Failure Mode and Effect Analysis (FMEA) of Vertical Axis Wind Turbine

Mohamad Kamal ALhijazi

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Approval of the Institute of Graduate Studies and Research

Prof. Dr. Mustafa Tümer
Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Mechanical Engineering.

Assoc. Prof. Dr. Hasan Hacisevki
Chair, Department of Mechanical Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Mechanical Engineering.

Assoc. Prof. Dr. Qasim Zeeshan
Supervisor

Examining Committee

1. Assoc. Prof. Dr. Hasan Hacisevki
2. Assoc. Prof. Dr. Qasim Zeeshan
3. Asst. Prof. Dr. Neriman Özada

ABSTRACT

FMEA is a widely used risk assessment tool for defining, identifying, and eliminating potential failures in a product, process, design, and services. Previous research efforts have focused on FMEA of Horizontal Axis Wind Turbines but not on the Failure Analysis of Vertical Axis Wind Turbines. This research aims at enhancement of reliability of vertical axis wind turbines using Failure Mode and Effect Analysis (FMEA) method. A total of 12 probable failure modes have been identified, quantified and prioritized based on FMEA. The list of failure modes are ranked according to the assigned Risk Priority Number (RPN), where the higher the RPN value indicates the higher rank of criticality for the related failure mode. Furthermore, based on the obtained results, a disposition and type of required maintenance activity is suggested for critical failure modes. For analysing, evaluating, and prioritizing of failure modes in vertical axis wind turbine, two main approaches of FMEA (i.e. traditional Risk Priority Number (RPN) approach, Fuzzy Logic (FL), and Dempster-Shafer (D-S) theory), the DS theory has been applied to accommodate the diversity of opinions and taking into account the effects of uncertainty in decision making, and the criticality of the components of system is compared using the aforementioned approaches. In traditional RPN, the risk factors of the system failure modes, Severity (S), Occurrence (O), and Detection (D) are scored and by multiplying of S, O, and D, the RPN value is determined. The crisp RPN approach has been criticised to have several deficiencies and for overcoming of shortcomings, the if-then rules of fuzzy logic have been developed for the system expressed in trapezoidal and triangular fuzzy membership functions; and to account for the uncertainty level of the system evaluation and analysis, D-S theory based on three experts' opinions (multi-criteria decision making) has been applied to the system as well, and finally the obtained results in every approach are compared together. The proposed method accounts for the uncertainty, and the lack of knowledge and experience of the FMEA team.

Keywords: Vertical Axis Wind Turbine, Failure mode and effects analysis, Dempster-Shafer theory, Fuzzy rule.

ÖZ

FMEA, ürün, süreç, tasarımlar ve hizmetlerdeki olası arızaları tanımlamak ve ortadan kaldırmak için yaygın olarak kullanılan bir risk değerlendirme aracıdır. Son araştırmalar, Yatay Eksen Rüzgar Türbinleri FMEA'ya odaklanmıştır, ancak Dik Eksen Rüzgar Türbinlerinin Arıza Analizine göz ardı edilmıştır. Dikey eksenli rüzgar türbininin güvenilirliğini arttırmayı amaçlayan bu araştırmada, Arıza Modu ve Etki Analizi (FMEA) yöntemi kullanılmıştır. Toplam 12 olası arıza modu belirlenmiş ve FMEA'ya göre öncelik verilmiştir. Arıza modlarının listesi, atanan Risk Önceliği Numarasına (RPN) göre sıralanır; burada RPN değeri, ilgili arıza modu için kritikliğin üst sırasını belirtir. Ayrıca, elde edilen sonuçlara dayanarak, her arıza modu için bir bakım ve gerekli bakım faaliyeti türü önerilmektedir. Dikey eksenli rüzgar türbini arıza modlarının analiz edilmesi, değerlendirilmesi ve önceliklendirilmesi için, FMEA'nın iki temel yaklaşımı (yani, Geleneksel Risk Öncelik Numarası (RPN) yaklaşımı, Bulanık Mantık (FL) ve Dempster-Shafer (DS) teorisi) uygulanmıştır Sisteme bağımsız olarak ve enerji sisteminin güvenilirlik seviyesiyle bağlantılı yaklaşım gücünün değerlendirilmesi için sistemin kritik bileşenleri karşılaştırılmıştır. Geleneksel RPN'de sistem hatası modlarının, Şiddet (S), Oluş (O) ve Tespit (D) risk faktörleri atılır ve S, O ve D çarpılarak RPN değeri belirlenir. Keskin RPN yaklaşımı, çeşitli eksikliklere sahip olduğu için eleştirildi ve eksikliklerin üstesinden gelmek için, bulanık mantık kuralları, yamuk veya üçgen bulanık üyelik işlevleri olarak ifade edilen sistem için geliştirildi; Sistem değerlendirilmesi ve analizinin belirsizlik düzeyini hesaba katmak için sisteme üç uzman görüşüne (çok kriterli karar verme) dayanan D-S teorisi uygulanmış ve sonuçta her yaklaşımda elde edilen sonuçlar birlikte karşılaştırılmıştır. Önerilen yöntem belirsizliği ve FMEA ekibinin bilgi ve deneyim eksikliğini açıklar.

Anahtar Kelimeler: Dik Eksenli Rüzgar Türbinleri, Arıza modu ve etkileri analizi, Dempster-Shafer teorisi, Bulanık kural.

DEDICATION

To my family

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LIST OF ABBREVIATIONS

RPN	Risk Priority Number
DS	Dempster-Shafer
FMEA	Failure Mode and Effect Analysis
Cp	Power coefficient
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
S	Severity
O	Occurrence
D	Detection
Bel	Belief
PL	Plausibility
MVRPN	Mean Value Risk Priority Number
MF	Membership Function
DS-RPN	Dempster-Shafer Risk Priority Number
Fuzzy-RPN	Fuzzy Risk Priority Number

Chapter 1

INTRODUCTION

A Wind turbine is the system that produces electricity from the kinetic energy of the wind. For small electricity production, small wind turbines where manufactured, which has different size than the typical large wind turbine and produces lower outputs. Furthermore, Micro wind turbines have many utilizes as spare electricity generator on a boat, big travel vehicles, houses roof tops, etc...

Recently, wind power has grown impressively throughout the world. The global installed capacity was about 318 GW at the end of 2013, which was at the end of the 2000 around 18 GW [1]. In 2013 around 35 GW of new wind capacity were added, the lowest growth since 2008, after 44 GW in 2012. Wind's center of growth has been moving from North America and Europe to Asia in the last few years, which emerged as the global leader.

Worldwide, a substantial share has been reached by the contribution of wind power to the energy supply. By the end of 2013 all wind turbines installed around the globe could have potentially saved a total of 640 TW/H electricity supply for the whole the globe, around 4% of the global electricity demand. For electricity generation, around 103 countries used wind energy in the year 2013 [2].

By 2020, European Wind Energy Association (EWEA) estimates that 192 GW of wind power capacity will be installed in the EU, producing 442 TWh of power, meeting 15% of the EU's electricity demand (2.9% from offshore). Wind provides 34% of electricity in Denmark, while Portugal and Spain get around 20% of electricity from wind power, followed by Ireland (16%), Germany (9%) and Italy (5%).

Based on the current growth rates, the global capacity was expected to increase up to 450`000 MW in 2016. Furthermore, at least 700'000 MW are expected to be installed globally to World by the end of 2020 [3].

Recently, the development of small wind turbines, quiet and specified for urban use, it is possible to harness wind power for on-site energy generation or domestic production or agricultural districts.

These turbines, reaching a maximum of 20 kW of power, can also find space in gardens or on rooftops, they have the ability to produce energy even from modest wind flows and they have relatively little visual impact. Moreover, in contrast to large wind turbines, such plants do not require major infrastructures for electricity transmission from utilities and lend themselves to distributed generation of electricity. Small wind systems can be utilized both as grid connected systems and as stand-alone systems, in addition to that both can be joint with other energy conversion systems, such as photovoltaics.

A cumulative total of 806.000 small wind turbines were installed worldwide (except Italy and India) by the end of 2012, 76'000 of which were newly erected [4]. The number of installed small wind turbines grew by 10% during 2012. China continues to overshadow all other major markets, including the USA and the UK, with its cumulative installed units of over 570’000, which represents 70% of the world market in terms of total as well as new installed units. According to estimations, around half of the turbines continue to produce electricity in China given that this market started already in the early 1980s [2].

By the end of 2012, more than 678 MW has been reached by the globally installed small wind capacity. The USA accounts for 31 % and China for 37% of this capacity [4]. In 2012 the new small wind capacity were added was more than 100 MW, a global capacity increase of 18%.

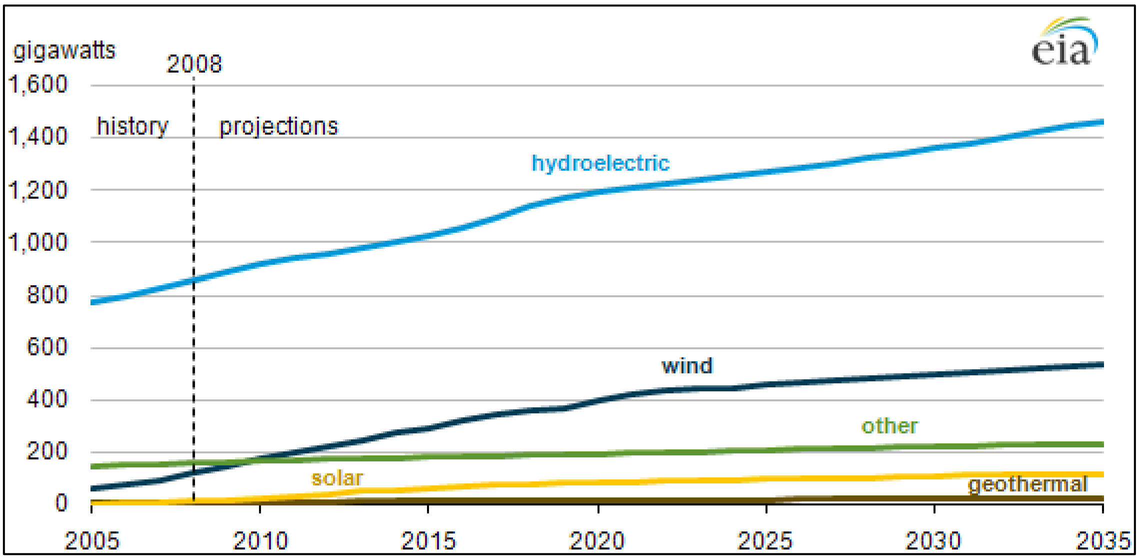

Figure 1 : Global Installed Power Generation Capacity by Renewable Source [5]

As a renewable energy resource, wind power application is growing dramatically and there are several aims to reach until the beginning of 2050 [6] as shown in figure 1. In the present and near future these aims will face many effects and obstacles on their planning and operation. And one of the most important effects is the reliability, so the requirement for productive device to distinguish and after that alleviate danger of failure is of growing significance.

This research will focus on the FMEA of a proposed micro wind turbine concept for low speed wind conditions in North Cyprus. The probable failure modes for the proposed design will be identified, analyzed and prioritized. Risk priority number (RPN) will be utilized to decide the hazard need request of failure modes [65-84].

Failure Mode and Effects Analysis has been widely utilized by wind turbine producers to prioritize the failure modes which have highest potential after investigating and assessing [7]. FMEA is an organized, base up approach that begins with the failure modes which are known or potential at one level and researches the impact on the following sub-framework level [8].

From the base of the hierarchy to the top an entire FMEA investigation of a framework frequently traverses every one of the levels (Fig.2).

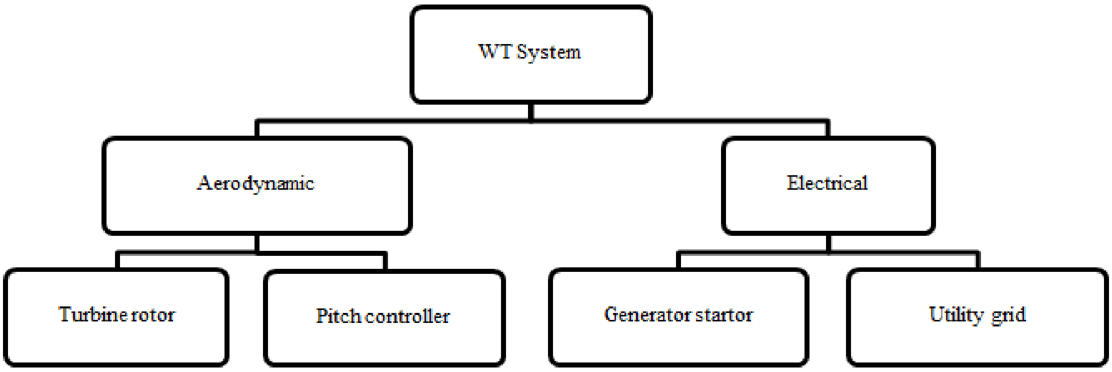

Figure 2 : Hierarchical Structure of a Typical Wind Turbine System

The failure modes are generally distinguished through visual examination, online condition checking systems; for example, ultrasonic testing and oil investigation [9], and time-based preventive upkeep activities. For each distinguished failure mode, their definitive impacts should be dictated by a cross-useful group which is normally framed by authorities from different capacities (outline, operation and upkeep, and power creation). The basic RPN is not enough when a few specialists give diverse evaluations of risks to a single failure mode, which might be uncertain and imprecise. For quantitating the uncertainty and the imprecision in failure analysing and reliability the theory of Dempster-Shafer has been utilized [86-90].

In this study, the Dempster–Shafer has been embraced to accumulate the distinctive assessment data by considering various specialists' assessment conclusions, failure modes and hazard figures individually. The results of D-S method have been compared with the Fuzzy Logic method results [91-106].

In Chapter 2, a review on all wind turbine types and most important differences between vertical and horizontal axis wind turbine. In Chapter 3, previous researches in the field of applying FMEA method to wind turbine components are surveyed. In Chapter 4, the FMEA process and its approaches are introduced with explanation of Dempster-Shafer theory and fuzzy logic.

In Chapter 5, application of two FMEA approaches (Dempster-Shafer FMEA and Fuzzy RPN based on 10 membership) to Vertical Axis Wind Turbine are compared and according to taken results.

Chapter 2

LITTERATURE REVIEW

2.1 Background on Wind Turbines

There are several ideas to depict the sort of wind machines utilized. Most of the wind machines fall into two sorts relying upon if the turbine rotates horizontally or vertically.

2.1.1 The Horizontal Axis Wind Turbines

The wind machines that belong to this class have the greatest hypothetical power coefficient Cp of roughly 0.45 [7]. The principle favorable position of this machine is its powerful coefficient contrasted with alternate types.

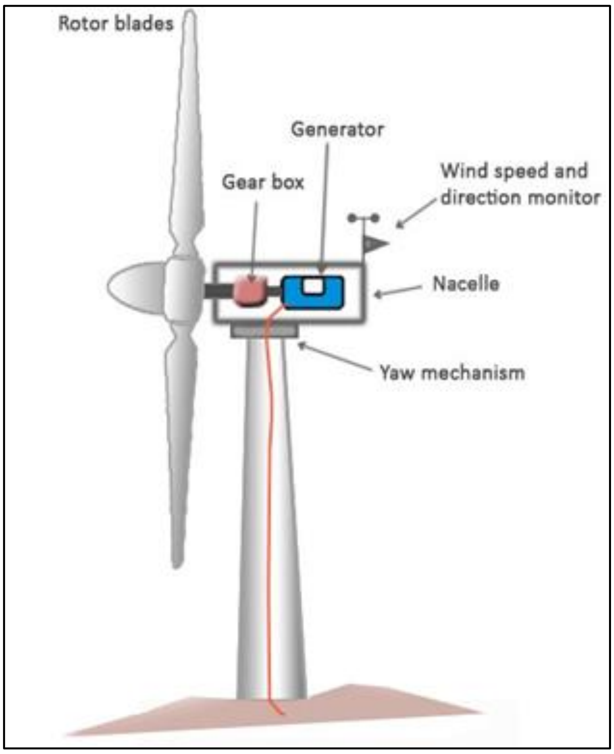

Figure 3 : Key Parts of Horizontal Axis Wind Turbines [10]

2.1.2 Vertical Axis Wind Turbines

This kind of wind machine is central to this study. The rotor of this wind machine swings in columnar direction to the course of the wind. It has a couple of advantages and disadvantages over the HAWT listed in the table at this end of this chapter.

Commonly VAWTs can be isolated into three essential sorts:

1. Darrieus rotor or D-rotor
2. Savonius rotor or S-rotor
3. Combined rotor amongst S and D

This kind of machine (Fig 4, Fig 5) can deliver the highest power coefficient while comparing that got from the Savonius.

Figure 4 : C-shaped VAWTs [11]

Figure 5 : Straight blade VAWTs [12]

The Savonius rotor contains two half chambers dislodged with the goal that one bended face and one indented face is focused to the wind (Fig 6, Fig 7). The refinement in delay two sides creates a torque for most, yet not total, acquaintances with the wind. This type is the slightest complex sort of vertical center point wind machines. It delivers a considerable beginning torque, and it is saving for the little power essentials, in the other hand it has a lower control coefficient [7]. In this way, not lesser than two rotors at different edges are required to promise self-beginning. Despite the way that they are anything but difficult to manufacture. They are considerable and overpowering differentiated and other contort turbines of relative power yield.

Figure 6 : Savonius wind turbine for pumping water

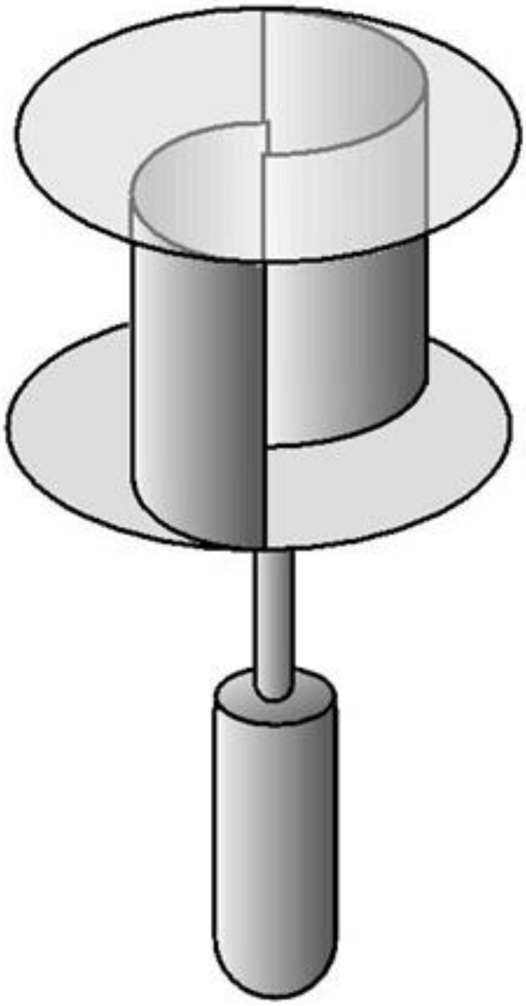

Figure 7 : Savonius Wind Turbine [13]

For dealing with the issue of small beginning torque on Darrieus wind machine Combined rotor is one of the various ways. In spite of the way that the D-rotor has a higher power coefficient than the S-rotor, but it is advantageous that the last has self-starting at low tip velocity ratio and considerable accelerating torque. So, it is quite possible to get the help of a Savonius for starting the Darrieus.

2.2 Review on Wind Energy with Emphasis on VAWTs

Gathering wind vitality started years prior. In the beginnings mariners utilized the force of wind to transport substantial merchandise. The primary known windmill outline was made in the first century BC by Hero of Alexandria under the name

Pneumatics [14]. A picture of this innovation can be found in Figure 8. It is uncertain whether this hardware really existed, but rather from the schematic the motivation behind crushing corn turns out to be clear. Another early idea was produced in 900 AD by Persians [15]. This windmill was drag driven and the first to turn around its vertical axis. A picture of the windmill is shown in Figure 9. These days, such a design is known as Savonius rotor.

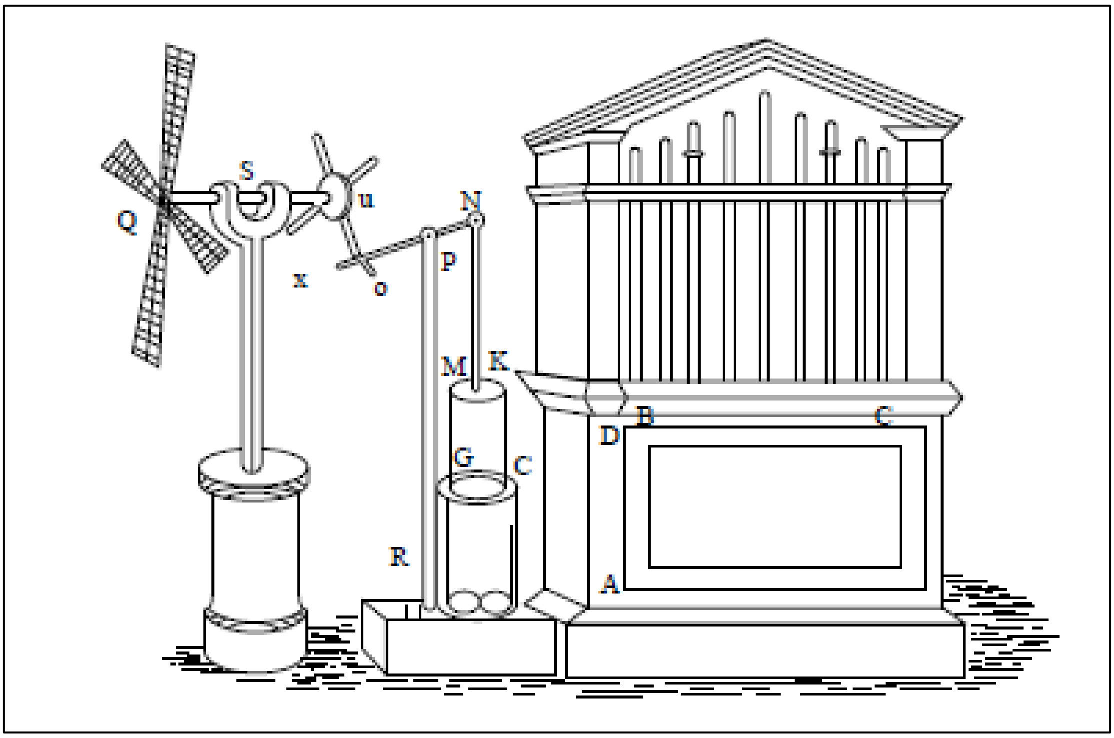

Figure 8 : Hero’s Windmill [14]

Figure 9 : Persian Windmill [16]

In Europe, the windmills showed up in the twelfth century [14]. While the motivation behind pounding corn and pumping water remained, the plan had changed a great deal. The windmill was mounted on a house and confronted the wind course. The rotor configuration comprised of 4 sails turning around a horizontal axis, in this way transmitting the movement to the pound stones. Before the modern upheaval, windmills were one of the real vitality sources [17]. Up to the eighteenth century the European windmills were created assist by having sails as blades and being somewhat twisted; an impression can be found in Figure 10. In the interim, an alternate arrangement built up in the United States, a multi-bladed windmill, alluded to as fan factories [14]. This wind factory was utilized mostly to pump water, which is the birthplace of its moniker Pumping Jack. A case is given in Figure 11. Until the nineteenth century more than 6 million fan mills were inherent the US [17].

Figure 10 : Dutch Windmill [14]

Figure 11 : American Fan Mills [14]

In 1887 started the time of power in wind energy in Great Britain and the United States, where the primary wind turbines, equipped for delivering power, were exhibited [18]. The standard of all current HAWT arrangements is the Danish Design by LeCour, who directed his study in 1890 [15]. The advancement of a more proficient generator helped the wind vitality segment as well. In 1931, G. Darrieus [19] proposed a plan that utilizations lift to produce torque around a columnar axis. Lift achieves more prominent qualities than drag while encountering a similar speed and will have a more noteworthy productivity [15]. Darrieus licensed his rotor shape additionally known under the name Troposkien (Figure 12) and turned into the beginning stage of VAWTs. Conversationally this shape is alluded to as eggbeater.

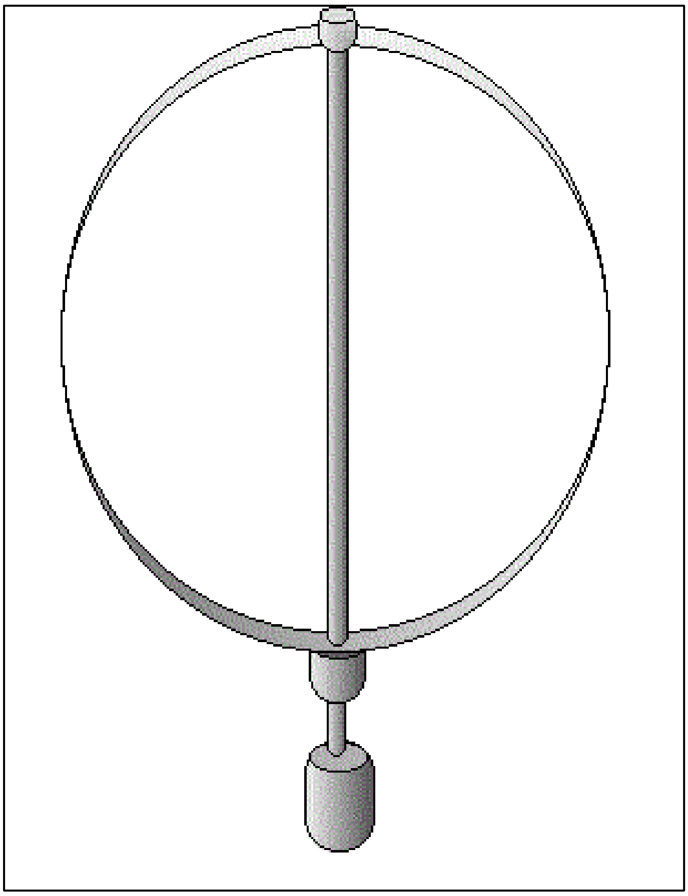

Figure 12 : Darrieus Concept [13]

Around the 1980s escalated inquire about tasks were begun in Sandia National Laboratory (SNL) with a 17 m high Darrieus molded turbine [20]. FloWind purchased the plan and made it prevalent through putting a large number of turbines in the United States (Figure 13). Subsequently FloWind turned into the best VAWT producer.

Figure 13 : FloWind Turbine along the Tehachapi Pass [21]

Beside the Darrieus shape, another shape began to show up. Dr. Peter Musgrove suggesteda VAWT with rectum blades, otherwise called H-rotor [21], which Mc Donnellused to build up a 40 kW H-rotor [22]. This sort of rotor did not have the disadvantage of being secured by Darrieus patent, through the distinction in rotor shapes. At the same time the idea of VAWTs began to be popular in Europe. Risø built theirown H-rotor which was equipped for creating 15 kW (Figure 14, [21]). VESTAS also tried their own idea of a VAWT which had an expanded solidness coming about out of the bi-plane Darrieus (Figure 15).

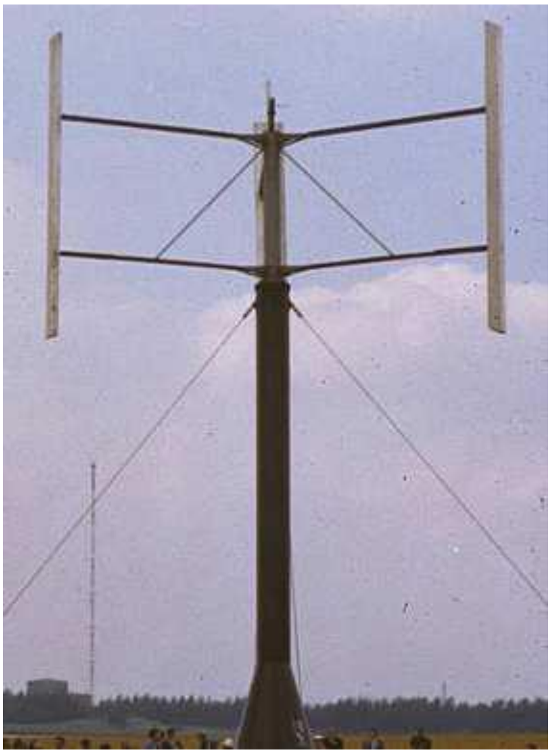

Figure 14 : Risø 15 kW Design [21]

Figure 15 : VESTAS bi-plane Darrieus [21]

As of now around then the possibility of Multi-Megawatt turbine emerged as observed on the 'Eole (Figure 16) which had a rater force of 3.5 MW. It just worked from 1987 to 1993, due to the way that bearings and upkeep were too exorbitant [23]. Not exclusively is 'Eole the largest VAWT, it can likewise be viewed as the last breakthrough of the early era. When the oil-prizes came back to a typical level, the enthusiasm for renewable vitality declined and as a result the VAWT studies ceased, while the advancement of HAWTs continued. At the start of the 21st century renewable energies came more into center to counter the quick environmental change [24]. In 1991 in Vindeby (Denmark) the main turbine was placed offshore [18], instating another innovation part 2.

Figure 16 : 3.5 MW ´ Eole in Canada [21]

2.3 Wind Turbine Applications

As a power creation source, substantial number of wind turbines has been used. Regardless, some decentralized uses on the immediate usage of mechanical shaft control from a wind machine may be simpler and more proficient as: Circulating consumable wastewater, Desalinating saline, warming water by fluid turbulence, circulating air through water, water pumping

2.4 Micro-Wind Turbines

These days, there are many available models of Vertical axis wind turbines, with various measurements and qualities as per the utilization (see Table 1). The power ranges from 200 W to 10 kW with an energy that surpasses 17,000 kWh/year as the yearly mean wind speed is around 12 m/s. The most generally utilized material for their fabricate is aluminum, since both the Savonius turbines and the Darrieus utilize blades with fixed chord geometry, that are appropriate to printing or expulsion generation forms. blades of Darrieus and Gorlov turbines frequently utilize glass fiber and carbon filaments.

2.4.1 Darrieus and Gorlov Turbines

Darrieus turbines, and their improvement, Gorlov turbines, constitute the best answer for get most extreme energy generation. They are the main turbines to achieve 10 kW control generators, despite the fact that with post mounted models which are powerful just for housetop introduced BAWT arrangements (UGE 9M, Kessler Spinwind). With a similar generator control, yields are for the most part higher than customary Savonius solutions(a UGE Vision Air 5 with 3.2 kW of force guarantees 4000 kWh/year of power creation at a mean speed of 5.5 m/s, while a tantamount Savonius display, Helix Wind S594, does not achieve 3,000 kWh/year even with a higher normal speed - 7 m/s - and an all the more capable generator – 4.5 kW).

Vitality yields in the request of 14 MWh/year are gotten with a mean wind velocity of 5.5 m/s. Their structure is characteristically more delicate than the Savonius, and they require stopping mechanisms if there should be an occurrence of unreasonably quick winds (models like the Kessler Spinwind do not work with wind velocity more than 16 m/s).

2.4.2 Savonius Turbines

The Savonius turbines, constructing their operation in light of wind drag more than wind lift, they are constrained by the tangential speed of the blades, which regardless can't surpass the speed of the wind pushing them. Despite the fact that they are snappier to begin than the Darrieus or Gorlov (items like Turbine Energy as of now deliver power with winds of 1.5 m/s), they require higher velocity to perform taking care of business, figuring out how to keep up efficiency even with winds surpassing 30 m/s (with a yearly normal rate of 18.5 m/s a Venger Wind V2 Turbo produces 23,400 kWh/year). More propelled models with settled stators notwithstanding the traditional rotors help to locally quicken the air to build execution: a Turbina Energy 4 kW with stators has a yearly yield which is more than twofold contrasted with a routine Helix Wind S594 at a similar normal speed, and the Venger WindV2 Turbo produces 70% more than a similar model without stators (17,600 kWh/year against 10,900, with a normal speed of 12 m/s). These qualities make them reasonable for establishment in air directs inside the building or holding fast to the rooftop and exteriors, where they can withstand turbulences superior to the Darrieus turbines.Other VAWT models accessible available, incorporate the Aeroturbines (Fig. 17), delivered by Aerotecture, which can likewise be mounted evenly, basically getting to be HAWT, as in the establishment on the top of the Mercy Housing Lakefront in Chicago by Murphy/Jahn Architects. There, eight turbines exploit the overall winds from North-East and from South-South West without breaking the strict neighborhood stature limits for structures, which would have kept the conventional vertical mounting.

Then again, the TR Innovative iWind is a combined sort VAWT turbine, with a Savonius rotor inside and Darrieus H formed blades outside. Because of their little size (1.5 m high and 1.0 m in distance across) and not heavy (carbon fiber cutting edges) they guarantee simple establishment and in addition brilliant execution (hypothetically 10,000 kWh/year with a speed of 4 m/s and a 6 kW generator).

Figure 17 : Aerotecture turbines on Mercy Housing Lakefront rooftop –Chicago [25]

Table 1 : Characteristics and Performance of Main VAWT Turbines Available on the Market (FIG. 18-FIG.26)

Producer	**Model**	**Power kW (m/s)**	**Capacity kWh/year (m/s)**	**Height m**	**Swept area m^2**	**Minimum production speed m/s**	**Material**
Gorlov Turbines							
UGE	Hoyi	0,2 (12)	n.d.	1,3	0,84	2,5	Glass Fiber
UGE	Vision Air3	1,0 (14)	770 (5.5)	3,2	5,76	4,0	Glass Fiber
UGE	4K GT	4,0 (12)	10.000 (7)	4,6	13,8	3,5	Carbon Fiber
UGE	Vision Air5	3,2(14)	4.000 (5,5)	5,2	16,60	4,0	Glass Fiber
UGE	9M	10,0 (12)	14.000 (5,0)	9,6	61,40	3,5	Glass Fiber and Steel
Darrieus Turbines							
Venger Wind	V300	0,3 (14)	661 (8)	1,0	1,0	3,5	Vetronite and steel
Ragosolar	SL30	3,0 (12)	10.000 (8)	3,5	10,5	3,0	Carbon Fiber
Kessler	Spinwind	10,0 (12)	n.d.	14,2	40,0	3,0	Aluminum
FreeTree	FreeTree	1,2 (14)	n.d.	1,9	3,5	3,4	Composites and Aluminum
Savonius Turbines							
Helixwind turbine	S594	4,5 (7)	3.000 (7,0)	6,0	5,88	5,0	Aluminum
Helixwind turbine	S322	2,0(7)	1.500 (7,0)	3,3	3,19	5,0	Aluminum
Venger Wind	V1	2,0 (18,5)	5.400 (12)	3,6	3,4	4,0	Aluminum
Venger Wind	V2	4,5 (20,5)	10.900 (12)	5,7	6,2	4,0	Aluminum
Venger Wind	V2 turbo	4,5 (15,2)	17.600 (12)	5,7	6,2	4,0	Aluminum
Kliux	Zebra	1,8 (n.d.)	3.717 (7)	3,1	7,3	3	Expanded polyurethane
Turbina Energy	1kw	1,0 (14)	1.820 (7)	1,9	2,0	1,5	Aluminum and Steel
Turbina Energy	4kw	4,0 (14)	8.130 (7)	3,2	6,7	1,5	Aluminum and Steel
Sauer Energy	Wind Charger	2,0 (11,1)	n.d.	1,8	1,68	5,0	Composites polymer

Figure 18 : UGE Hoyi

Figure 19 : UGE 4K GT

Figure 20 : UGE 9M

Figure 21 : Venger Wind V300

Figure 22 : Kessler Spinwind

Figure 23 : Helixwind S594

Figure 24 : Venger Wind V1

Figure 25 : Venger Wind V2 Turbo

Figure 26 : Turbina Energy 1kW

2.4.3: Consideration on the productivity of VAWT wind turbines

As vastly mentioned, VAWT wind turbine advancement is as of now grew enough to allow greater scale use in urban concentrations and on structures particularly. The data used for the examination is taken from details given by the producers. The examination between the two turbines sorts indicates how the Darrieus display constantly introduce a higher generation of power per control unit for any wind speed contrasted with the Savonius show, even in the event of high deviations of the normal yearly wind speed contrasted with the base and most extreme normal. However regarding created energy cost for normal yearly wind velocities surpassing 12 m/s the Savonius is more advantageous. The creation of electrical vitality of Darrieus turbines stays in actuality consistent more than 9 m/s, while the generation of the Savonius ascends with the ascent of the twist speed without working limits [2].

2.4.4 Wind Turbine Diagnostics

Wind energy is accessible with no restrictions. Saddling this energy utilizing wind control advancements takes into account the potential extraction of a huge amount of megawatts around the world. While focusing on extracting this energy in an effective way when pay back periods and power production are to be met, for such technologies, reliability is critical.

In the course of recent years, wind control innovations have encountered fast mechanical headway in power electronics, aerodynamics and basic dynamics. For improving the extraction of energy by incorporating each of these innovations, it is foremost in the accomplishment of wind turbine outline and execution. It is accounted that by the foundation of more wind observing stations, enhanced upkeep methods and condition checking, the yearly power yield of wind turbines can be expanded [26]. For keep up framework reliability, and focusing on Fault Detection Systems and growing new Condition Monitoring Systems for applying on wind turbines researches has been carried out. The Scientific Measurements and Evaluation Program proved the requirement for such a framework in which field tests demonstrated that from an aggregate number of 5500 repair activities, 25% were created by failure, wear and untightened parts. Detecting the parts errors can be accomplished prematurely, repair activities can be arranged along these lines dispensing with the requirement for responsive sort upkeep. Utilizing this procedure, machine downtime can be minimized impressively which supposedly has immense cost suggestions especially on seaward applications [27]. For analyzing the condition of components, CMS are currently generally utilized and can be utilized for prescient blame discovery and preventive support. The way of wind turbine deficiencies supposedly varies extensively between various machines which are because of the distinctions in outline and framework intricacy. While considering the basic segments that make up a wind turbine framework, to be specific rotor gathering, transmission and gadgets plainly such parts are regular to any wind control innovation. Figure 27 shows the % distribution of number of failures for wind turbines in Sweden.

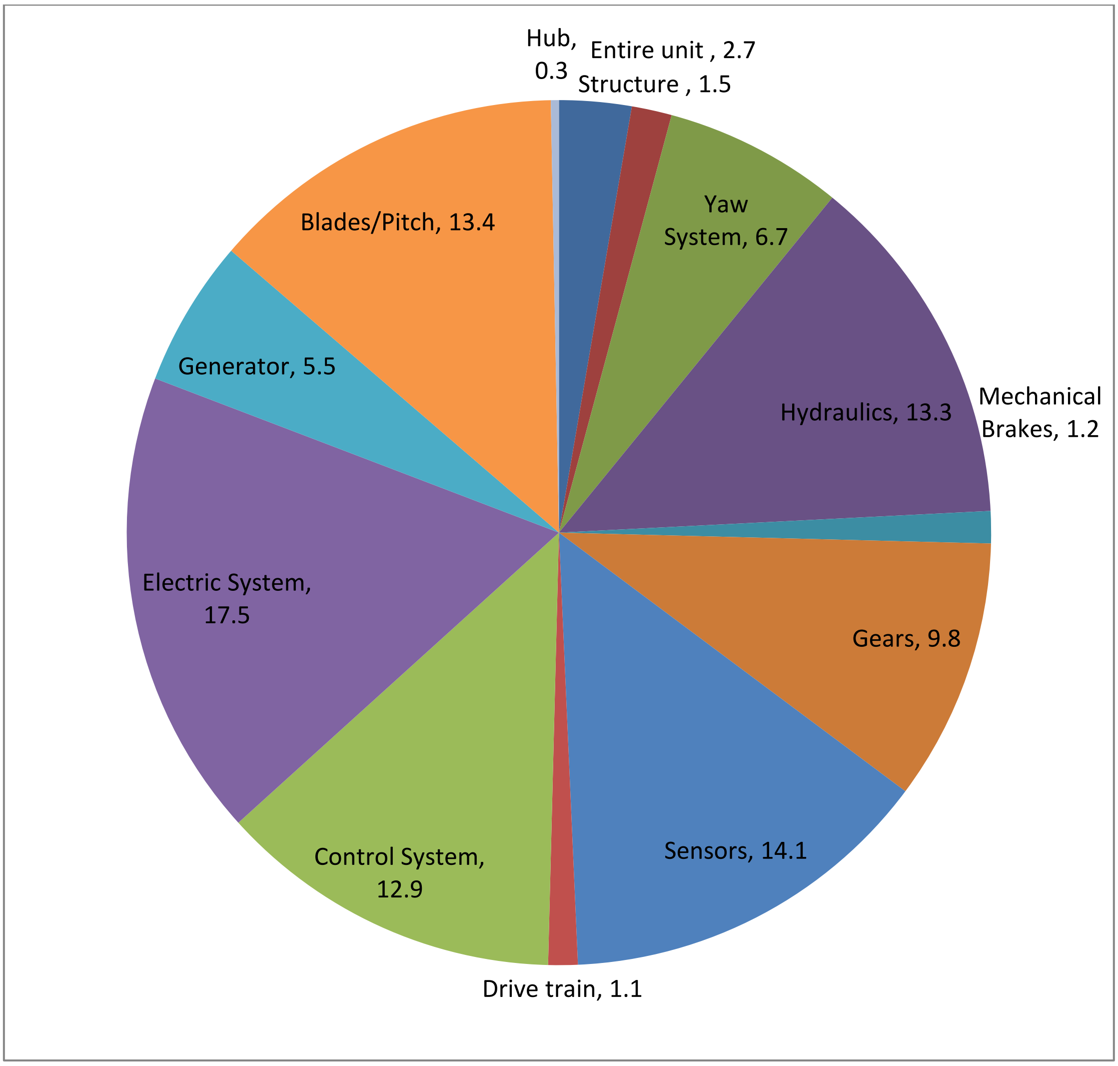

Figure 27 : Distribution of Wind Turbine Failures in Sweden [28]

2.5 Difference between HAWT and VAWT

Here, the H-rotor, Darrieus and HAWTs are the considered wind machines .Particularly, a comparison of the aforementioned wind turbines considering critical operation factors such as basic transient and steady state characteristics, control frameworks, maintainability, producing and electrical equipment. Table 2 shows a summary and give primary contrasts, while discussion follows in the accompanying pages. In addition, the similar characteristics of the H-rotor and the Darrieus turbine permit their consideration in most VAWTs. Using different criteria, H-rotor and Darrieus turbines are looked into for similarities and distinctions [29].

Table 2 : Comparison of Technical Specifications and Summary of Critical Differences for Several Turbines

		H-rotor	Darrieus	HAWT
The most important differences	Blade profile	Uncomplicated	Complex	Complex
	Yaw mechanism	Not required	Not required	Yes, required
	Pitch mechanism	Yes, possible	Not possible	Yes, possible
	Tower	Present	Absent	Present
	Guy wires	Optional	Yes	No
	Noise	Little	Modest	Much
	Blade area	Modest	Big	Little
	Generator site	Ground	Ground	Tower top
	Blade load	Moderate	Small	Large
	Self-starting	No	No	Yes
	Tower interference	Little	Little	Much
	Foundation	Modest	Simple	Broad
	Whole structure	Uncomplicated	Uncomplicated	Complicated
Technical specifications	Rated power (kW)	500	500	500/600
	Swept area (m2)	850	955	1370/1520
	Rated wind speed (m/s)	~13.5	12.5	15
	No. of blades	2	2	3
	Tower height (m)	30	50	47/50

	Turbine diameter (m)	35	34	42/44
	Blade length (m)	24.3	54.5	18/19
	Blade material	Composite	Aluminum	Composite
	Yaw mechanism	No	No	Yes
	Pitch or active stall mechanism	No	No	Yes
	Gear box	Some yes/ Some no	Yes	Yes
	Guy wires	No	Yes	No
	Generator site	Tower/ ground	On ground	In nacelle
	Rotation speed (rpm)	Some constant 13.6/20.4 /some variable	Semi-variable, 28–38	Constant, 18/ 28
	Overall structure	Simple	Moderate	Complicated
	Mass blades only (t)	6	-	13/15
	Mass turbine (t)	~24	72.2	13/15
	Mass nacelle (t)	Some ~20/some without nacelle	Absent	20/23
	Mass tower (t)	153/32.8	Absent	36/42
	Overall weight beyond ground level (t)	197/56.8	72.2	68/80

2.5.1 Aerodynamics

Performance

A power coefficient is the major factor in the wind turbine performance, which shows the amount of the power in the wind that is consumed by the wind turbine. For a perfect wind turbine, the Betz limit is known as hypothetical greatest power coefficient and is 0.59 [30].The power coefficient in horizontal wind turbine varies in a range from 0.40 to 0.50 [31]. In VAWT the expression of the correct estimation of power coefficient is hard while the operation of a couple turbines. Estimations of power coefficient are hence in light of hypothetical reviews and on test come about because of various reviews and are for the most part about 0.40. In 1987, Peter expressed that broad trial and hypothetical reviews had demonstrated that VAWTs had productivity equivalent with the best current HAWTs [32]. Amid the most recent two decades, the HAWT innovation has grown further, which suggests that VAWTs could be produced in a similar manner if cash and time resources were put into related scientific studies. For VAWT, about 20 to 30 years old are the commonly known power coefficient. Vital advance in material and aerodynamic studies have been made from that point forward, which should improve their efficiency. Fig. 28 shows the power curves for the various turbines.

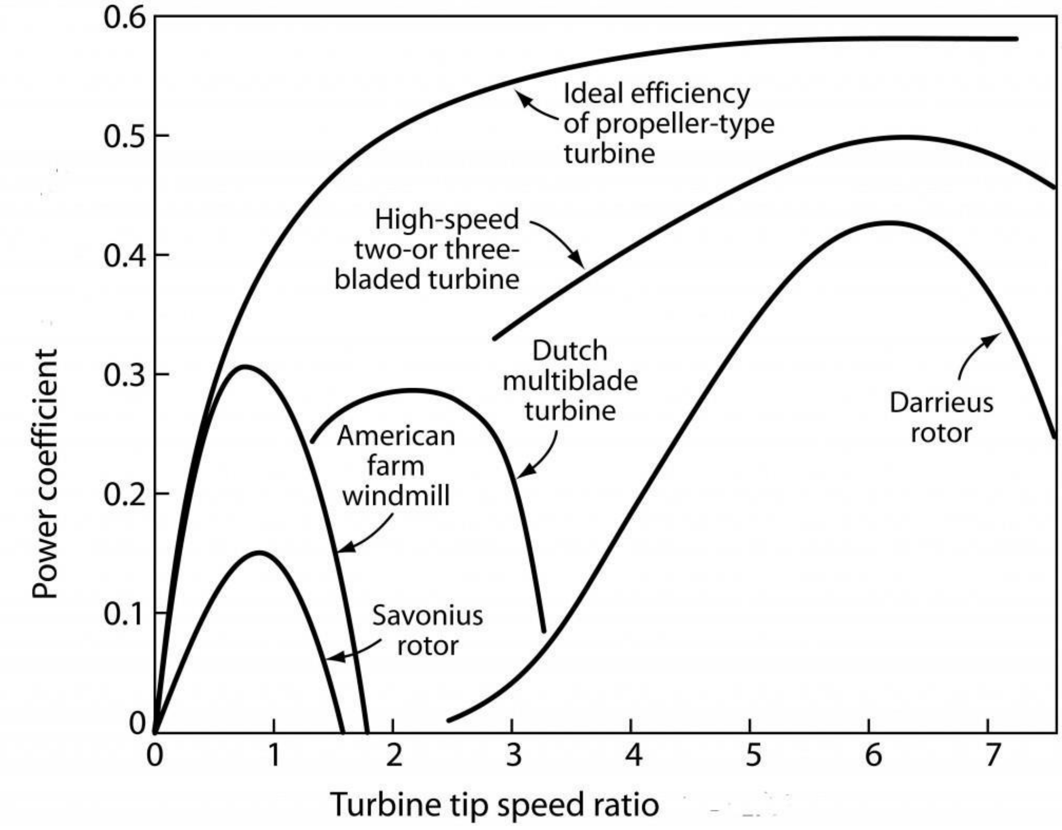

Figure 28 : Power Curves for Different Turbine Types [33]

Power Control

It is fundamental that power obtained from the wind can be controlled. Additionally, there ought to be a working ability to permit the stop of turbines at extreme wind speeds. For the most part, HAWTs utilize pitch control or dynamic slow down control. This requires a sophisticated control structure and also for turn out the blades of the wind a mechanical system will be required. Using pitch control system the power cannot be controlled in a Darrieus. In rapid wind velocity, the ability of blades to fold by the variable geometry invented by Peter Musgrove, One of the leading researchers in VAWT advancement, for decreasing the probability of over speeding of the turbine[34]. the rotational speed is kept fairly constant by the control system. In order to decrease the power absorbed on high wind velocity, a reduction in the ratio of tip speed will take place. Furthermore, in most cases, it is desired to employ mechanical brakes to complement the aerodynamic or electrical brakes. In the case of VAWT, it is possible to install mechanical brakes around the tower base.

2.5.2 Design

2.5.2.1 Structural mechanics

HAWT have blades that are subjected to inverse stress bring about by gravity around the base of the blade; VAWT blades are devoid of this problem [35]. The aforementioned problem is perhaps the major limitation when the sizes of HAWTs are to be increased [36, 32]. In addition, owing to wind shear, HAWT have blades that are subjected to periodic loads. Such loads bring about considerable fatigue on the blades [30]. That is, rotor blades H are subjected to high twisting moments owing to the centripetal force [37]. The rotor H experiences larger twisting moments as compared to the Darrieus owing to having long and straight blades. This problem dwindles as turbine size gets larger, as the centripetal force reduces with larger turbine size, supposing that blade speed is constant. Generally, HAWTs possess fairly stable torque. Conversely, VAWTs are known to exhibit intrinsic torque fluctuation [38]. This torque fluctuation is usually as a result of the constantly varying direction of incidence of perceptible wind and blades. Torque fluctuations can rapidly influence the stress life cycle of composition drive train elements and therefore impact output power quality [39]. One can systematically alleviate the problem of torque fluctuations by employing at least three blades rather than two which is typically used. In addition, the issue of torque fluctuation is lessened when the turbine is worked at a steady velocity [38].The aerodynamic forces on the sharp edges brought on by the changing wind direction will likewise bring about cyclic aerodynamic pressure on the cutting edges. A portion of the machines manufactured in the 1980s experienced stress damage at the sharp edges because of repeating aerodynamic pressure on the turning cutting edges [40]. The aluminium is the material used to fabricate such a blades, but nowadays, the composite materials are better to handle the properties of fatigue [40].

2.5.2.2 Construction

HAWTs possess blades which must be capable to support it self since they are connected just to the base. Bolster arms are used to bolster H-rotor blades. In the other hand, more weight and structure will be added. While comparing Darrieus and HAWT blades with H-rotor blades, the fabrication of the latter is quite simpler. Darrieus and HAWT blades have the ability to twist, and along its whole length the shape is different. Moreover, H-rotor blades have straight curvature distributed on the whole length, and have a bigger area surface compared to a HAWT with the same specified power. More materials will be utilized while making a blade with bigger area.

Occasionally, it is affirmed that the VAWT have no towers and are in this way situated close to the ground with the end goal that wind is inconsistent. On the whole, this is not usually the case. For instance, Darrieus turbine is invariably sited about ground level and possesses an extensive form such that wind shear is quite perceptible [41]. Conventionally, the H-rotor is positioned at the peak of a considerably tall tower, along with the HAWT; this allows the system to experience winds of reduced turbulence. Furthermore, it is possible to sustain turbine shafts with Guy wires; thereby giving to it improved rigidity and robustness. Also important is that owing to interference with the turbines, HAWTs do not possess cables which support the whole framework.

For Darrieus turbines, Guy wires are typically employed. Conversely, Guy wires are somewhat not compulsory in the case of H-rotors; they are beneficial in some situations since cables are desired, but undesirable for applications including offshore, greatly developed sites. Occasionally, owing to tower shadow, HAWTs experience problems related to turn interference. Fortunately, the aforementioned issue is less severe in the counter-current turbine as compared to the downwind turbine. The tower shadow interacts with turbine operating characteristics, encourages power instability and amplifies noise during operation [30].

On the other hand, VAWTs are free of lattice interference given that the blades have considerable separation from the tower. However, owing to the fact Darrieus systems require no tower, it is possible to construct them with unelaborated foundations; this contrasts with the other two turbines. The H-rotor must possess a modest base, while HAWTs typically require extensive base given that much of its weight as well as the whole drive train is situated at the tower peak.

2.5.2.3 Yaw mechanism

The major dissimilarity of VAWTs as against HAWTs is that VAWTs possess the capability to receive wind irrespective of its direction; that is, omnidirectional. Obviously, this comes with many gains. For example, a yaw system is not needed for the turbine; yaw systems are also costly and occasionally collapse while in use. Typically, yaw systems comprise control systems with drive mechanisms. Some of the expenses attributed to this system are the purchasing expense of the equipment, installation expense and other expenses such as for operation and maintenance. Moreover, omnidirectional turbine operates without power loss for the period of the time required for the turbine for the lace; it also retains this feature when there are short wind blasts accompanied with short-term variations in wind direction. In addition, there is zero power loss when running the yaw framework.

An omnidirectional turbine might be found where the wind is turbulent and wind course changes as often as possible. Hence, VAWTs have some benefits over HAWT in considerably hilly sites, in areas where winds are exceptionally powerful and in developed settlements.

[42] Research indicates a clear advantage in using VAWT on roofs [43]. In addition, HAWT make more noise than VAWT, which makes the last preferred in urbanized areas [42]. Interestingly, rooftop VAWTs are now being highly considered for Freedom Tower's energy supply in New York [44].

2.5.2.4 Direct drive

The direct drive shows a situation where a turbine is expressly, via a pole, connected to a generator rotor. The utilization of a direct drive generator constrains the system such that the framework excludes a gearbox. A gearbox is frequently connected with breakdown and need of support [45]. Moreover, a direct drive framework is a great deal more proficient as compared to a generator that comprises a gearbox, given that such gearbox is an origin of problems corresponding to the problems in the generator such as wear and tear. The general framework, while barring a gearbox, is more straightforward and it is less demanding to introduce. Going further, directly coupled wind turbines possess the capacity to respond quicker to variations in the wind speed and direction. Moreover, direct drives decrease the torsional stress on drive shafts set up as a result of eigen recurrence motions which in this way constrains the pole such that its thinner than when an apparatus box is utilized; hence, H-rotors systems can be set up with considerable reduction in the mass of supporting tower [46].

The direct drive system is usually enormous and relies on larger measurements as compared to the ordinary generator; therefore exist focal points in utilizing a vertical pivot turbine with a direct drive generator and setting the generator on the foundation level, considering that bulkiness is not a concern. So far, HAWTs that rely on direct drive machines have remained quite competitive and some corporations that deal with such include Enercon, one of the major manufacturers of turbines for wind systems in Germany [47].

2.5.2.5 Pivot direction

The perpendicular rotating pivot of a VAWT allows for the positioning of the generator at the tower bottom. This arrangement allows the establishment, running and maintenance of the whole setup much less demanding.

Considering a VAWT, it is possible to construct the tower of lesser weight as the nacelle is excluded; this lessens auxiliary burdens, including problems about erecting the tower [37].

It is important that the setup and generator configuration are centered around productivity, expense and minimizing upkeep. Moreover, it is likewise possible to situate on the ground the control framework; this setup will encourage access.

2.5.2.6 Size

An approach for wind control advancement is to expand the span of turbines. Also, the enthusiasm for seaward wind control has expanded. Considering seaward applications, the establishment and establishment expenses are high to the point that it turns out to be more practical with bigger turbines [32]. Eurowind Developments Ltd. [48] puts stock in MW (Mega-Watt) VAWTs [48, 49]; interestingly, Musgrove had some 20 years earlier recommended the same [32]. They together argued that HAWTs having realized its greatest range, hence financial advantage could no longer be obtained as a function of its size [36, 32]. The purpose behind this is the consistently turning around gravity stacks on the sharp edges, which becomes severe for more extensive turbine estimates. Conversely, such breaking points are not found in VAWTs in this way VAWTs can be decently swapped for HAWTs since the capacity of such turbines is required to keep growing [49,32]. Then again Riegler reserves great admiration for small VAWTs [42]. In addition, HAWTs were posited as quite prudent and surpassing their overall usefulness as compared to huge turbines would be difficult. However, it was considered that for ranges for which HAWTs have low efficiency, it is possible to adopt small VAWTs. An example of the aforementioned situation includes hilly territories or districts with a great degree of turbulent winds, for instance rooftop tops.

2.5.3 Cost

Generally, the overall expenditure for a wind turbine comprises the costs for construction cost, reliability analysis, location arrangement, foundation and maintenance [47]. When looking at the assembling expenses of VAWTs and HAWTs, such expenses should assume that the HAWTs are manufactured in extensive numbers and some time has elapsed after its delivery. Incorporating the time perspective offers more astute and less expensive arrangements, since massive number of parts produced can be delivered in masse; this setup considerably reduces overall costs. Besides, with rapid growth in innovation, it is now conceivable to considerably the capacity of HAWTs, significantly bringing down the cost for every introduced kW. Presently, there are no large scale manufacturers of VAWTs. We note that wind turbine cost is often expressed as cost for every produced useful power; that is cost/kWh. The created usefulness of a specific turbine relies upon the proficiency of the turbine, that is assessed using a power coefficient, CP. The distinction in expenses amongst VAWTs and HAWTs meant for arranging, delivering, conveying, raising a turbine and for operation and maintenance is mostly administered based on the diverse expenses used for creating the turbine, including the expenses for operation and maintenance, but with few exemptions. It is probably simpler to construct a less bulky and extensive VAWT tower, and it may be less demanding to convey the smaller HAWTs sharp edges, though Darrieus turbine bended cutting edges are extremely hard for conveying. Interestingly, in order to estimate HAWTs CP, the CP for VAWTs is usually relied upon [50]. Furthermore, the H-rotor’s plan depends on effortless operation. When yaw frameworks and substantial nacelles are precluded, and along with employing plain cutting edges, generation expenses can be brought down despite the fact that the H-rotor as a rule possess more protracted sharp edges than a HAWT. In Darrieus turbines, cutting edges are costly to produce given that they are protracted and as well twisted and here and there likewise turned. [51] shows that VAWTs expenses could perhaps be outrageous as compared to HAWTs. It is vital to lessen the expenses connected with running and upkeep such that the aggregate cost is maintained relatively low. Considering the seaward commerce, it turns out to be significantly more critical to have a machine that necessities as meager upkeep as could reasonably be expected. This gives leeway for the VAWT given that its basic setup and couple of portable constituents need not as much of upkeep as compared to the HAWT. Besides, twist turbines devoid of yaw framework and pitch framework, but with every single electrical part on the ground, can for the most part be kept up from the tower bottom such that the need for cranes or mounting is eliminated. In the case of HAWTs, many of the parts are required to be kept up from the tower peak.

2.5.4 Environment and noise

At the point where we employ guy wires to bolster wind turbines, extensive ground territory is secured. In any case, space can as a rule by obtained given that wind turbines ideally are assembled in locations of level of ground, also ensuring that considerable distance separates the setup and structures. Moreover, safety measures for streets and structures are imperative at any rate, particularly if icing should be considered. In cultivated zones, this could turn into an issue. The H-rotor is required to create a great deal less commotion as compared to a HAWT. Wind turbines possess two primary hotspots where considerable clamour occur; streamlined commotion attributed to the turbine's sharp edge ends and rotary commotion which are attributed to drive prepare parts. The streamlined clamour becomes more severe with expanding edge end and turbine speed [52]. A VAWT for the most part has a tip speed which is roughly a large portion of the tip speed of a HAWT and it in this manner delivers less streamlined commotion [50]. Given that VAWTs have driven prepare segments on the ground, conceivable clamour originating from such constituents won't spread as effortlessly as compared to when drive prepare segments are arranged at tower peak [38].

Generally, Darrieus turbines pivot quicker as compared to H-rotors, yet for a particular size, it is not as quick as the HAWT. It will in this way deliver more commotion as compared to H-rotors yet lesser clamour as compared to HAWTs. The VAWT 260 when observed in operation was found to generate lesser noise [53]. The H-rotor can be considered not that destructive to flying creatures, given that the edges revolve at low speeds; the speed of the edge appears to influence the hazard for crash incredibly [54]. Moreover, issues with frosting are seldom extreme in VAWTs as compared to HAWTs. Also, not much security separation is necessitated. One can attribute this feature to the smaller revolution speed of a VAWT given that frosty part that comes off are not able to achieve a speed focused upwards when coming off a VAWT; this may be the situation with frosty parts coming off a HAWT sharp edge.

2.6 Advantages and Disadvantages of VAWTs compared to HAWTs

The relative points of interest and impediments of VAWTs and HAWTs are given below:

Table 3 : Advantages and Disadvantages of Vertical Axis Wind Turbine

Advantages	Disadvantages
VAWT does not require positioning of the rotor toward wind courses because it is an omni-directional machine. In this way, the yaw component is unnecessary for VAWT which was used as a component of typical HAWTs. Hence, whilst the rotor is moving in the direction of wind course power is not lost [55].	For a similar wind velocity, HAWT has higher performance comparing to VAWT, achieving less power yield.
Many VAWT is situated on the ground while HAWTs are positioned on high area tower. Following this setup for VAWTs, the significant transmission structure, control box, gearbox and generator and may be assembled on the foundation level, allowing accessibility for maintenance and uncomplicated operation.	VAWTs are for the most part not self-beginning (aside from by all around outlined components). In any case, the Savonius rotor is an exemption yet it has genuinely low effectiveness [19].
The general structure of VAWT is shorter than HAWT realizing less commendable visual impact on its surroundings.	VAWT is situated and assembled near the foundation level, it is exposed to more stress and less wind speed. In this way, HAWT has greater power yield than VAWT with a rotor that has the same and weight and size.
Many VAWT are easy to fabricate, for instance, Savonius wind machine producing satisfactory torque for several applications. In this way, VAWT must be considered. in the uses which escape from expensive pays.	Some VAWT types need a guy cable to fix it upright.
In HAWT are exposed to cantilever loads causing curvature force at the base of the blade. But, centrifugal force balancing is an initial parameter while designing a VAWT. The blades [56].	In HAWT, the power yield and the torque are approximately stable. In the other hand, in VAWT, the power yield and torque produced vacillate in a cyclic way amid every acceleration and deceleration.

2.7 Previous FMEA Applications on Wind Turbines

Previous researches in failure mode and effect of wind turbines had focused on horizontal axis wind turbines, aiming to improve their quality for high electricity production (Wind farms, Huge wind turbines, etc…) considering the number of components. In this thesis the FMEA is utilized for analyzing the reliability of VAWTs, which has less number of parts.

Table 4 : Previous Studies on Failure Mode and Effect Analyses of Wind Turbines

Component	Failure type	Literature	HAWT Type	VAWT Type	Analysis Method
Blades	Mechanical failure (Cyclic fatigue)	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
		Veers (1983) [62]		100 kw	Fatigue analysis
		Veers(1982) [63]		100 kw	Fatigue life assesment
Tower and structure	Fracture and fatigue	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Gearbox	Fracture and cyclic fatigue	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA

	of internal components	Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Tavner et al (2010) [61]	2MW		Basic FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Hydraulic systems	blockage and thermal	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Mechanical Brakes	Mechanical failure (Cyclic fatigue)	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Main shaft	Fracture and thermal	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)

Rotor Bearings	lifetime	Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Rotor Hub	Mechanical failure (Cyclic fatigue)	Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Pitch Mechanism	Mechanical failure (Cyclic fatigue)	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Generator	Overheating	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Tavner et al (2010) [61]	2MW		Basic FMEA
		Klein et al (1990) [64]	200 KW		Basic RPN
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Yaw System	Mechanical failure (Cyclic fatigue)	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA

		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Electrical systems	Mechanical failure (Cyclic fatigue)	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Converter	Overload	Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA
		Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Tavner et al (2010) [61]	2MW		Basic FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Main frame	Mechanical failure (Cyclic fatigue)	Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
Nacelle	Mechanical failure (Cyclic fatigue)	Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Hoseynabadi et al (2010) [57]	2MW		Software Based FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and

					criticality analysis. (FMECA)
Screws	Corrosion	Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
Transformer	Short-circuit	Dinmohammadi et al (2013) [58]	5 MW		Basic FMEA
		Tavner et al (2010) [61]	2MW		Basic FMEA
		Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
Drive train	Deterioration	Tavner et al (2010) [61]	2MW		Basic FMEA
Controller	Mechanical failure (Cyclic fatigue)	Bharatbhai (2015) [59]	5 MW		Failure modes, effect and criticality analysis. (FMECA)
		Kahrobaee et al (2011) [60]	3 MW		Risk-Based FMEA

- **[Hoseynabadi et al] (2010)**

The core framework researched is a 2 MW wind turbine based on a Doubly Fed Induction Generator (DFIG), which is then contrasted and a theoretical wind turbine framework utilizing the Brushless Doubly Fed Generator (BDFG) of a similar rating. As soon as FMEA data was created, it was adjudged during assembling such that failure problems can be identified for the whole framework, subassemblies and parts. This could be a valuable methodology for manufacturers to spot lapses in the WT architecture. The outcomes demonstrated that the R80_ was more dependable than the R80 because of the more solid generator and gearbox composition [57].

- **[Dinmohammadi et al] (2013)**

The benefits of the suggested fuzzy rule bases and grey hypothesis approach for application to FMEA of seaward wind turbine frameworks can be abridged as below:

a. The proposed fuzzy-FMEA technique gives a sorted out system to consolidate the subjective (specialist knowledge) and quantitative (SCADA field information) knowledge to be utilized for FMEA analysis;

b. The suggested fuzzy-FMEA technique becomes invaluable when failure data are inaccessible or inconsistent;

c. The utilization of semantic terms in the investigation empowers the specialists to express their assessments all the more practically and consequently enhancing the relevance of the FMEA method in seaward wind sites;

d. The relative impacts of hazard variables are thought about during the time spent prioritization of failure modes such that suggested FMEA becomes more reasonable, deployable and adaptable [58].

- **[Bharatbhai] (2015)**

The outcomes of failure analysis show that the general failure resistance of the 5M wind turbine is quite low.

Besides, this examination concentrated on reliability study when the turbine was not able to deliver any electrical power. In the event that the meaning of failure was adapted to consider pitch and yaw framework collapse, the ruggedness and resilience of the turbine would be considerably lessened.

The research also recognized major constituents vulnerable to failure, for example, the turbine cutting edges and greasing framework, and showed the requirement for condition observing to ascertain valuable maintenance [59].

- **[Kahrobaee et al] (2011)**

This research presented another quantitative approach for the FMEA investigation of the wind turbines in view of their failure modes impact on the overall failure cost. This strategy was employed for a 3MW direct drive twist turbine as a contextual investigation, and results show a more reasonable recognition of failure modes. The estimations of CPN presented in the study indicate the crucial failure modes, as well as be used for estimating of overall failure expenses of wind turbines for time periods of concern. Intricacy of utilizing customized software was eliminated by utilizing MS Excel spreadsheet, and accordingly, this strategy can easily be utilized for various sorts and areas of the wind turbines [60]. Lastly, sensitivity studies were carried out keeping in mind the end goal to observe the effect of different parameters on AFC wind turbines.

- **[Tavner et al] (2010)**

This paper applied the FMEA to the design for availability of a 2MW, geared, exemplar R80 wind turbine design used in the EUFP7 ReliaWind Consortium. The technique was used to compare the prospective reliabilities of three versions of the geared R80 turbine with different drive train solutions. These solutions have been proposed to reduce overall wind turbine failure rate and raise its availability [61].

- **[Klein et al] (1990)**

The study showed the outcomes of FMEA experiments for the wind turbine generators. The FMEA was carried out for the operational constituents of every system, subsystem, or segment [89].

The FMEA showed the requirement for various plan changes [64]:

1. Disk brakes on high speed shaft
2. Primary safety devices
    a. Overspeed
    b. Vibration
    c. Feather pressure
    d. brake pressure
    e. Yaw error
    f. Alternator over/reverse current

3 Redundant sensors

4 Intruder alarm

The last FMEA additionally gave project administration staffs guidelines on the level programs for safety and risk assessment that are acceptable for this design.

Chapter 3

METHODOLOGY

3.1 FMEA PROCESS

The emergence of a failure is a phenomenon that can make a disorder in any complex system and result in a delay in production [65]. Therefore, for confronting the different failures which may occur, the experts take the proper measures in different steps like designing, manufacturing, and operation [66]. Failure Mode and Effect Analysis (FMEA) is a risk management approach that prevents probable failures in the system and provides the foundation for policies and remedial measures to tackle them.

FMEA was first employed in the 1960s in aerospace companies as a risk management tool during designing phase, and afterwards, this method is being used in other sectors such as automotive industry [67].

Risk management is mandatory based on ISO 31000:2009 which provides generic guidelines and frameworks to risk management processes. Using ISO 31000:3009 is beneficial to effectively achieve organizational objectives and utilize resources for risk treatment by identifying opportunities and threats [68].

In FMEA process, the main objective is to distinguish the critical components of the system, and the output of this technique is scheduled plans for performing preventive or predictive maintenance strategies before any potential failure occurs. In other words, the aim of FMEA is (1) to recognize the failure modes occurring during a definite period of system, (2) to determine the reasons for any failure occurrence, (3) to evaluate the effects of each failure, and (4) to prioritize the failures [69]. The flowchart of FMEA hierarchical process is shown in Figure 29.

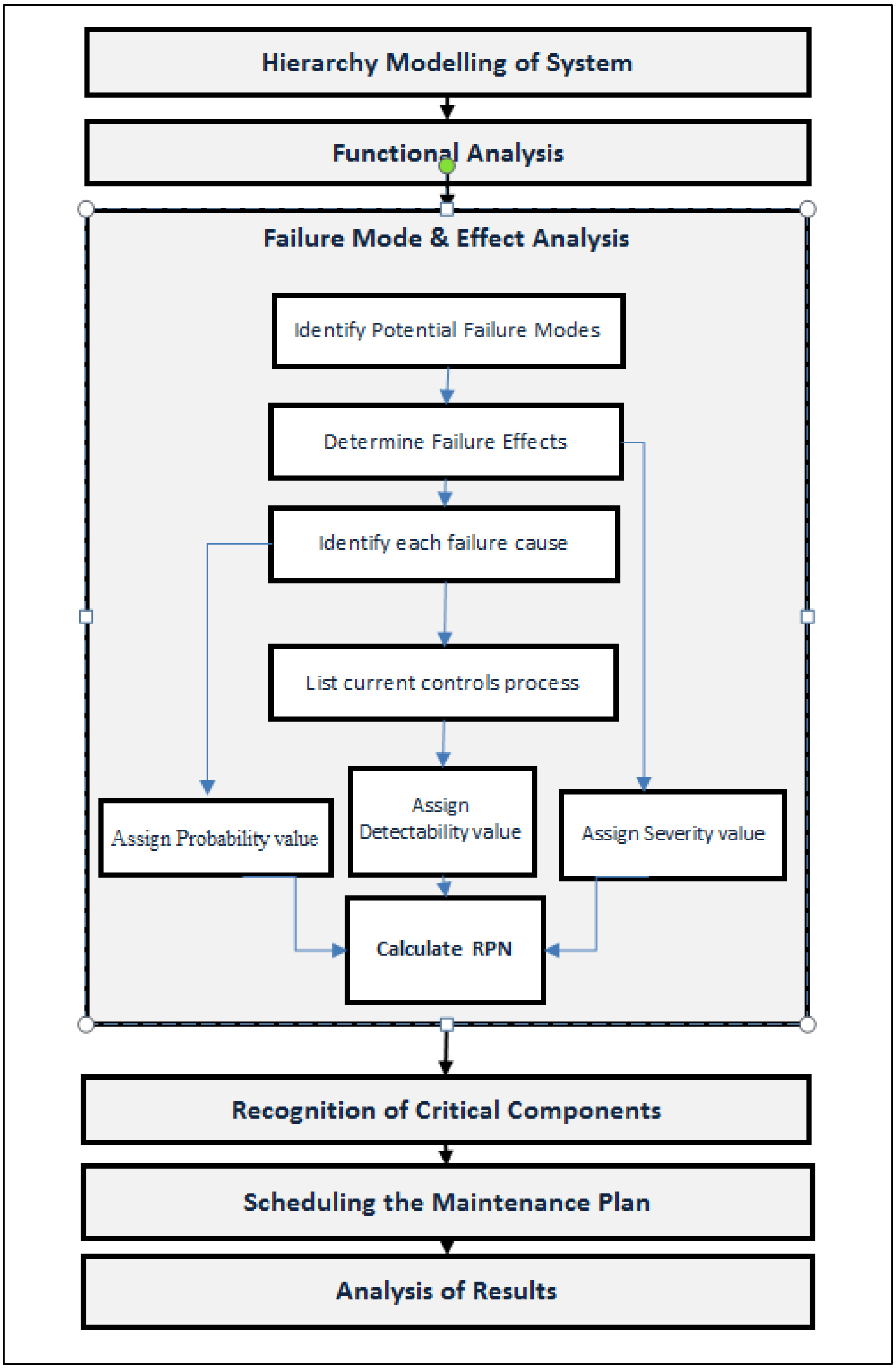

Figure 29: FMEA Process Flowchart

In general, FMEA method can be categorized in three main types [70]:

System/Concept FMEA "S/CFMEA" (Driven by System functions):

A system can be conceived of as a connected configuration of subsystems and parts to perform various functions. FMEAs frameworks are commonly ahead of schedule, before the determination of particular system components.

Design FMEA "DFMEA" (Driven by component functions):

A Design/Part is a unit of physical equipment that is envisioned as a solitary replaceable part as for repair. FMEA plans are normally carried out later on in the assembling stage when particular components are known.

Process FMEA "PFMEA" (Driven by process functions & part characteristics):

A Process is a chain of steps that are set out to deliver a product or function. A FMEA process may include fabricating, assembling and exchanges or support.

A FMEA procedure is led in three fundamental strides:

Step 1: By dividing the system into subsystems and components, the main modules are categorized in a bottom-up diagram (as shown in Figure 30), and upon the occurrence of any failure in any component, the effect chain is traceable at higher levels [71-73].

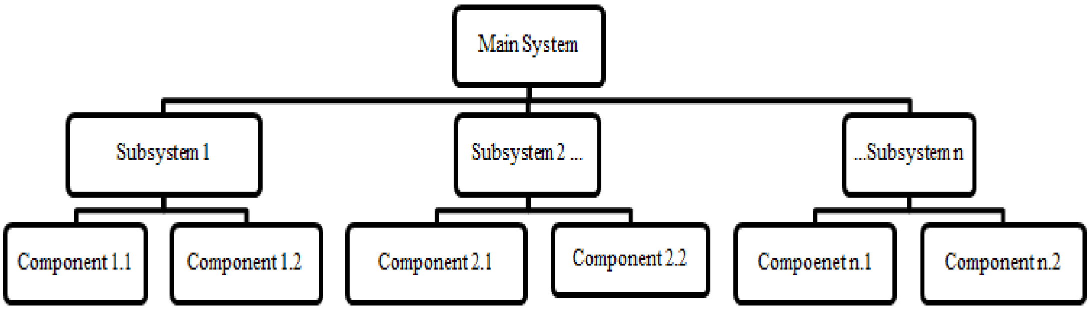

Figure 30 : System Hierarchical Structure

Step 2: FMEA method is evaluable both qualitatively and quantitatively. By considering three parameters, i.e. Severity (S), Occurrence (O), and Detection (D), and allocating a number between1and10, Risk Priority Number (RPN) is calculated according to the following formula [73-76].

$$RPN = S \times O \times D \qquad (1)$$

The method of allocating a number to any risk parameter is summarized in Tables 6 to 8. RPN shows the amount of potential risk in the observed failure modes of the system. The key parameter of basic approach of FMEA process in selecting the maintenance policy is allocation of a number between 1 and 10 to every risk factor of failure mode and categorizing them so that the more critical failure is, the allocated number is higher and the more periodic inspection of the related component is required.

Table 5 : Severity Rating Criteria of a Failure in FMEA [77-82]

Rating	**Effect**	**Severity of effect**
10	Dangerous with no cautioning	Very high severity ranking when a probable failure mode affects system operation without warning
9	Dangerous with	Very high severity ranking when a potential failure
8	Extremely high	System unusable with catastrophic failure
7	High	System unusable with equipment damage
6	Moderate	System unusable with minor damage
5	Low	System unusable without damage
4	Extremely low	System usable with considerable degradation
3	Minor	System usable with little degradation of
2	Extremely minor	System usable with least interference
1	None	No effect

Table 6 : Occurrence Rating Criteria of a Failure in FMEA [77-82]

Rating	Probability of Occurrence	Failure Probability
10	Almost Certain	>0.5
9	Very High	0.16666666
8	High	0.125
7	Moderately High	0.05
6	Moderate	0.0125
5	Low	0.0025
4	Very Low	0.0005
3	Remote	0.000066
2	Very Remote	0.0000066
1	Nearly impossible	0.00000066

Table 7 : Detection Rating Criteria of a Failure in FMEA [77-82]

Rating	Detection	Likelihood of detection by control mechanism
10	Total uncertainty	Control system cannot recognize probable reason for
9	Extremely remote	Extremely remote prospect the control mechanism will spot probable reason for failure mode
8	Remote	Remote prospect the control mechanism will spot probable reason for failure mode
7	Very low	Extremely small prospect the control mechanism will spot probable reason for failure mode
6	Low	Small prospect the control mechanism will spot probable reason for failure mode
5	Moderate	Moderate prospect the control mechanism will spot probable reason for failure mode
4	Moderately high	Moderately high prospect the control mechanism will spot probable reason for failure mode
3	High	High prospect the control mechanism will spot probable reason for failure mode
2	Extremely high	Extremely high prospect the control mechanism will spot probable reason for failure mode
1	Nearly certain	Near certain prospect the control mechanism will spot probable reason for failure mode

Allocation of numbers in RPN method is accomplished by specialists who are experts in system functions and the amount of the effect of any failure, so two factors, i.e. the experience and knowledge of specialists, are effective on the final results. Therefore, an improved parameter called Weighted RPN is utilized. The weighting is based on the following coefficients given to the obtained RPN: out of question (1), very confident (0.9), confident (0.7), less confident (0.25), and not confident (0.1). By considering experience and knowledge in the final results, the RPN value will be a qualitative evaluation, and the numbers are just comparative in rating the critical parts of the system.

Due to numerous criticisms against RPN method, it has not been considered as an ideal approach and has been replaced by alternative methods in FMEA. The most important criticisms are: ([78], [83], and [84])

- Distinctive combinations of O, S and D evaluations may create a similar estimation of RPN, yet their concealed risk basis might be diverse completely. For instance, two distinctive failure modes with the estimations of 5, 7, 2 and 10, 1, 7 for O, S, and D, individually, will have an identical RPN estimation of 70. In any case, the concealed risk basis of the two failure modes might be altogether different as a result of the diverse severities of the failure outcome. Now and again, this may bring about a high-risk failure mode being undetected.

- RPNs are not persistent, and massively produced at the scale from 1 to 1000. This result to issues in deducing the significance of various RPNs. For instance, is the contrast between the neighbouring RPNs of 1 and 2 the same as or not exactly the distinction somewhere around 10 and 20?

3.2 Dempster-Shafer Theory

Based on the work done by Dempster [85] this theory was created and demonstrated by Shafer [86]. For describing the uncertainty set in the hypothesis the belief interval is adopted by the DS theory. Furthermore, when uncertainty, impreciseness and incompleteness take place in information set by several sources, this strategy can solve it [87].

3.2.1 The Frame of Discernment

Assume that Θ be the set of N elements which is a finite nonempty complete set of mutually exclusive possibilities. Θ is defined as the frame of discernment. The power set of Θ is all the possible subsets, noted as 2^{Θ}. There are 2^{N} elements in the 2^{Θ}. For example, if Θ = {1, 2, 3} and N = 3, the power set is 2^{Θ} = {ø, 1, 2, 3, 12, 13, 23, 123}, where ø denotes the empty set. The D–S evidence theory starts by defining the frame of discernment.

3.2.2 The Basic Belief Assignment (BBA)

The basic belief assignment is a primitive from of evidence theory, which is denoted by m(X). The function m(X) is a mapping: m(X): 2^{Θ} →[0, 1], and satisfies the following conditions:

$$\mathrm{m}(\emptyset) = 0 \tag{2}$$

$$\sum_{X \in 2^{\Theta}} \mathrm{m}(X) = 1 \tag{3}$$

$$0 \leq \mathrm{m}(X) \leq 1 \quad X \in 2^{\Theta} \tag{4}$$

m(X) expresses the precise probability in which the evidence corresponds to m supports proposition X. X may not only be a single possible event, but could be a set of multiple possible events.

3.2.3 Belief Function (Bel)

A belief function is often defined by the basic probability assignment function which is represented by Bel(X).

$$\mathrm{Bel}(X) = \sum_{Y \subseteq X} m(Y) \tag{5}$$

Bel(X) describes the overall amount of probability which have to be shared among elements of X. It shows unavoidability, indicating the overall level of belief of X, and represents a lower limit function on the probability of X [88]. Apparently,

$$\mathrm{Bel}(\emptyset) = 0 \tag{6}$$

$$\mathrm{Bel}(\Theta) = 1 \tag{7}$$

Shafer proved that for natural number n, $X_k \subseteq \Theta$:

$$\mathrm{Bel}(X_1 \cup X_2 \cup \cdots X_n) \geq \sum_i \mathrm{Bel}(X_i) - \sum_{i\backslash i} \mathrm{Bel}(X_i \cap X_j) + \cdots + (-1)^n \mathrm{Bel}(X_1 \cap X_2 \cap \cdots X_n) \tag{8}$$

Where i, j, k = 1, 2, … , n.

3.2.4 Plausibility Function (pl)

A Plausibility function (Pl) is defined below:

$$\mathrm{Pl}(X) = 1 - \mathrm{Bel}(\overline{X}) = \sum_{Y \cap X \neq \emptyset} m(Y) \tag{9}$$

Where $\overline{X}$ is the negation of a hypothesis X. Pl(X) quantifies the maximal amount of probability that can be shared among the elements in X. It expresses the overall degree of belief associated to X and represents an upper limit function on the probability of X [88].

[Bel(X), Pl(X)] is the posteriori confidence interval which describes the uncertainty of X. When the unawareness to proposition X is reduced, the length of interval is lessened. The association between Bel(X) and Pl(X) is illustrated in Fig. 31.

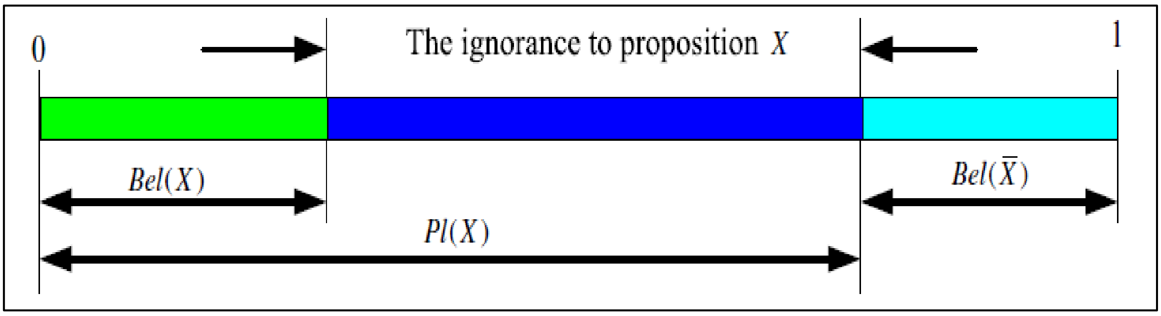

Figure 31: Belief Function and Plausibility Function

Dempster's Combination Rule

The D–S evidence theory can amass several origins of evidence through the combination rule. Dempster's combination rule is stated thus: given two basic probability assignment functions m_i (X) and m_j(Y), the Dempster's combination rule can be defined by:

$$m(C) = \left(m_i \oplus m_j\right)(C) = \begin{cases} 0, & C = \emptyset \\ \frac{\sum_{X \cap Y = C, \forall X,Y \subseteq \Theta} m_i(X) \times m_j(Y)}{1 - \sum_{X \cap Y = \emptyset, \forall X,Y \subseteq \Theta} m_i(X) \times m_j(Y)}, & C \neq \emptyset \end{cases} \tag{10}$$

Where, m(C) represents the BBA of c that is supported by ith and jth combination.

3.3 Risk Priority Number based on DS Theory

As quickly discussed in the preceding section, the D-S data theory utilizes the confidence interval to describe the inconsistency of the hypothesis and can successfully deal with the inadequate, inaccurate and unverifiable data of a system. Also, the new allocation of aggregate belief can be accomplished by consolidating numerous origins of evidence utilizing a combination rule. In addition, because of the adaptability of the essential axoims in the hypothesis of proof, no different theory is required to measure the inexact data of the system [89]. In this segment, the D-S adapted evidence theory is utilized to process and model the distinction and inconsistency of assessment data gotten from a various specialists in FMEA. The strategy accumulates the assessment data of a many specialists on risk factors. The assessment outcome of every specialist as for every risk calculates for every state of failure is viewed as another evidentiary body.

3.3.1 The Structure to Frame of Discernment

There are three risk factors: occurrence (O), severity (S) and detection (D) contained in the RPN. Since the three risk factors are unrelated to one another, three discernment frames are required and represented by Θ_O, Θ_S and Θ_D. In this study, going by Tables 5–7, the discernment frame:

$$\Theta_{\mathrm{i}} = (1,2,3,4,5,6,7,8,9,10) \ \ \mathrm{i} = \mathrm{O}, \mathrm{S}, \mathrm{D} \tag{11}$$

Only a single value can be given to the conventional risk factor in FMEA. Diverse specialists might give out various assessments for similar risk factors, On account of their distinctive expertise and foundations, There might be a few values for one risk factor.

Assume there are L experts in a TEMA group and N failure modes: (E_1,…, E_L) and (F_1, ... , F_N). Therefore, each failure mode possess three discernment frames. Θ_i^n is used to express the discernment frame of the nth failure mode to the *i*th risk factor,

$$\Theta_i^n = (1,2,3,4,5,6,7,8,9,10) \;\; i = O, S, D; \quad n = 1,2, \dots, N \tag{12}$$

Clearly, the quantity of frames of discernment is 3N. At the point when hazard variables are examined by specialists, there are infrequently large contrasts in the evaluations of risk factors given by specialists.

For simplicity sake and building application, the frames of discernment can be adapted. Practically speaking, it is possible to simplify the system of discernment.

$$\Theta_i^n = \min X|_{X\subseteq\Theta_i^n}, \min X|_{X\subseteq\Theta_i^n} + 1, \cdots, \max X|_{X\subseteq\Theta_i^n} \tag{13}$$

Where, min $X|_{X\subseteq\Theta_i^n}$means the minimum of the rank of the nth failure mode to the ith risk factor in the evaluations of L experts. Likewise, max$X|_{X\subseteq\Theta_i^n}$, denotes the maximum of the rank of the nth failure mode to the ith risk factor in the evaluations of L specialists. Additionally, it is possible to realize the subsequent:

$$1 \leq \min X|_{X\subseteq\Theta_i^n} \leq \max X|_{X\subseteq\Theta_i^n} \leq 10 \tag{14}$$

3.3.2 The Modified Belief Function and Combination Rule

The fundamental notion of a risk factor for a failure mode is allotted by various specialists. Distinctive specialists can have diverse assessment given a similar risk factor contingent upon their area expertise and foundation. Every specialist carries out individual risk evaluation as indicated by its own particular guidelines [90]. With a specific end goal to separate the level and the expertise of specialists, the weight of a specialist is considered. For the three risk factors and specialists, the weight can be represented as the matrix shown below.

$$\omega = \begin{pmatrix} \omega_{01} & \cdots & \omega_{0L} \\ \omega_{S1} & \ddots & \omega_{SL} \\ \omega_{D1} & \cdots & \omega_{DL} \end{pmatrix} \tag{15}$$

where, ω_{ij} is the relative weight on the importance of jth expert to ith risk factor and is normalized, so that

$$0 \leq \omega_{ij} \leq 1 \quad i = 0, S, D \tag{16}$$

The bigger the ω_{ij} is the larger the importance of the expert jth for the risk factor. If there is no sufficient rationale or knowledge to differentiate the difference of specialists going by their assessment level, then experts are to assigned identical weights. Taking into account the weight, the new BBA can be expressed as $\overline{m}_{ij}^{n}(.)$

$$\overline{m}_{ij}^{n}(C) = \omega_{ij} \times m_{ij}^{n}(C) C \subset \Theta_i^n, \quad C \neq \Theta_i^n \tag{17}$$

$$\overline{m}_{ij}^{n}(\Theta_i^n) = 1 - \sum_{B \subset \Theta_i^n} \omega_{ij} \times m_{ij}^{n}(B) \;\; B \neq \Theta_i^n \tag{18}$$

where, i = O, S, D, j = 1, 2, ... , L, L is the number of experts, n = 1, 2, ... , N, N is the number of failure modes.

The new combination rule of DS theory is then expressed as

$$m_{i.jg}^{n}(C) = \left(\overline{m}_{ij}^{n} \oplus \overline{m}_{ig}^{n}\right)(C) = \begin{cases} 0, & C = \emptyset \\ \dfrac{\sum X \cap Y = C, \forall X, Y \subseteq \Theta_i^{n(\omega_{ij}.m_{ij}^{n}(X)) \times (\omega_{ig}.m_{ig}^{n}(Y))}}{1 - \sum X \cap Y = \emptyset, \forall X, Y \subseteq \Theta_i^{n(\omega_{ij}.m_{ij}^{n}(X)) \times (\omega_{ig}.m_{ig}^{n}(Y))}}, & C \neq \emptyset \end{cases} \tag{19}$$

Note that is possible to generalize Dempster's combination rule such that it is applicable to three or more specialists, as expressed in Eq. (19). The end outcome characterizes the artificial consequences of each and every one source of evidence.

$$\mathrm{M}_{\mathrm{i}}^{\mathrm{n}} = \mathrm{M}_{\mathrm{i1}}^{\mathrm{n}} \oplus \mathrm{M}_{\mathrm{i2}}^{\mathrm{n}} \oplus \cdots \oplus \mathrm{M}_{\mathrm{iL}}^{\mathrm{n}} = (((\mathrm{M}_{\mathrm{i1}}^{\mathrm{n}} \oplus \mathrm{M}_{\mathrm{i2}}^{\mathrm{n}}) \oplus \cdots) \oplus \mathrm{M}_{\mathrm{iL}}^{\mathrm{n}}) \tag{20}$$

3.3.3 Risk Priority Number

Utilizing equation (19), by combining the outcomes of various specialists in risk evaluations the new abridged allotment function of three risk factors can be gotten by combining the outcomes of various specialists in risk evaluations. It is possible to conceive the new BBA as a level of belief for the observations. Since BBA fulfills the maxim of additivity, it is possible to consider the degrees of belief as the likelihood of ranking risk factors. The three risk factors can be viewed as discrete arbitrary variables [87]. RPN is an function of discrete arbitrary variables. Accordingly, the RPN is a discrete arbitrary variable with a few unique notations and the respective associated likelihoods. Assume RPN possess various ratings$(RPN_n^1,\ldots,RPN_n^q)$ with respective probabilities$P(RPN_n^1,\ldots,RPN_n^q)$ for nth failure mode based on Eq. (19) employing random theory. With a specific end goal to assess the total risk for every failure mode, the average estimation of RPN is required, that is expressed as given below:

$$\mathrm{MVRPN}_{\mathrm{n}} = \mathrm{E}(\mathrm{RPN}_{\mathrm{n}}) = \sum_{\mathrm{q}}\left(\mathrm{RPN}_{\mathrm{n}}^{\mathrm{q}}\right).\ \mathrm{P}(\mathrm{RPN}_{\mathrm{n}}^{\mathrm{q}}) \tag{21}$$

3.4 Fuzzy FMEA

The common fuzzy approach can be described as a general method substituting older ones for risk analysis. There are several reasons why this approach is evaluated as better than the previous one [91].

Firstly, it can handle both precise and imprecise information in a consistent manner. Second, it allows combination of likelihood of failures incidence, impact and identification in a more pragmatic manner [69]. Ultimately, the risk assessment function can be varied based on the specific system under consideration [92].Basic fuzzy steps at prioritization of failure modes are shown in the following Figure 32:

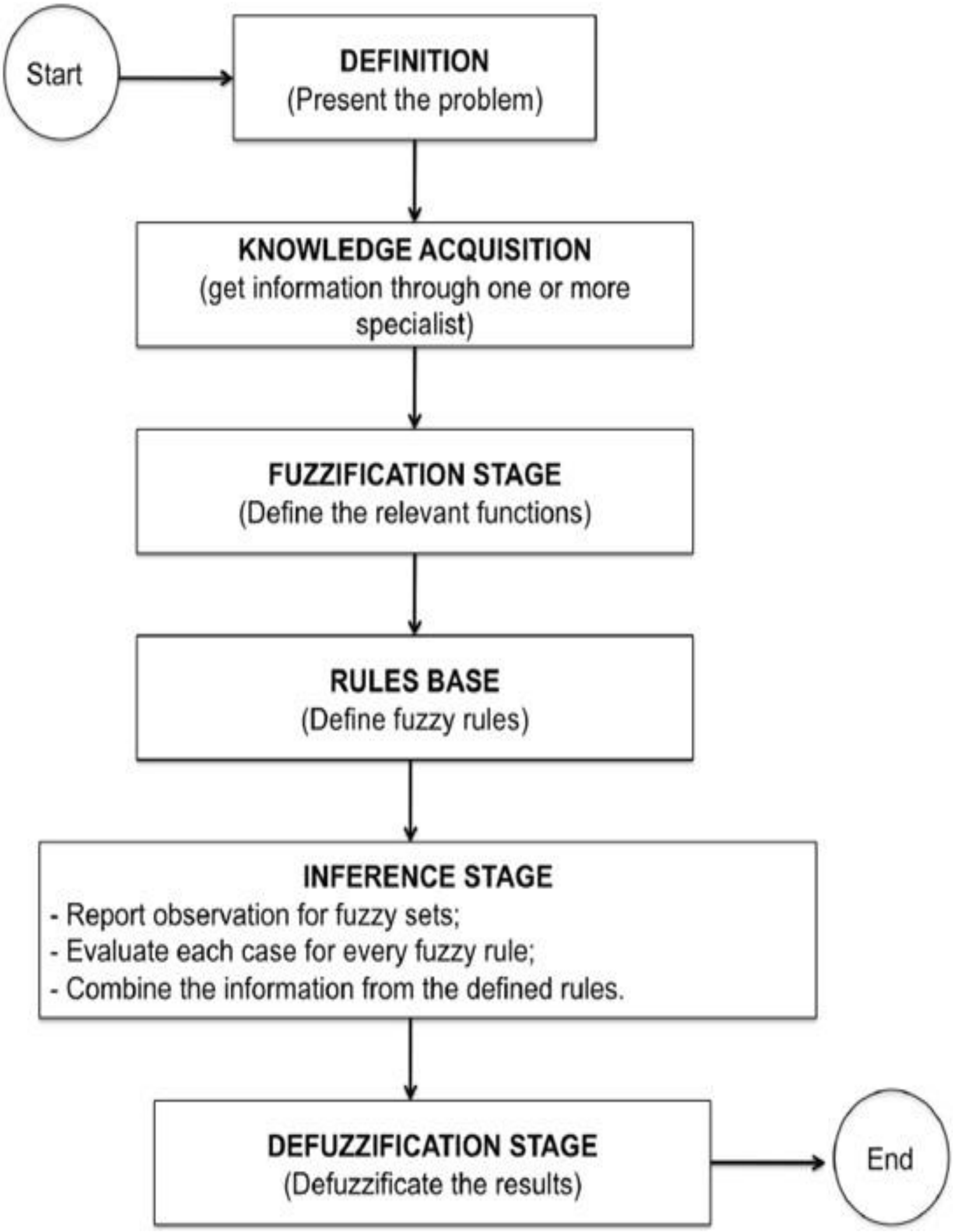

Figure 32 : Fuzzy Analysis Flowchart [93]

Prior to description of Fuzzy RPN approaches (based on 10 membership functions), it is required to be two concepts of Membership Function and Fuzzy if-then rules introduced.

A membership function (MF) is a curve that describes how every point in the input space is associated to a membership value somewhere from 0 to 1. The input space is also known as the universe of discourse (UOD).

The output-axis is a number known as the membership value between 0 and 1. The curve is known as a membership function and is often given the designation of μ. The only condition a membership function must really satisfy is that it must vary between 0 and 1. The function itself can be an arbitrary curve whose shape we can define as a function that suits us from the point of view of simplicity, convenience, speed, and efficiency. A classical set might be expressed as:

Conventionally, membership values are found on the output-axis and ranges from 0 to 1. The curve is referred to as a membership function and is usually denoted by μ. The main condition a membership function should truly fulfill is such that it varies somewhere from 0 to 1. The function is typically any arbitrary curve that given the shape, it is possible to describe a function which is applicable considering straightforwardness, ease, swiftness, and efficiency. For example, we can represent a classical set as below:

$$A = \{x \mid x > 6\}. \tag{22}$$

A fuzzy set is an expansion of a classical set. Assume X is the universe of discourse and its elements are represented by x, subsequently a fuzzy set A in X is described as a set of ordered pairs.

$$(A = \{x, \mu A(x) \mid x \in X\}) \tag{23}$$

μA(x) is known as the membership function (or MF) of x in A. The membership function associates every element of X to a membership value from 0 to 1.

The simplest membership functions are linear forms employing straight lines (Non-linear shapes are introduced in Appendix A). Of these, the simplest is the triangular membership function, and has been given the function name “trimf”. This function is nothing more than a collection of three points forming a triangle. The trapezoidal membership function, trapmf, possesses a level top and actually is only a trimmed triangle curve. The straight line membership function has the benefit of being quite simple (as shown in Figure 33).

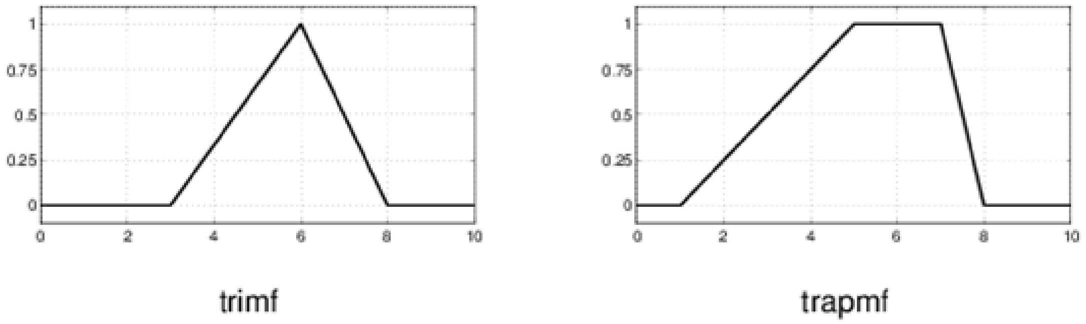

Figure 33 : Linear Fuzzy Membership Functions

The subjects and verbs of fuzzy logic make up fuzzy sets and fuzzy operators. The if-then rule statements are employed for formulating the conditional statements that make up fuzzy logic. A single fuzzy if-then rule typically is of the nature if x is A then y is B; where, A and B are semantic values defined by fuzzy sets on the ranges X and Y, respectively. The if-part of the rule "x is A" is known as the antecedent, whereas the then-part of the rule "y is B" is known as the consequent. The consequent is described by a number from 0 to 1, and the antecedent is an analysis that results in a just a number from 0 to 1.

Conventionally, the input to an if-then rule is the present value for the input variable and the output is a whole fuzzy set. Subsequently, the set is defuzzified; that is, allotting just one value to the output in the end. Interpreting an if-then rule comprises different parts. Firstly, we perform the evaluation of the antecedent (which entails input fuzzifying and employing suitable fuzzy operators). Secondly, we apply the outcome obtained from the first part to the consequent. The Fuzzy RPN (based on 10 membership functions) is derived from the “if-then” rules and it will be determined based on the integer numbers allocated to S, O, and D (from 1 to 10) and two steps of fuzzy logic control which are mentioned below [94].

Step 1- Based on the combination of S (as input 1 in step 1) and O (as input 2 in step 1) values (each risk factor from 1 to 10), and according to the rules in Table 5 a fuzzy number is exploited [94]. This step is as the first stage of multi-stage fuzzy architecture which the related generated surface of logic controller is shown in Figure 34 [95-104].

Step 2- The rules utilized in this step are same as previous step (Table 8), and just input parameters will be detection value of failure mode (as input 2 in step 2) and the output number of step 1 (as input 1 in step 2) [105-106]. This step is as second stage of multi-stage structure and as far as rules have been kept the same as step 1, so generated surface won’t be changed as well.

Table 8 : Fuzzy Rules Based on 10 Membership Functions

		The Input 2 value									
		10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
The Input 1 value	**10**	10	10	9	9	8	8	7	7	6	6
	9	10	9	9	8	8	7	7	6	6	5
	8	9	9	8	8	7	7	6	6	5	5
	7	9	8	8	7	7	6	6	5	5	4
	6	8	8	7	7	6	6	5	5	4	3
	5	8	7	7	6	6	5	5	4	3	3
	4	7	7	6	6	5	5	4	3	3	2
	3	7	6	6	5	5	4	3	3	2	2
	2	6	6	5	5	4	3	3	2	2	1
	1	6	5	5	4	3	3	2	2	1	1

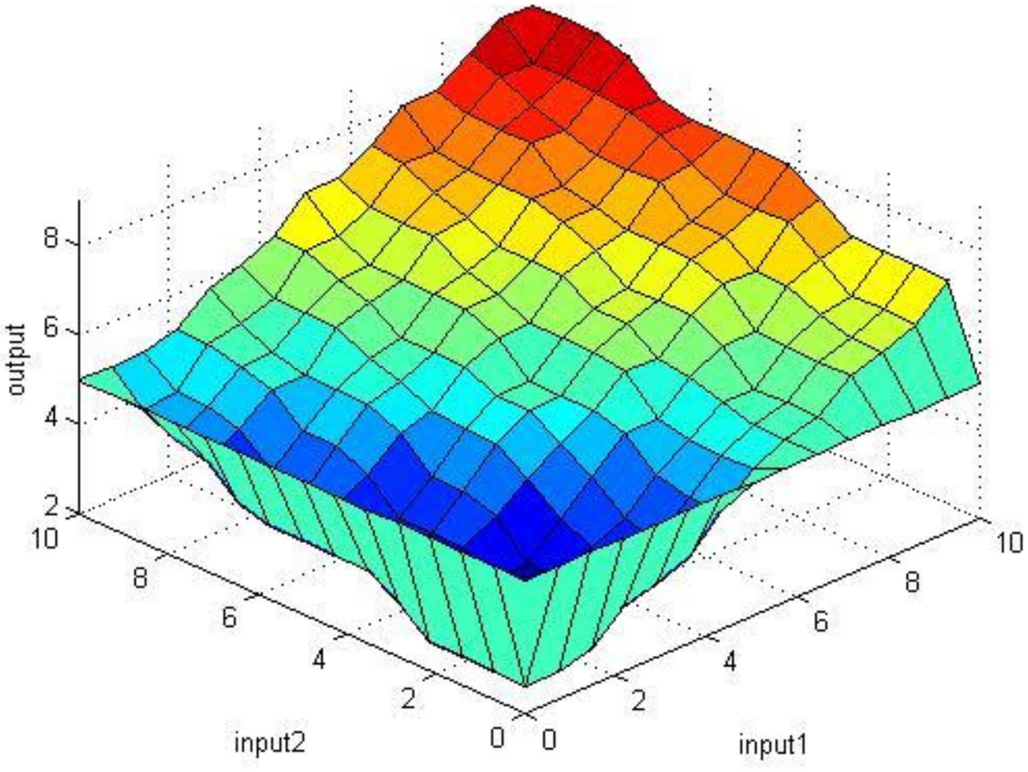

Figure 34: Surface Viewer of Fuzzy Controller First Stage

Table 9 : FMEA worksheet

Component	Failure type	EXPERT 1			EXPERT 2			EXPERT 3			RPN	MVRPN	Rank (RPN)	Fuzzy Logic	MV Fuzzy Logic	Rank (Fuzzy logic)
		S	O	D	S	O	D	S	O	D						

Therefore by selection of RPN method as a basic FMEA approach and different Fuzzy RRN methods as superseded approaches, the possible failure modes of Vertical Axis Wind Turbines introduced at next chapter will be prioritized and compared.

Chapter 4

RESULTS AND DISCUSSION

In this chapter, the typical failure modes of Vertical Axis wind turbine are listed based upon [57], [58], [59], [60], [61], and [64] and for every failure mode, values of risk factors and the amounts of DS-RPN, and Fuzzy RPN (based on 10 membership functions) are provided. The values are obtained from survey responses from three specialists who are expert in Vertical Axis Wind Turbine (Weight of opinions 1.0). After scoring and determination of failure rankings, critical components are introduced and the related maintenance action for preventing from occurrence should be incorporated prior to other actions.

4.1 Application of fuzzy rule based on 10 membership functions to the Horizontal Axis Wind Turbine.

Firstly, a fuzzy FMEA has been applied to the Horizontal Axis wind turbine, basic RPN, fuzzy RPN based on 10 membership functions and a comparison between ranks are provided.

Table 10 : Fuzzy FMEA for HAWT

Component	Failure type	S	O	D	RPN	Rank (RPN)	Fuzzy Logic	Rank (Fuzzy logic)
Brake system	Mechanical failure (Cyclic Fatigue)	2	2	7	28	11	3	3
Main shaft	Fracture and thermal	2	3	7	42	8	3	3
Gearbox	Fracture and cyclic fatigue	3	5	7	105	2	5	1
Cables	Corrosion and lifetime	3	2	1	6	14	2	4
Transformer	Short-circuit	3	5	4	60	6	4	2
Generator	Overheating	2	5	7	70	5	4	2
Power converter	Overload	4	3	7	84	4	5	1
Bearings	lifetime	3	2	4	24	12	3	3
Blades	Mechanical failure (Cyclic Fatigue)	3	5	7	105	2	5	1
Hub	Mechanical failure (Cyclic Fatigue)	2	5	4	40	6	3	3
Screws	Corrosion	1	2	1	2	16	1	5
Tower	Fracture and Fatigue	4	5	7	140	1	5	1
Main frame	Mechanical failure (Cyclic Fatigue)	4	2	4	32	10	3	3
Yaw system	Mechanical failure (Cyclic Fatigue)	2	2	4	16	13	2	4
Pitch system	Mechanical failure (Cyclic Fatigue)	4	2	7	56	7	5	1
Nacelle housing	Deterioration	3	2	1	6	14	2	4

The more critical failures are located at higher ranks and by increment of rates, the criticality decreases as shown in Table 10. The most critical failures of the system were identified: the tower, the generator and the blades which received the highest ranking numbers (between 1st to 3rd rankings at each approach) based on the basic RPN. In the other hand, Fuzzy RPN rank has shown an equal priority to: Tower, Gearbox, Power converter, Blades and Pitch system. Also trend of scored numbers in analysis of each utilized method was very similar and it shows the same risk importance for recognized failure modes of system, the results are listed in figure

4.2 Application and Analysis of the Proposed Technique to the Vertical Axis Wind Turbines.

Here, the proposed technique is employed for a FMEA instance of VAWT. In the FMEA of VAWTs, there are three specialists, every giving an alternate hazard appraisal. Every specialist assesses the failure modes and observes the rating data for the three hazard variables. Table 11 presents as summary the consequences of the three specialists' appraisal of the 12 components based on the three primary hazard factors.

For this circumstance, we suppose that the impact evaluation of the specialist is identical, and ωij is 1. The comprehensive estimation of the failure mode (screws) can be communicated as takes after. Going by section 3, the frame of discernment can be built individually:

By assuming that Screws are the failure mode 1: $\Theta_{\mathrm{o}}^{\mathrm{screws}} \rightarrow \Theta_{\mathrm{o}}^{1}$

$\Theta_{\mathrm{S}}^{1} = (1)$, $\Theta_{\mathrm{o}}^{1} = (2{,}1)$, $\Theta_{\mathrm{D}}^{1} = (1)$

For the risk factors: O, the modified brief function can be attained using Eq. (17):

$\overline{\mathrm{m}}_{\mathrm{o1}}^{1}(2) = 0.80$, $\overline{\mathrm{m}}_{\mathrm{o1}}^{1}(1) = 0.20$; $\overline{\mathrm{m}}_{\mathrm{o2}}^{1}(2) = 0.25$, $\overline{\mathrm{m}}_{\mathrm{o2}}^{1}(1) = 0.75$; $\overline{\mathrm{m}}_{\mathrm{o3}}^{1}(2) = 0.60$, $\overline{\mathrm{m}}_{\mathrm{o3}}^{1}(1) = 0.40$.

Secondly, the combined brief function can be obtained using Eq. (19) between Expert 1 and Expert 2:

$$\mathrm{m}_{\mathrm{o},12}^{1}(2) = \overline{\mathrm{m}}_{\mathrm{o}1}^{1}(\mathrm{X}) \oplus \overline{\mathrm{m}}_{\mathrm{o}2}^{1}(\mathrm{Y}) = \frac{\sum \mathrm{X} \cap \mathrm{Y} = 2, \forall \mathrm{X}, \mathrm{Y} \subseteq \Theta_{\mathrm{o}}^{1 \overline{\mathrm{m}}_{\mathrm{o}1}^{1}(\mathrm{X}) \times \overline{\mathrm{m}}_{\mathrm{o}2}^{1}(\mathrm{Y})}}{1 - \sum \mathrm{X} \cap \mathrm{Y} = \emptyset, \forall \mathrm{X}, \mathrm{Y} \subseteq \Theta_{\mathrm{o}}^{1 \overline{\mathrm{m}}_{\mathrm{o}1}^{1}(\mathrm{X}) \times \overline{\mathrm{m}}_{\mathrm{o}2}^{1}(\mathrm{Y})}}$$

$$= \frac{0.80 \times 0.25}{1 - (0.20 \times 0.25 + 0.75 \times 0.80} = 0.571$$

$$\mathrm{m}_{\mathrm{o},12}^{1}(1) = \overline{\mathrm{m}}_{\mathrm{o}1}^{1}(\mathrm{X}) \oplus \overline{\mathrm{m}}_{\mathrm{o}2}^{1}(\mathrm{Y}) = \frac{\sum \mathrm{X} \cap \mathrm{Y} = 1, \forall \mathrm{X}, \mathrm{Y} \subseteq \Theta_{\mathrm{o}}^{1 \overline{\mathrm{m}}_{\mathrm{o}1}^{1}(\mathrm{X}) \times \overline{\mathrm{m}}_{\mathrm{o}2}^{1}(\mathrm{Y})}}{1 - \sum \mathrm{X} \cap \mathrm{Y} = \emptyset, \forall \mathrm{X}, \mathrm{Y} \subseteq \Theta_{\mathrm{o}}^{1 \overline{\mathrm{m}}_{\mathrm{o}1}^{1}(\mathrm{X}) \times \overline{\mathrm{m}}_{\mathrm{o}2}^{1}(\mathrm{Y})}}$$

$$= \frac{0.20 \times 0.75}{1 - (0.20 \times 0.25 + 0.75 \times 0.80} = 0.429$$

Then, the final consequence can be attained through fusing Expert 3 using eq(19):

$$\mathrm{m}_{\mathrm{o}}(2) = \overline{\mathrm{m}}_{\mathrm{o},12}^{1}(\mathrm{X}) \oplus \overline{\mathrm{m}}_{\mathrm{o}3}^{1}(\mathrm{Y}) = \frac{\sum \mathrm{X} \cap \mathrm{Y} = 2, \forall \mathrm{X}, \mathrm{Y} \subseteq \Theta_{\mathrm{o}}^{1 \overline{\mathrm{m}}_{\mathrm{o},12}^{1}(\mathrm{X}) \times \overline{\mathrm{m}}_{\mathrm{o}3}^{1}(\mathrm{Y})}}{1 - \sum \mathrm{X} \cap \mathrm{Y} = \emptyset, \forall \mathrm{X}, \mathrm{Y} \subseteq \Theta_{\mathrm{o}}^{1 \overline{\mathrm{m}}_{\mathrm{o},12}^{1}(\mathrm{X}) \times \overline{\mathrm{m}}_{\mathrm{o}3}^{1}(\mathrm{Y})}}$$

$$= \frac{0.571 \times 0.60}{1 - (0.429 \times 0.60 + 0.40 \times 0.571} = 0.666$$

$$\mathrm{m}_{\mathrm{o}}(1) = \overline{\mathrm{m}}_{\mathrm{o},12}^{1}(\mathrm{X}) \oplus \overline{\mathrm{m}}_{\mathrm{o}3}^{1}(\mathrm{Y}) = \frac{\sum \mathrm{X} \cap \mathrm{Y} = 1, \forall \mathrm{X}, \mathrm{Y} \subseteq \Theta_{\mathrm{o}}^{1 \overline{\mathrm{m}}_{\mathrm{o},12}^{1}(\mathrm{X}) \times \overline{\mathrm{m}}_{\mathrm{o}3}^{1}(\mathrm{Y})}}{1 - \sum \mathrm{X} \cap \mathrm{Y} = \emptyset, \forall \mathrm{X}, \mathrm{Y} \subseteq \Theta_{\mathrm{o}}^{1 \overline{\mathrm{m}}_{\mathrm{o},12}^{1}(\mathrm{X}) \times \overline{\mathrm{m}}_{\mathrm{o}3}^{1}(\mathrm{Y})}}$$

$$= \frac{0.429 \times 0.40}{1 - (0.429 \times 0.60 + 0.40 \times 0.571} = 0.334$$

As a last step, the respective probability of each rate will be obtained as result of combining the opinion of Expert 1, Expert 2 and Expert 3. The obtained values will be used in order to get the Mean Value Risk Priority Number.

Table 11 : FMEA table for vertical axis wind turbine

Component	Failure type	EXPERT 1			EXPERT 2			EXPERT 3			RPN	MVRPN	Rank (RPN)	Fuzzy Logic	MV Fuzzy Logic	Rank (Fuzzy logic)
		S	O	D	S	O	D	S	O	D						
Brake system	Mechanical failure (Cyclic Fatigue)	2 :60% 1 :40%	2 :10% 1 :90%	7	2 :75% 1 :25%	2 :60% 1 :40%	7	2 :80% 1 :20%	2 :90% 1 :10%	7	15.493 5.194 0.416 0.139	21.24	9	2.33 2.33 2 2	2.165	7
Main shaft	Fracture and thermal	2 :75% 1 :25%	3 : 80% 2 : 20%	7	2 :40% 1 :60%	3 :90% 2: 10%	7	2 :20% 1 :80%	3 :25% 2 :75%	7	12.96 0.710 12.92 0.70	27.29	8	2.61 2 2.61 2	2.305	6
Gearbox	Fracture and cyclic fatigue	3	5	7	3	5	7	3	5	7	105	105	1	5	5	1
Cables	Corrosion and lifetime	3	2	1	3	2	1	3	2	1	6	6	11	2	2	8
Transformer	Short-circuit	3 :80% 2 :20%	5 :75% 4 :25%	4	3 :90% 2 :10%	5 :60% 4 :40%	4	3 :25% 2 :75%	5 :80% 4 :20%	4	52.44 2.208 3.04 0.128	57.816	5	2 1.61 2 1	1.6525	9
Generator	Overheating	2	5	7	2	5	7	2	5	7	70	70	3	4	4	2
Power converter	Overload	4 : 80% 3 : 20%	3 : 60% 2 : 40%	7	4 : 25% 3 : 75%	3 :90% 2 :10%	7	4 :20% 3 :80%	3 : 75% 2 : 25%	7	20.244 0.504 45.549 1.134	67.431	4	3 3 2.7 2.34	2.76	5
Bearings	lifetime	3 : 90% 2 : 10%	2 : 75% 1 : 25%	4	3 :20% 2 :80%	2 : 60% 1 :40%	4	3 :80% 2 :20%	2 :40% 1 :60%	4	16.146 2.691 1.236 0.206	20.279	10	1.61 1.61 1 1	1.305	10
Blades	Mechanical failure (Cyclic Fatigue)	3 :40% 2 :60%	5 :20% 4 :80%	7	3 : 60% 2 : 40%	5 :75% 4 :25%	7	3 : 90% 2 : 10%	5 :40% 4 :60%	7	31.119 49.86 2.5641 4.1087	87.65	2	2.67 3 2.67 3	2.835	4
Hub	Mechanical failure (Cyclic Fatigue)	2	5	4	2	5	4	2	5	4	40	40	7	3	3	3
Screws	Corrosion	1	2 :80% 1 :20%	1	1	2 :25% 1 :75%	1	1	2 :60% 1 :40%	1	1.332 0.334	1.666	12	1 1	1	11
Tower	Fracture and fatigue	4 : 60% 3 : 40%	5 :10% 4 :90%	4	4 : 75% 3 : 25%	5 : 20% 4 : 80%	4	4 :20% 3 :80%	5 : 25% 4 : 75%	4	0.416 32.95 0.288 22.81	56.464	6	2 2 2 2	2	8

Consequently, the discrete random variable O (2, 1) and the corresponding likelihood (0.67, 0.33) can be accomplished. S is Similar to D, S (1, 100%) and D (1, 100%). Since S and D have respective values which tend to a probability of 1, S and D can be considered as steady variables. As posited by the random theory, the average estimation of RPN can be achieved utilizing equation (21) as:

$$\mathrm{MVRPN}_{\mathrm{screws}} = \mathrm{E}(\mathrm{RPN}_{\mathrm{screws}}) = \sum_{\mathrm{q}} \left(\mathrm{RPN}^{\mathrm{q}}_{\mathrm{screws}}\right) .\ \mathrm{P}(\mathrm{RPN}^{\mathrm{q}}_{\mathrm{screws}})$$

$$= 1 \times 2 \times 0.666 \times 1 + 1 \times 1 \times 0.334 \times 1 = 1.666$$

As in other failure modes, the average RPN value can be achieved and expressed in Table 11.

After scoring of system failure modes it is possible to prioritize them in descending order. In the resulted ranking, the more critical failures are located at higher ranks and by increment of rates, the criticality decreases.

As shown in Table 11, the most critical failures of system were identified: the tower and the gearbox which received the highest ranking numbers (between 1st to 2nd rankings at each approach). Also trend of scored numbers in analysis of each utilized method was very similar and it shows the same risk importance for recognized failure modes of system. Finally it is resulted that by enhancement of Dempster-Shafer theory and Fuzzy logic, precision of results is increased and aggregation of team members' opinions has the same effect at elevation of precision in final findings.

So in FMEA method for increasing the availability of different systems' parts and improving the reliability of system operation, it is necessary to have a special attention to most critical failure modes during scheduling of the maintenance actions.

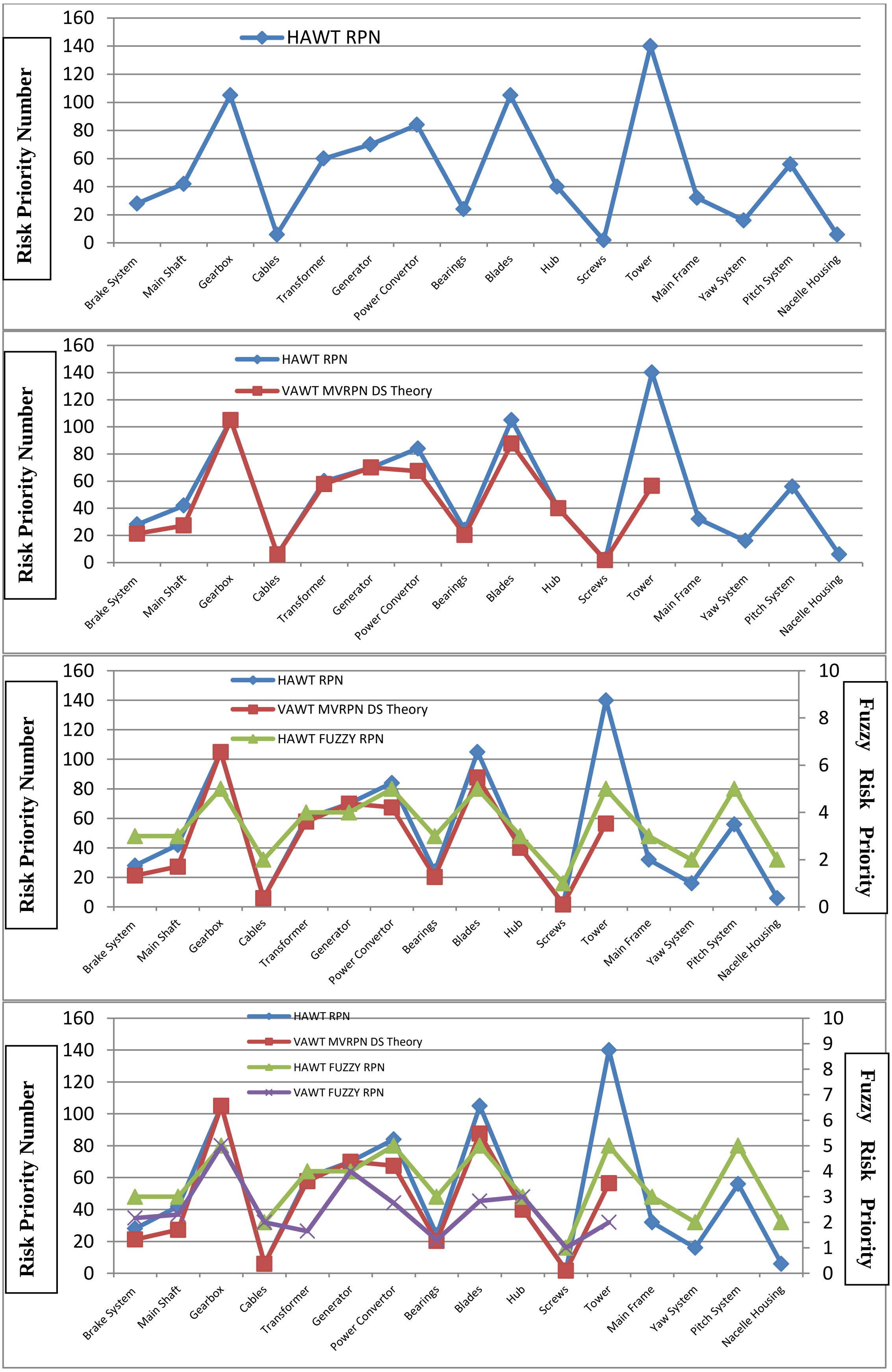

Figure 35 : (a) Basic RPN for HAWT, (b) Fuzzy RPN for HAWT, (c) MVRPN DS Theory for VAWT, (d) Fuzzy RPN for VAWT and Comparison of All Approaches.

As clearly shown in Fig 35 (c), regarding the Horizontal Axis Wind Turbine, the components Gearbox, Power converter, Blades, Tower and Pitch system have the highest RPN based on Fuzzy logic equivalent to 5, therefore failure modes are to be treated similarly. Moreover, the Tower has the largest basic RPN followed by blades and gearbox. And for the Vertical Axis Wind Turbine, based on DS-RPN, the Gearbox has the largest rank, followed by the Blades, and Generator, which all has RPN higher than 70. Screws are apparently the least overall risk. But based on fuzzy logic, the Gearbox has the highest rank, followed by the generator due to their internal components. Moreover, the Tower showed a lower rank Fig 35 (b).

Regarding Fig 35 (d), at the point when the fuzzy logic MT among the diverse failure modes is unchanged, therefore failure modes are to be treated similarly with regard to hazard. For instance, cables and Tower possess identical fuzzy logic MV equivalent to 2.

Since the architecture of the VAWT has past data, the result of the failure mode estimation is contrasted against past data. The outcomes are reliable and agree with practical engineering context and show that the posited methodology is sound and proficient.

4.3 Designing a plan for preventing Generator failures:

Inside the generator there are many vulnerable parts to failure like bush and windings, which may be damaged after a period of time, so by determining an early safe failure time based on the estimated lifetime and performing a predictive maintenance generator is overhauled (major repair) and afterwards, it is permitted to operate until the next overhaul service. During overhaul process, internal parts are inspected prior to occurrence of failure and necessary measures are taken for maintaining the serviceability of them.

4.4 Designing a plan for preventing Tower failure:

At present, lots of wind turbines are upheld by cone like tubular steel towers. Such towers correspond to 30% – 65% of the turbine weight and in this manner constitute a substantial part of the turbine transportation costs. The utilization of materials of lesser weight for tower construction can extraordinarily lessen the total transport and development cost of wind turbines; nonetheless, firmness and sturdiness characteristics should not dwindle [107].

4.5 Designing a plan for preventing Gearbox failure:

Wind turbine gearboxes can flop in drastically unique ways. Improvements in unwavering quality and accessibility need to adopt an all-encompassing strategy including configuration, fabricating, testing, bundling/shipping/handling, establishment, operation, and maintenance. Every recognition system has its own particular points of interest and impediments. The same is valid for oil test/channel component investigation, and end clients need to concoct an answer that is the most temperate and viable for their benefits. Take note of that one solution for one plant may not make a difference to an alternate site. Following and knowing your fleet condition through different instrumentation and information mining are basic. Regardless of the possibility that the majority of the accepted procedures with respect to specification, fabrication, transportation, and installation of the gearbox were taken after, a gearbox is not liable to give solid administration unless it is worked and looked after appropriately. Legitimate maintenance is additionally basic to solid gearbox operation. The most imperative preventive maintenance exercises include keeping the gearbox oil perfect, dry, and cool. A large portion of the disappointment modes (micropitting, macropitting, scraping, scraped spot) can be brought about in entire or to a limited extent by grease condition, and appropriately keeping up the lubrication system is the best method for keeping these disappointment modes. Occasional lubrication condition observing is a critical part of a precaution maintenance program. The observing recurrence ought to be set with the end goal that lubrication issues are recognized well before critical gear harm has happened. Data gave by oil condition testing can be utilized to make a move to enhance grease condition preceding the event of a calamitous disappointment or to recognize and repair a fizzling segment before it falls flat and causes broad blow-back to other gearbox parts. General change out of channel components is imperative to keep up oil cleanliness, which is basically essential to rigging and bearing life. Maintenance of the oil cooling system is additionally critical, as oil consistency is a solid capacity of temperature, and a gearbox that is working with oil at hoisted temperatures will have bring down lubrication film thickness and expanded rates of apparatus and bearing life utilization.

Chapter 5

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

In this chapter, conclusions about this work with some suggestions are explained.

5.1 Conclusion

Vertical Axis Wind Turbines are turning out to be especially fascinating as result of the possibility to generate power and with lesser failure probability. Wind generators (200 W - 10kW) can be utilized as matrix associated platforms or as solitary platforms and both can be combined with other vitality change platforms, for example, photovoltaics

Ranging from 2 meters to 10 meters in height, little wind turbines can be put in urban locations on roads or on housetops, they have generally minimal visual effect and can deliver vitality even from moderate wind streams, and may likewise be coupled to the systems of lighting on roads. Furthermore, little wind turbines and especially the Vertical Axis Wind Turbine is less susceptible to bird impact, therefore it is environment friendly.

In this research, the Failure Mode and Effect Analysis (FMEA) method with approach of failures prioritization based on D–S evidence theory (DS-RPN), Fuzzy RPN (based on 10 membership functions), have been applied to Vertical Axis Wind Turbine (VAWT).

D–S hypothesis is embraced to account for hazard assessment data of numerous specialists, which might be conflicting, loose and questionable. An adapted support hypothesis is proposed for managing distinctive assessments of various specialists, numerous failure modes and three hazard factors RPN study of FMEA of vertical axis wind turbine. In addition, the combined three hazard components are viewed as the discrete arbitrary factors. Therefore, the RPN somewhat depends on the discrete irregular variable. The average estimation of RPN is utilized for the hazard priority estimation of failure modes. Considering the VAWT, the suggested technique is shown by a use of hazard priority estimation of failure modes in FMEA.

Increasing of Fuzzy rules for the risk analysis of FMEA team members' opinions are the known factors for enhancement of results precision and the uncertainty level of risk importance factors of failures is diminished. The different evaluation information of three experts about 12 components is aggregated. Nevertheless, Vertical Axis Wind Turbine has less failure modes than Horizontal ones, and severities in VAWT's are lower than in HAWT's. The average value of RPN is attained based on Dempster-Shafer evidence theory and fuzzy logic.The obtained results are compared and regarding the criticality level, suitable failure dispositions are offered and the required maintenance activity for each of failures is introduced as well.

5.2 Suggestions for Further Research

The following points for future research are suggested based on the research presented in this thesis:

- Application of Risk Based – Failure Mode And Effects Analysis for Vertical Axis Wind Turbines :

To moderate the impacts of failures in various segments of power generation frameworks, Risk-based FMEA will be useful for getting failure impacts rather than the rating scales for every failure mode in Vertical axis wind turbine.

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APPENDIX

FUZZY RISK NUMBER PROGRAM IN MATLAB SOFTWARE

```
[System]
Name='RPN'
Type='mamdani'
Version=2.0
NumInputs=3
NumOutputs=1
NumRules=987
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='input1'
Range=[0 10]
NumMFs=10
MF1='1':'trimf',[0 1 2]
MF2='2':'trimf',[1 2 3]
MF3='3':'trimf',[2 3 4]
MF4='4':'trimf',[3 4 5]
MF5='5':'trimf',[4 5 6]
MF6='6':'trimf',[5 6 7]
MF7='7':'trimf',[6 7 8]
MF8='8':'trimf',[7 8 9]
MF9='9':'trimf',[8 9 10]
MF10='10':'trimf',[9 10 11]

[Input2]
Name='input2'
Range=[0 10]
NumMFs=10
MF1='1':'trimf',[0 1 2]
MF2='2':'trimf',[1 2 3]
MF3='3':'trimf',[2 3 4]
MF4='4':'trimf',[3 4 5]
MF5='5':'trimf',[4 5 6]
MF6='6':'trimf',[5 6 7]
MF7='7':'trimf',[6 7 8]
MF8='8':'trimf',[7 8 9]
MF9='9':'trimf',[8 9 10]
MF10='10':'trimf',[9 10 11]

[Input3]
Name='detection'
Range=[0 10]
NumMFs=10
MF1='1':'trimf',[0 1 2]
MF2='2':'trimf',[1 2 3]
MF3='3':'trimf',[2 3 4]
MF4='4':'trimf',[3 4 5]
MF5='5':'trimf',[4 5 6]
MF6='6':'trimf',[5 6 7]
MF7='7':'trimf',[6 7 8]
MF8='8':'trimf',[7 8 9]
MF9='9':'trimf',[8 9 10]
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MF10='10':'trimf',[9 10 11]

[Output1]
Name='output'
Range=[0 10]
NumMFs=10
MF1='1':'trimf',[0 1 2]
MF2='2':'trimf',[1 2 3]
MF3='3':'trimf',[2 3 4]
MF4='4':'trimf',[3 4 5]
MF5='5':'trimf',[4 5 6]
MF6='6':'trimf',[5 6 7]
MF7='7':'trimf',[6 7 8]
MF8='8':'trimf',[7 8 9]
MF9='9':'trimf',[8 9 10]
MF10='10':'trimf',[9 10 11]

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