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**

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**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**<br>Istanbul Technical University | ........................ |
| **Jury Members :** | **Prof. Dr. Name SURNAME**<br>Middle East Technical University | ........................ |
| | **Prof. Dr. Name SURNAME**<br>Boğaziçi University | ........................ |
| | **Prof. Dr. Name SURNAME**<br>Bilkent University | ........................ |
| | **Prof. Dr. Name SURNAME**<br>Sabancı University | ........................ |
| | **Prof. Dr. Name SURNAME**<br>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 |
| $\mathbf{M_x, M_y}$ | : Torque Components |
| $\mathbf{N_x, N_y, N_z}$ | : Normal Power Components |
| **q** | : Phase load |
| **t** | : Time |
| **u, v** | : Displacement Vector Components |
| **w** | : Angular velocity |
| **XC** | : Capacitive reactance |
| **XL** | : Inductive reactance |
| $\alpha$ | : Angle of deviation from the direction of the principal stresses |
| $\rho$ | : Density |
| $\sigma_x, \sigma_y, \sigma_{xy}$ | : Shell internal stresses |

## LIST OF TABLES

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**LIST OF FIGURES**

# 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.

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.

# 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

Electric motors are divided into two classes depending on their power supply type: direct current (DC) or alternating current (AC). The latter can be broken into two classes as synchronous or induction according to their operating speed. Induction motors, which operates slightly lower than synchronous speed, are also sub-divided as wounded and squirrel-cage motors. In this study, squirrel-cage induction motors have been investigated by means of induction motors, since the squirrel-cage type is predominantly used in industrial applications.

Induction motors run at a speed slightly lower than synchronous speed at the point where motor torque and load torque are equal [manual for industrial]. The difference between the actual speed and synchronous speed is known as slip [sourcebook].

synchronous speed equation comes here.

slip equation comes here.

In Principle, induction motors transfer electrical energy into mechanical energy by interlinking two electrical components: stator as stationary part and rotor as rotational part. Electrical energy transmitted from stator to rotor via electromagnetic induction, then a mechanical component bearing guides rotor to provide mechanical power [electric motor, induction motor fault diag].

motor diagram comes here.

### 2.1.2 VFD-fed induction motors

two figures will be added from iet 108.

A variable frequency drive, also called as adjustable-frequency drive (AFD), variable-speed drive (VSD) or inverter, fed motor system controls the rotation speed of the induction motor by controlling the supply frequency and voltage of the motor. The main difference between line-start and VFD-fed induction motors is that while in line-start mode supply voltage is the only controllable parameter, on the other hand, VFD-fed has the ability to control torque and speed easily [IET energy].

From a historical point of view, DC motors have been utilised in speed control applications. However, as a result of advances in power semiconductor technology used in inverters, the performance of AC motors in terms of precision, response, and speed range began to exceed that of DC motors [improving, historical]. As a driving force behind the induction motor control dominance today, VFDs generally have the following control strategies regarding speed and torque regulation:

- Voltage per Frequency Control (V/f)
- Field Oriented Control (FOC)
- Direct Torque Control (DTC)

The common idea behind these methods is based on controlling the torque and flux references applied to the motor separately, as in DC motor control [iet energy]. In the scope of this thesis, only the V/f control strategy emphasized due to the widespread adoption of the control method in pump, compressor and fan applications.

V/f control can be employed in both open-loop and closed-loop modes. Open-loop V/f control, which is by far the most popular control due to its simplicity, as the name implies, creates a constant air-gap flux by keeping the ratio between the voltage and frequency applied to the induction motor constant, and as a result, it provides the opportunity to work at operating frequencies from zero to nominal frequency [bose].

VFDs come with benefits such that energy savings, reliability and product quality, yet in concern of fault diagnosis they introduce a number of factors, which will be discussed later on, that increase the complexity.

### 2.1.3 Need for condition monitoring

Condition monitoring defined as measuring activities concerning characteristics and parameters of a pyhsical equipment at predetermined intervals either manually or automatically [bsi]. Leveraging rapid technological advancements in data storage, data process and network structure, condition monitoring became one of the driving force behind the industry 4.0 paradigm. The key goal behind this paradigm is to acquisition, transmition and analysis of data in order to predict future behaviours of a machinery, or plant in a larger scale, to boost efficiency and reliability [a pred model, pred maint].

Researchers from both academia and industry have devoted significant attention to condition monitoring of induction motors over decades. Even though induction motors renowned for robustness, environmental, electrical and mechanical effects may lead induction motors to failure. As a result, industrial processes subjected to potential losses in a manner of time and money, so the desire to minimize or even prevent these losses emerges the need for condition monitoring.

### 2.1.4 Maintenance strategies


**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.

## 2.2 Induction Motor Fault Types

### 2.2.1 Bearing related faults

### 2.2.2 Stator related faults

### 2.2.3 Rotor related faults

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**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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| Column A | Column B | Column C | Column D |
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| Row B | Row B | Row B | Row B |
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**Table 2.2 :** Table captions must be ended with a full stop.

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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 |
| Row 1 | -7.680442 | 7.6986348 | 0.00 | 0.00 | 0.00 | 12 | 12 |
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| 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 |

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) |
| 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) |

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

Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Stet clita kasd gub rgren, no sea takimata sanctus est Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut lab ore sit et dolore magna.


**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.

dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum.

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

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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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- 1950-1956 Istanbul Technical University at the Central Laboratory of Theoretical Physics.
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**PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:**

- **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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- **Chen, Z.** 2013. Intelligent Digital Teaching And Learning All-In-One Machine, Has Projection Mechanism Whose Front End Is Connected With Supporting Arm, And Base Shell Provided With Panoramic Camera That Is Connected With Projector. Patent numarası: CN203102627-U. (Patent Instance)

**OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:**

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CONDITION MONITORING AND FAULT DIAGNOSIS OF VFD-FED INDUCTION MOTORS

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