employed in a system that converts electrical power into mechanical power in not only industrial applications but also residential, agricultural and transportation purposes. Taken together with systems they drive, electric motors use more than 40% of all electricity consumption and almost twice as much as the next largest user lighting [1]. Considering only industrial usage, electric motors dominate and account close to 70% of the total electricity consumption [1, 2].

There are many different motor types available in industrial facility operations, but asynchronous alternating current (AC) induction motors are the most preferred type because of their simple, reliable and rugged design. Relatively lost cost, low maintenance, high reliability and long lifespan are most advantageous features of AC induction motors which drive core electro-mechanical systems such as material handling,material processing, pumping, ventilation and compressed air generation [3]. Especially HVAC (Heating, ventilation and air conditioning) sector requires special attention as they have the largest share of industrial electrical consumption and reasonably high saving potentials [3].

In recent years raised awareness about global warming demands more efficient systems including electric motor-driven systems. Policymakers such as European Parliament and European Council implementing new requirements to increase efficiency by encouraging the usage of high-efficiency premium motors and variable frequency drives (VFD) [2, 4].

VFDs regulate motor's output torque and speed to match the mechanical system loads and enables significant energy efficiency where variable mechanical power needed that have highly non-linear input power and output torque and speed such as pumps, fans and compressors. Previously Direct Current (DC) motors have been dominant for variable motor speed control, yet developments in semiconductor technology became the drive force behind prevalence usage of VFDs with AC motors [5]. Motor speed control is advantageous in terms of lower system energy costs, increased system reliability and less maintenance.

Considering 20-year in service, power consumption of an electric motor depicts 90% of the total cost of ownership and followed by downtime costs as 5% and rebuild costs as 4% [1]. The initial purchase price represents only 1% of the total cost and it can be concluded that savings can be achieved by actions taken during operation of motor [1].

Industry 4.0 shaping industrial operations through automation and efficiency. Condition monitoring paves the way to Industry 4.0 through evaluating state of plant and/or equipment throughout its service life [6]. Maintenance can be defined as actions to retain or restore of an equipment in order to maintain its designed functions within entire lifespan [6].Traditional maintenance relies on periodically health checks to provide operability, but researches shows that even if maintenance is done on time and correctly vast majority of failures arises during operation state [7]. Condition monitoring and diagnostics can help to schedule maintenance to prevent such situations whilst avoiding unintended downtime and financial losses. Also, condition monitoring has the opportunity to build database to understand better via trend analysis of the equipment or plant that leads more reliable system in the long run.

There are many condition monitoring methods available such as vibration, temperature, and current monitoring that can be used to assess insights into the health of equipment varying from bearings to electric motors and pumps. Current monitoring distinguishes itself from other methods since it is readily measured to control induction motor operation. VFDs are presenting great potential to not only controlling the motor operation but also can be utilised as a connection to the Internet of Things structure to serve Industry 4.0.

1.2 Objectives of Research

This study aims to diagnose and identify mechanical and electrical faults of VFD-fed induction motors under various loads and speeds via monitoring only motor current. As an outcome of this research comparative results among time-domain versus frequency-domain analysis and classical machine learning algorithms versus deep learning algorithms are presented. Also, these analyses investigated under single-fault and multiple-fault approaches.

The achievement of this study was facilitated by the following specific objectives:

- Analyse motor faults under VFD controlled motor current
- Investigate effects of various loads and speeds
- Build different feature engineering methods
- Benchmark Classical ML and Deep Learning algorithms
- Investigate single-fault scenarios and multiple-fault scenario

1.3 Organization of Thesis

Thesis organised in five chapters to achieve aforementioned objectives;

- Chapter-2 provides an in-depth background to condition monitoring and fault diagnosis of AC induction motors including general information about induction motors, fault types, condition monitoring and signal processing techniques followed by fault diagnosis methods.
- Chapter-3 presents the experimental testing system and used methodology.
- Chapter-4 discusses the diagnostics of faults via two different approaches: component-based and motor-based condition monitoring.
- Chapter-5 remarks obtained results with different approaches and concludes with future recommendations.

2. CONDITION MONITORING OF INDUCTION MOTORS: BACKGROUND

2.1 Introduction of Induction Motors

2.1.1 Principle of operation

2.1.2 VFD-fed induction motors

2.1.3 Need for condition monitoring

2.1.4 Maintenance strategies

Tables and figures given in appendices must be numbered with the number of the appendix they are in (i.e. Table A.1, Table A.2, Figure A.1, Figure A.2).

In tables and figures, font size could be reduced to 8 pt, if necessary.

Tables must be prepared using the same font type as the thesis. The font type used in figures must be consistent throughout the thesis.

Tables and figures must be placed after they are first cited in the main text body, but must be as close as possible, in accordance with the rules in this guideline (Figure 2.1). All tables and figures must be cited before they are used in the main text body (Table 2.1).

All tables and figures must be horizontally centered on the page.

The numbering of the tables and the figures must be such that the first number is the number of the chapter the table/figure is placed under (for appendices, the letter of the appendix), and the second number is the number of order (i.e. Table 2.2, Figure 2.2, Table A.1, Figure 2.3). The words "Table" and "Figure" and numbers must be bold.

For table numbers and captions, 1 line spacing, 12 pt (before) and 6 pt (after) paragraph spacing must be set. Table captions must be ended with a full stop. A table and its caption must be on the same page.

Multiple tables/figures could be placed on one page, however, table/figures spanning more than 4 consecutive pages must be given in appendices rather than the main text body.

The first paragraph following a table must have 12 pt (before) and 6 pt (after) paragraph spacing. Titles following a table must have the standard formatting as previously specified.

Footnotes for a table must be written with 1 line spacing and a font size 2 pt smaller than the main text body. For figure numbers and captions, 1 line spacing, 6 pt (before) and 12 pt (after) paragraph spacing must be set. Figure captions must be ended with a full stop. A figure and its caption must be on the same page.

For figures spanning more than one page, the same number and caption must be written below the continued figure, with the expression ”continued” added in brackets (i.e. **Table 2.1 (continued):** Metal composition of wastes. **Figure 2.1 (continued):** Water supply network of ISTANBUL.).

Plots, images and musical notes must be numbered and captioned as figures. Musical notes must be written according to the format rules set by the ITU School of Traditional Turkish Music.

It is recommended that elements that increase the page thickness and disrupt the binding structure of theses such as folded pages or additional items embedded on pages are given as appendices.

Figure 2.1 : All tables and figures must be horizontally centered on the page.

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Figure 2.2a : First subcaption of the subfigure.

Figure 2.2b : Second subcaption of the subfigure.

Figure 2.2 : An example of subfigure main caption.

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2.2 Induction Motor Fault Types

2.2.1 Bearing related faults

2.2.2 Stator related faults

2.2.3 Rotor related faults

Figure 2.3 : Example figure.

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Figure 2.4 : Landscape-oriented, full-page figure.

Figure 2.5 : Landscape-oriented, full-page figure.

2.3 Condition Monitoring Techniques

2.3.1 Temperature monitoring

2.3.2 Vibration monitoring

2.3.3 Motor current monitoring

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Table 2.1 : Table with single row and centered columns.

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Row A	Row A	Row A	Row A
Row B	Row B	Row B	Row B
Row C	Row C	Row C	Row C

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Table 2.2 : Table captions must be ended with a full stop.

Column A	Column B	Column C	Column D
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Row C	Row C	Row C	Row C

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2.4 Signal Processing Techniques

2.4.1 Time domain based signal analysis

2.4.1.1 Higher order statistics

2.4.2 Time-frequency based signal analysis

2.4.2.1 Wavelet Transform

2.4.3 Frequency based signal analysis

2.4.3.1 Shannon-Nyquist sampling theory

2.4.3.2 Fast Fourier transform

2.4.3.3 Power spectral density estimation

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Table 2.3 : Prof. Dr. Galip TEPEHAN   Captioning in landscape-oriented pages: the most important aspect is to align the lines horizontally.

Parametre	Column 2	Column 3	Column 4			Column 5	
			Subcolumn	Subcolumn	Subcolumn	Subcolumn	Subcolumn
Row 1	-7.680442	7.6986348	0.00	0.00	0.00	12	12
Row 2	140	-	0.50	0.00	0.00	0	0
Row 3	37.174357	37.16192697	0.00	0.00	0.00	0	24
Row 4	140	-	0.50	0.00	0.00	0	0
Row 5	37.174357	37.16192697	0.00	0.00	0.00	0	24
Row 6	140	-	0.50	0.00	0.00	0	0
Row 7	37.174357	37.16192697	0.00	0.00	0.00	0	24
Row 8	140	-	0.50	0.00	0.00	0	0
Row 9	37.174357	37.16192697	0.00	0.00	0.00	0	24
Row 10	140	-	0.50	0.00	0.00	0	0
Row 11	37.174357	37.16192697	0.00	0.00	0.00	0	24
Row 12	140	-	0.50	0.00	0.00	0	0
Row 13	37.174357	37.16192697	0.00	0.00	0.00	0	24
Row 14	140	-	0.50	0.00	0.00	0	0
Row 15	37.174357	37.16192697	0.00	0.00	0.00	0	24

Table 2.4 : Prof. Dr. Galip TEPEHAN   Captioning in landscape-oriented pages: the most important aspect is to align the lines horizontally.

Parametre	Column 2	Column 3	Column 4			Column 5	
			Subcolumn	Subcolumn	Subcolumn	Subcolumn	Subcolumn
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Row 5	37.174357	37.16192697	0.00	0.00	0.00	0	24
Row 6	140	-	0.50	0.00	0.00	0	0
Row 7	37.174357	37.16192697	0.00	0.00	0.00	0	24
Row 8	140	-	0.50	0.00	0.00	0	0

Table 2.5 : Neighborhoods Visited

Variable	Values	Count	%	Cum. %
visit	FALSE	2	33.33	33.33
	TRUE	3	50.00	83.33
	NA	1	16.67	100.00
	Total	6	100.00	

Table 2.6 : Feasible triples for highly variable Grid, MLMMH.

Time (s)	Triple chosen	Other feasible triples
0	(1, 11, 13725)	(1, 12, 10980), (1, 13, 8235), (2, 2, 0), (3, 1, 0)
2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
5490	(1, 12, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)
164700	(1, 13, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
0	(1, 11, 13725)	(1, 12, 10980), (1, 13, 8235), (2, 2, 0), (3, 1, 0)
2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
5490	(1, 12, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)
164700	(1, 13, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
0	(1, 11, 13725)	(1, 12, 10980), (1, 13, 8235), (2, 2, 0), (3, 1, 0)
2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
5490	(1, 12, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)
164700	(1, 13, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
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2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
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8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)

Table 2.6 (continued) : Feasible triples for highly variable Grid, MLMMH.

Time (s)	Triple chosen	Other feasible triples
164700	(1, 13, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
0	(1, 11, 13725)	(1, 12, 10980), (1, 13, 8235), (2, 2, 0), (3, 1, 0)
2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
5490	(1, 12, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)
164700	(1, 13, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
0	(1, 11, 13725)	(1, 12, 10980), (1, 13, 8235), (2, 2, 0), (3, 1, 0)
2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
5490	(1, 12, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)
164700	(1, 13, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
0	(1, 11, 13725)	(1, 12, 10980), (1, 13, 8235), (2, 2, 0), (3, 1, 0)
2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
5490	(1, 12, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)
164700	(1, 13, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
0	(1, 11, 13725)	(1, 12, 10980), (1, 13, 8235), (2, 2, 0), (3, 1, 0)
2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
5490	(1, 12, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)
164700	(1, 13, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
0	(1, 11, 13725)	(1, 12, 10980), (1, 13, 8235), (2, 2, 0), (3, 1, 0)
2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
5490	(1, 12, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)
164700	(1, 13, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
0	(1, 11, 13725)	(1, 12, 10980), (1, 13, 8235), (2, 2, 0), (3, 1, 0)
2745	(1, 12, 10980)	(1, 13, 8235), (2, 2, 0), (2, 3, 0), (3, 1, 0)
5490	(1, 12, 13725)	(2, 2, 2745), (2, 3, 0), (3, 1, 0)
8235	(1, 12, 16470)	(1, 13, 13725), (2, 2, 2745), (2, 3, 0), (3, 1, 0)

2.5 Fault Diagnosis Techniques

2.5.1 Model based condition monitoring

2.5.1.1 State estimation

2.5.1.2 Residual generation

2.5.1.3 Identification

2.5.2 Model free condition monitoring

2.5.2.1 Signal analysis

2.5.2.2 Classical machine learning methods

Support Vector Machines

Naive Bayes

k-Nearest Neighbour

Random Forest

Multi Layer Perceptron

2.5.2.3 Deep learning methods

1D Convolutional Neural Networks

Long-Short Term Memory Networks

3. EXPERIMENTAL SETUP AND METHODOLOGY

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The gap at the bottom of the page is 2.5 cm.

Keeping more redundant space is incorrect. So, this gap should not be. Texts, tables, figures, etc. in the pages must be arranged considering this situation.

- Figures, tables can be enlarged and be reduced.
- The explanations except from the first reference about the figure or table can be placed either before the figure/table or after.
- After referring to a figure or table it is placed to the closest and convenient location. Convenient location must be arranged considering the gap at the bottom of the page.

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Figure 3.1 : Neuron cell, adapted from (Çetin, 2003).

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$$y_t = \phi_1 y_{t-1} + \varepsilon_t \tag{3.1}$$

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Figure 3.2 : For a multi-line figure captions, it is important that all the lines of the caption are aligned.

$$R_0 = 0 \tag{3.2a}$$

$$N_0 = 0 \tag{3.2b}$$

Each parameter is described, as seen in equation **(3.1)**, or in 3.1. Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore equation 3.1'in magna aliquyam erat Equation **(3.2)** into Equation **(3.2a)** and Equation **(3.2b)**.

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Figure 3.3 : Figure captions must be ended with a full stop.

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$$D\left(C_A, C_B\right) = \min X_A \in C_A, X_B \in C_B d\left(X_A, X_B\right) \tag{3.3}$$

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4. FAULT DIAGNOSIS METHODOLOGY

In this section, information will be given about how citations, quotings and footnotes should be.

4.1 Component Based Fault Diagnosis

4.1.1 Bearing fault analysis

4.1.1.1 Motor current signal analysis

4.1.1.2 PSD analysis

4.1.1.3 PSD+MCSA analysis

4.1.1.4 Deep learning analysis

References are cited with the surname of author and year. In the references section, the references are listed alphabetically according to the surname of the author.

Citing of a reference at the beginning of or within a sentence must be as Boran (2003), whereas a citation at the end of a sentence must be as (Boran, 2003). The full-stop is placed directly after the citation.

A reference with two authors must be cited as Yılmaz and Johnson (2004) at the beginning of or within a sentence, or as (Yılmaz and Johnson, 2004) at the end of a sentence.

A reference with more than two authors must be cited as Yılmaz et al. (2004) at the beginning of or within a sentence, or as (Yılmaz et al, 2004) at the end of a sentence.

Different publications of an author published in the same year must be cited as Feray (2005a), Feray (2005b).

While citing a part of a publication; the number of the page the cited material (chapter, table, figure, or equation) is on must be indicated. While citing, the expression “page” must be abbreviated, but "chapter" must not. For example; (Centers for Disease Control and Prevention, 2005, p. 10), (Shimamura, 1989, Chapter 3).

Citing multiple publications in one pair of brackets; (Berndt, 2002; Harlow, 1983).

Citing personal communication in main text body; (V.–G. Nguyen, personal communication, September 28, 1998), (J. Smith, personal communication, August 15, 2009).

In the references section, reference tags must be listed according to the surname of author.

For citing of secondary references (In case the reference cites another reference), the secondary reference must be cited in brackets. In the references section, the reference tag is organized according to the secondary reference, the original reference must not be used as a tag. For example; In his e-mails, Smith argued that asynchronous line dancing would be the next Internet meme (as cited in Jones, 2010).

4.1.2 Stator fault analysis

4.1.2.1 Motor current signal analysis

4.1.2.2 PSD analysis

4.1.2.3 PSD+MCSA analysis

4.1.2.4 Deep learning analysis

References are cited by numbering and indicating the number in square brackets ([]) in the main text body. The first reference cited in a thesis is numbered [1] and the following references are numbered according to the order of appearance.

In the main text body, references must be cited as specified below:

[1] Reference no. 1

[1–3] References from no.1 to 3 (thus, references 1,2 and 3)

[1,3] References no. 1 and 3

[1,3,8] References no.1, 3 and 8

[1,3–8] References no.1, and from no.3 to 8 (thus, references 1, 3, 4, 5, 6, 7 and 8)

Different volumes of a reference must be cited and numbered individually.

4.1.3 Rotor fault analysis

4.1.3.1 Motor current signal analysis

4.1.3.2 PSD analysis

4.1.3.3 PSD+MCSA analysis

4.1.3.4 Deep learning analysis

Generally, quoting is done by remaining faithful to the original text in terms of words, spelling and punctuation. In case there is a mistake, the correct version is written in square brackets in the quoted text.

Short quotations (not longer than 40 words) must be given in quotation marks. Following the text quoted, the reference must be written and a full-stop must be placed afterwards.

Quotations longer than 40 words must not be shown in quotation marks. Instead, they must be indented 1 tab space (1.27 cm) from the left side of the page. The font size for long quotations indented from the left must be 2 pt smaller than the font size used in main text body. However, it is not advised to quote very long texts and to quote very frequently. Unlike short quotations, references of long quotations must be placed after the full stop. (i.e., .(p.196))

Example for a quotation at the beginning of a sentence;

According to Jones (1998), "Students often had difficulty using APA style, especially when it was their first time" (p. 199).

Example for a quotation in the middle of a sentence;

Interpreting these results, Robbins et al. (2003) suggested that the “therapists in dropout cases may have inadvertently validated parental negativity about the adolescent without adequately responding to the adolescent’s needs or concerns” (p. 541) contributing to an overall climate of negativity.

Example for a quotation at the end of a sentence;

Confusing this issue is the overlapping nature of roles in palliative care, whereby "medical needs are met by those in the medical disciplines; nonmedical needs may be addressed by anyone on the team" (Csikai & Chaitin, 2006, p. 112).

Detailed information on quoting could be found on websites of Graduate Schools and associated links.

Footnotes could be used in theses to add content-expanding, content-enhancing, or additional information. Footnote numbers must be placed directly after a quotation. In case the quotation is a paragraph, the footnote numbers must be placed directly after the last word of the paragraph (as superscript). In case the quotation is a concept or a noun, footnote numbers must be placed directly after that concept or noun (as superscript).

Footnote numbers in the main text body must be indicated as superscript, as shown[1]. A punctuation mark must not be placed after the number.

Footnotes must be written with a font size 2 pt smaller than the main text body font size.

1 space must be set between footnote line and footnote number, 1/2 space must be set between footnote number and the first line of the footnote. Footnotes must be separated from the main text body with a thin horizontal line.

Detailed information on footnotes could be found on the websites of Graduate Schools and associated links.

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[1] Reference display can not be done with footnotes. Footnotes could be used in theses to add content-expanding, content-enhancing, or additional information. If these information must include references, these references must be indicated in References section.

Figure 4.1 : Example figure.

4.2 Motor Based Fault Diagnosis

4.2.1 Motor current signal analysis

4.2.2 PSD analysis

4.2.3 PSD+MCSA analysis

4.2.4 Deep learning analysis

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This indicates that the ANN is accurate at base flow and flow height values lower then 3 m.

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[2] Footnotes must be written with a font size 2 pt smaller than the main text body font size.

Table 4.1 : Example table.

Column A	Column B	Column C	Column D
Row A	Row A	Row A	Row A
Row B	Row B	Row B	Row B
Row C	Row C	Row C	Row C

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Figure 5.1 : Example figure in chapter 5.

5. CONCLUSIONS AND RECOMMENDATIONS

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In this thesis, the necessary steps for constructing an end-to-end streamflow forecasting system were discussed. These steps include the use.

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This indicates that the ANN is accurate at base flow and flow height values lower then 3 m.

Table 5.1 : Example table in chapter 5.

Column A	Column B	Column C	Column D
Row A	Row A	Row A	Row A
Row B	Row B	Row B	Row B
Row C	Row C	Row C	Row C

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APPENDICES

APPENDIX A.1 : Example table and equations in the Appendices
APPENDIX A.2 : Additional information provided in the Appendices
APPENDIX B.1 : More additional information provided in the Appendices
APPENDIX B.2 : More and more additional information provided in the Appendices

One way of implementing multiple appendix in a row is to use itemize as in below to prevent issues on the indentation in the second line.

APPENDIX A.1 : Example table and equations in the Appendices
APPENDIX A.2 : Additional information provided in the Appendices
APPENDIX B.1 : More additional information provided in the Appendices
APPENDIX B.2 : More and more additional information provided in the Appendices can go to the second line

APPENDIX A.1

Table A.1 : Example table in appendix.

Column A	Column B	Column C	Column D
Row A	Row A	Row A	Row A
Row B	Row B	Row B	Row B
Row C	Row C	Row C	Row C

$$y_t = \phi_1 y_{t-1} + \varepsilon_t \tag{A.1.1}$$

Each parameter is described. As seen in equation **(A.1.1)**, or in A.1.1.

$$y_t = \phi_1 y_{t-1} + \varepsilon_t \tag{A.1.2}$$

APPENDIX A.2

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$$y_t = \phi_1 y_{t-1} + \varepsilon_t \tag{A.2.1}$$

Each parameter is described. As seen in equation **(A.2.1)**, or in A.2.1.

APPENDIX B.1

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$$y_t = \phi_1 y_{t-1} + \varepsilon_t \tag{B.1.1}$$

Each parameter is described. As seen in equation **(B.1.1)**, or in B.1.1.

$$y_t = \phi_1 y_{t-1} + \varepsilon_t \tag{B.1.2}$$

Each parameter is described. As seen in equation **(B.1.2)**, or in B.1.2.

Table B.1 : Example table in appendix.

Column A	Column B	Column C	Column D
Row A	Row A	Row A	Row A
Row B	Row B	Row B	Row B
Row C	Row C	Row C	Row C

APPENDIX B.2

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$$y_t = \phi_1 y_{t-1} + \varepsilon_t \tag{B.2.1}$$

Each parameter is described. As seen in equation **(B.2.1)**, or in B.2.1.

Table B.2 : Example table in appendix.

Column A	Column B	Column C	Column D
Row A	Row A	Row A	Row A
Row B	Row B	Row B	Row B
Row C	Row C	Row C	Row C

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- **Ganapuram S., Hamidov A., Demirel, M. C., Bozkurt E., Kındap U., Newton A.** 2007. Erasmus Mundus Scholar's Perspective On Water And Coastal Management Education In Europe. *International Congress - River Basin Management*, March 22–24, 2007 Antalya, Turkey. (Presentation Instance)

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OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

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CONDITION MONITORING AND FAULT DIAGNOSIS OF VFD-FED INDUCTION MOTORS

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