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** 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.

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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 [8]. The difference between the actual speed and synchronous speed is known as slip [5].

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 [9,10].

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 [11].

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 [4, 5]. As a driving force behind the induction motor control dominance today, VFDs generally have the following control strategies regarding speed and torque regulation [12, 13]:

- 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 [11]. 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 [14].

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 physical equipment at predetermined intervals either manually or automatically [6]. 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, transmission and analysis of data in order to predict future behaviours of machinery, or plant on a larger scale, to boost efficiency and reliability [15, 16].

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 capital, so the desire to minimize or even prevent these losses emerges the need for condition monitoring.

2.1.4 Maintenance strategies

Maintenance can be defined as the combination of all technical and administrative actions taken to maintain or restore an item throughout its life cycle in a condition where it can fulfil its designed function [6]. A motor maintenance program should effectively address reliability, cost, and scheduling issues, as well as the causes of the most common motor failures. Essentially, there are two types of maintenance strategies: corrective and preventive.

bsi map comes here as figure.

Corrective maintenance is a type of maintenance performed after the induction motor failure to detect the fault and restore it to operational condition [6]. The main purpose of this type of maintenance is to get the equipment up and running as soon as possible by repairing or replacing the defective equipment. However, corrective maintenance as a failure-driven method contains a high-risk potential as faults may occur at unexpected times, can disrupt the operation. Since this type of maintenance approach does not take into account the damages that may occur, it may be suitable for equipment that is not critical to the business that does not pose a safety risk.

Preventive maintenance, on the other hand, aims to detect faults at an early stage and correct them before they introduce risk to operation [6]. Preventive maintenance employed to increase efficiency and reliability by taking into account the probability of failure or the ageing of the equipment, at certain intervals or according to pre-planned scheduling. Although this approach is beneficial in cases where the wear-out characteristics are evident, it has disadvantages, especially in terms of not being able to use equipment lifespan efficiently and increasing the maintenance cost compared to the corrective maintenance approach [17].

Predictive maintenance is a condition-based approach to maintenance that is used to evaluate the parameters and characteristics of the equipment or to make predictions based on repeated analysis [6]. Compared to preventive maintenance, predictive maintenance maximizes equipment service-life whilst minimizing unnecessary maintenance. In 99% of machine failures, it is possible to observe indications that malfunctions will occur, in other words, the necessary measures can be taken before 99% of the faults occur by continuously monitoring the machine [17].

Under the predictive maintenance approach, decision-making can be divided into two: diagnosis, which is the analysis of the current situation, and prognosis, which is the assessment of conditions measured over time [18]. A P-F curve can be used to better understand diagnostic and prognostic monitoring systems.

PF diagram comes here.

The downside of predictive maintenance is that it requires additional equipment and relatively high investment costs. But the advantage of VFDs also comes out here. As they currently monitor motor parameters in control applications, they have a high potential for predictive maintenance applications without the need for additional sensors and investments.

2.2 Induction Motor Fault Types

From a mechanical perspective, induction machines basically consist of three components: stator, rotor and bearing. Electrical, mechanical, and environmental disturbances constantly affect asynchronous motor components and cause most malfunctions [19]. Table 2.1 exhibits various surveys that studied and categorized the most common failures [7, 20–23].

As can be seen in Table 2.1, most of the faults associated with bearings followed by stator related faults. It also should be noted that these surveys do not include the effects of power electronics. A motor controlled by VFD is subjected to short and high voltage pulses called PWM (Pulse Width Modulation), which are sent at a very high frequency,

Table 2.1 : Table with single row and centered columns.

Component	IEEE	EPRI	Thorsen-Dalva	Bonnet-Yung
Bering	44	41	51	69
Stator	26	37	16	21
Rotor	8	10	5	7
Other	22	12	28	3

which can have a detrimental effect on the wire insulation and cause a burn on the stator [8]. Although this problem can be solved with high-quality insulation, PWM signals also create non-continuous electrical discharges on the bearings, causing wear which reduces bearing lifespan [24]. Therefore, it would not be wrong to conclude that bearing and stator failures will also have a high rate in VFD-fed induction motors.

2.2.1 Bearing related faults

In all kinds of electrical machines, the mechanical element positioned between the frame that initiates the movement and the rotating axis shaft is called a bearing. These mechanical elements, which help the rotational movement of the electric motor, are exposed to many internal and external destructive effects during their operation and failures arise as a result. Major sources of bearing failures are given below [19,25–29]:

Mechanical stresses: Fatigue, which mostly begins on the surface, turns into small-sized material ruptures at the beginning and later dimensional surface indentations and protrusions. Loose motor connection, misalignment where the motor shaft and load shaft are connected without aligning on the same axis, angular misalignment where the motor shaft and load shaft axes are connected at a certain angle, and unbalanced load connection, which is an unbalance condition where the centre of gravity of the load connected to the motor shaft is not on the rotation axis are other mechanical disturbances on the bearing.

Environmental stresses: Corrosion occurs on the bearing surfaces used in high humidity working environments. Especially the moisture absorbed in the bearing oil initiates this process and the rust that occurs due to corrosion causes deterioration that turns into indentation and protrusion on the surface of the bearing element, and cracks in the later stages.

Thermal stresses: Insufficient lubrication generally causes problems with bearing components. Normally, there is a layer of oil in the bearing that prevents direct contact between the rotating elements so that their surfaces do not wear out quickly. In case of insufficient lubrication, excessive wear and subsequent material deterioration occur as a result of increased friction due to direct contact between metal surfaces.

Electrical stresses: the electrical discharge current effect occurs with a fault current flowing through the bearings from the motor frame to the ground in motors that do not have a suitable ground connection. Asymmetry of stator windings, permanent magnetism effect developing in the motor over time, electrostatic charge accumulation in the motor frame and application of voltage to the motor shaft from the outside, or common end voltages generated due to the high switching frequency of semiconductor power electronics (VFDs using PWM) are the factors that cause this malfunction. The irregular current will cause wear and tear on the bearing metal surface, and as a result, the degree of material rupture and surface deterioration increases.

Vibration in the motor causes the rotor to rotate irregularly or axially unbalanced in the motor air gap. Any axial misalignment that occurs in the motor air gap adversely affects the air gap flux density and causes the formation of harmonic components [11, 28, 29]. Consequently, this can induce harmonic components in the current drawn by the motor with frequencies given by formula [28]:

$$f_{bng} = f_e \pm m f_{\mathrm{v}} \quad \textbf{(2.1)}$$

where,

f_e is the electrical supply frequency;

f_{v} is the rotational speed frequency of the rotor;

m is the harmonic number $1, 2, 3 \ldots$..;

f_{bng} is the current component frequency due to air gap changes.

2.2.2 Stator related faults

As researches have shown, stator faults occupy an important place among asynchronous motor faults after bearing [7, 20–23]. Mechanical, electrical, thermal and environmental factors cause malfunctions in the stator windings, as well as their laminations [10, 30]. Winding faults, as the most common stator faults, are winding short-circuit faults that are mostly the result of the aforementioned effects of the winding insulation. Types of winding faults are as follows [10, 30, 31]:

- Short-circuit between two turns in the same phase, (turn-turn failure)
- Short-circuit between two coils side by side in the same phase (coil-coil failure),
- Short-circuit between the turns of two phases (phase-phase failure),
- Short circuit consisting of all three-phase turns,
- Short-circuit between the conductor of the winding and the stator core (phase-ground short circuit),
- Open-circuit fault when winding gets break.

The factors that cause the motor winding insulation to deteriorate are explained below [10, 11, 30]:

Mechanical stresses: While the motor is running, the rotor may rub or hit the inner surface of the stator due to motor shaft deterioration, bearing failures and misalignment. This force creates a turn-to-turn or a phase-to-earth short-circuit, causing the stator coil and the stator winding insulation to break down. On the other hand, winding breakage may occur due to vibration during operation and therefore the motor produces the open-circuit fault.

Environmental stresses: The environment in which the motor is running can be very hot, cold or humid. On the other hand, substances in the external environment can contaminate the windings, causing the heat dissipation to deteriorate and the insulation to be damaged. In addition, the airflow can be blocked and cannot absorb the air required for cooling. Therefore, it causes the motor windings to heat and consequently the insulation to deteriorate.

Thermal stresses: Thermal effects occur as a result of overloading or a motor failure. With motor overload, the motor temperature rises above the limit value of the insulation class and the insulation deteriorates. At this point, every 3.5% unbalance in the motor supply voltage increases the temperature of the motor by 10°C. In addition, every 10°C temperature increase above the limit temperature value of the insulation halves the life of the insulation.

Electrical stresses: The main reason for this is sudden changes in supply voltage. Transients during commissioning and decommissioning and voltage fluctuations frequently occur, especially in asynchronous motors powered by variable frequency drives. Winding insulations deteriorate due to these voltage variations.

Under the inter-turn short-circuit condition, a significant deviation in rotor slot harmonics components,called as principle slot harmonics (PSH), occurs and can be obtained by given formula [32];

$$f_{st} = f_e \cdot \left[n \cdot \frac{(1-s)}{p} \pm k \right] \quad \textbf{(2.2)}$$

where,

f_e is the electrical supply frequency ;

p is the number of pole pairs of the motor ;

n = $1,2,3\ldots(2p-1)$;

s is the slip ;

k is the harmonic number $1,2,3\ldots$..;

f_{st} is the principle slot harmonic frequencies.

2.2.3 Rotor related faults

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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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 2.2 : 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 2.3 : 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	
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Row 1	-7.680442	7.6986348	0.00	0.00	0.00	12	12
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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 2.4 : 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 2.5 : 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 2.5 (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

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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

$$y_t = \phi_1 y_{t-1} + \varepsilon_t \qquad \textbf{(A.1.1)}$$

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

$$y_t = \phi_1 y_{t-1} + \varepsilon_t \qquad \textbf{(A.1.2)}$$

APPENDIX A.2

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$$y_t = \phi_1 y_{t-1} + \varepsilon_t \qquad \textbf{(A.2.1)}$$

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

APPENDIX B.1

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed ac augue vel dui adipiscing placerat et nec metus. Donec bibendum sodales mollis. Cras in lacus justo, at vestibulum quam. Sed semper, est sit amet consectetur ornare, leo est lacinia velit, adipiscing elementum lectus felis at sem.

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

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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