SAFETY AND RELIABILITY OF DYNAMIC POSITIONING SYSTEMS: A REVIEW OF MONTE CARLO SIMULATION AND FAULT TREE ANALYSIS METHODS

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Abstract: This paper provides a comprehensive review of the safety and reliability of Dynamic Positioning (DP) systems, focusing on the use of Monte Carlo Simulation (MCS) and Fault Tree Analysis (FTA) techniques. DP systems, vital in offshore oil and gas operations, enable vessels and floating structures to maintain their position autonomously through coordinated thrusters and reference systems, which are essential for various operations such as drilling and diving in deep waters. Despite design and regulatory guidelines advancements, DP systems remain susceptible to failures that can lead to significant safety hazards, environmental damage, and financial losses. MCS and FTA methods have been widely applied in assessing the reliability of complex systems, including DP systems, by simulating random failure events and modeling the propagation of faults through the system. This paper reviews studies that have applied these techniques to enhance DP system performance and reliability. Through case studies and examples, we analyze how MCS and FTA can be integrated to predict failures, identify critical system components, and develop risk mitigation strategies. The reviewed literature highlights that combining these techniques provides a robust framework for addressing technical and human factors in DP operations, offering more comprehensive insights than traditional qualitative methods. This review emphasizes the need for continuous advancements in DP system reliability to mitigate operational risks, especially in increasingly complex marine environments. The findings offer valuable contributions to DP systems' design, operation, and maintenance, with implications for improving safety, reducing downtime, and preventing catastrophic failures in offshore operations.

Keywords: Dynamic Positioning System, Monte Carlo Simulation, Fault Tree Analysis, Propulsion System, Power System.

Introduction

As the oil and gas industry expands further offshore, traditional shallow water techniques that have been effective for hydrocarbon extraction have become less suitable. The need arose for innovative methods to position vessels and offshore structures in deep waters. DP systems were developed to meet this demand, enabling vessels or floating structures to maintain their position automatically through the coordinated use of thrusters and reference systems. DP refers to automatically regulating a vessel's position and orientation by managing thrusters based on one or more position references. The entire setup responsible for maintaining this automatic control is known as a DP system (IGSODP, 2009). Precise station-keeping is crucial for many offshore operations, such as working in proximity to other vessels or structures, supporting diving activities, anchor handling, and drilling.

Dynamically positioned vessels are predominantly utilized by the offshore oil and gas industry; however, an increasing number of other ship types are now being equipped with DP systems. The 'Wärtsilä DP unit' reported a successful test of the remote control of ship operations. During the test, both DP and manual joystick control were used to guide the vessel through various maneuvers. Remarkably, the test vessel was located in the North Sea, while navigation was remotely managed from Wärtsilä's office in San Diego, California, 8,000 kilometers away (Wärtsilä Corporation, 2017). This advancement marks a significant step toward remotely operated vessels, indicating that DP systems and associated technologies will continue to have a lasting presence in the shipping industry. The effectiveness of DP operations depends on the reliability of the equipment, the operators' skills and training, and the mitigation of related risks. However, despite the numerous regulations and guidelines established by regulatory bodies in recent years, the risk of operational or technical failures remains. Loss of position (LOP) incidents still occur and can have severe consequences, including loss of life, irreversible environmental damage, and significant financial losses for operators.

Drive-off and Drift-off are the two primary types of position loss commonly linked to DP system failures (Hansen & Ole, 2011). A drift-off occurs when there is insufficient thruster capacity or if the DP control system mistakenly believes that the vessel is holding its position, causing it to gradually move off course (FMEAs, 2016). In contrast, a drive-off happens when the DP control system detects that the vessel is out of position and actively uses its thrusters to correct it. The worst-case scenario for drive-off typically involves maximum thrust being applied in the same direction as the environmental forces (Hansen & Ole, 2011). Due to the increased forces involved, drive-off incidents tend to cause more damage than drift-off events. The type of failure dictates the nature of the LOP incident. Understanding the possible impacts of a failure enables the DP operator to take the necessary precautions to prevent such occurrences. This knowledge is also crucial during risk assessments, especially when a vessel must continue operations with malfunctioning equipment or systems (Hansen & Ole, 2011).

Many current studies and publications on the reliability and performance of DP systems are primarily theoretical and aimed at enhancing the design and manufacture of robust and redundant systems. These works often address the question of "What could happen?" rather than "What has happened?" From a DP operator's perspective, this theoretical information can be overly complex and offer little practical support for the day-to-day operation and maintenance of DP systems and related equipment.

Conducting DP trials and performing Failure Modes & Effects Analyses (FMEAs) is a useful way to maintain crew knowledge and periodically assess the condition of the vessel and its DP system. However, the purpose of these trials is to identify potential design or operational failures before they occur (RadaScan, 2017), rather than focusing on the reliability of individual components. The overall reliability of any system is dependent on the quality and condition of its parts, as a system is only as strong as its weakest link. During planned maintenance, it can be beneficial to identify which components and subsystems are most prone to failure, allowing for increased focus on these areas. Some authors, such as Vedachalam & Ramadass (2017), emphasize that reliability is a critical aspect of DP systems, ensuring the safe and efficient execution of vital offshore operations.

A global standard for DP systems for all new vessel types was established in 1994 when the International Maritime Organization (IMO) released the first official guidelines for vessels having DP systems. The IMO circular provides the basic specifications for DP vessels; however, the International Maritime Contractors Association (IMCA) produces more comprehensive guidelines. The book "Guidelines for the Design and Operation of Dynamically Positioned Vessels" discusses various facets of DP systems, such as related operational risks and equipment safety. "DP vessel design philosophy guidelines," which provide specific needs and design recommendations for DP vessels, were created by the DP Committee. The DP and IMCA committees actively participate in the development and publication of comprehensive recommendations that address numerous aspects of DP and related equipment, in addition to the publications mentioned above. While some focus on the theoretical analysis of this complex system, others depend on historical events and data.

The increasing complexity and demands on marine equipment systems have highlighted the importance of reliability. FTA combined with MCS is applied to assess the reliability of a full-ocean-depth unmanned submersible (FODUS) (Luo et al., 2022). This approach determines the system's life distribution function, calculates the Mean Time Between Failures (MTBF), and identifies the critical reliability index for each basic component. These results offer valuable insights and serve as a useful reference for future research focused on the reliability of deep-sea submersibles.

Wang et al. 2023 reviewed the challenges and methodologies associated with reliability and risk analysis in offshore DP operations. They discussed two typical DP operation contexts and surveyed various reliability analysis techniques, including FMEA, FTA, Markov models, and Bayesian networks, which are used to assess both the technical and human reliability of DP systems. They also highlighted that traditional qualitative risk assessments may be insufficient, as FMEA alone might not identify combinations of hardware, software, and human failures. Quantitative methods like Markov models and Bayesian networks offer a more comprehensive evaluation but face challenges due to the complex interplay of technical, human, and organizational factors in DP failures.

Usman et al. (2021) introduced a risk-informed method for managing railway drainage assets, utilizing FTA and MCS to assess and mitigate risks related to poor track drainage. This approach helps identify and quantify factors that contribute to drainage failures, allowing asset managers to efficiently prioritize maintenance efforts, especially in high-risk areas such as the Clay Cross Tunnel in the UK. The researchers developed a probabilistic FTA model to connect the factors leading to drainage failures, improving decision-making for maintenance strategies.

In 2019, Cheliyan & Bhattacharyya adopted the MCS for the analysis of a Dynamic fault Tree that models a DP system. Calculating the vessel's LOP or unavailability while the DP system is in operation is the main goal of this study. Their result shows that the reliability of the system is projected to be 99.5% after 1 year, 95.13% after 10 years, 90.5% after 20 years, and 60.68% after 100 years, demonstrating a gradual decline over time (Cheliyan & Bhattacharyya, 2019).

Barbosa et al. (2019) introduced a novel methodology for assessing the reliability of substations by combining FTA with MCS. These methods, which have historically been applied independently, are combined here to identify vulnerabilities in substations and help make better maintenance and investment choices. According to the study, the single-section bus and single-bus arrangements were shown to be less reliable than the ring substation configuration. This ranking highlights the impact of configuration complexity on overall reliability. The correctness and practical usefulness of the methodology are confirmed by comparison with analytically solved systems and traditional dependability methodologies. The findings showed that both approaches yielded similar expected results, demonstrating the practical applicability and accuracy of the new methodology (Barbosa et al., 2019).

Taheriyoun & Moradinejad (2015) used FTA and MCS to assess the reliability of the Tehran West Town wastewater treatment plant (WWTP). The main issue is that landscape irrigation violates effluent Biological Oxygen Demand (BOD) regulations. Systemic errors were found and analyzed using FTA, and the results showed that mechanical problems, human error, and environmental factors were the primary reasons systems fail. Using FTA and MCS, the study determined the system's reliability to be 0.71 and 0.73, respectively. The results demonstrated the important role that human factors play, indicating that increasing plant reliability requires advancements in automation, monitoring, and operator training.

Shi & Bazzi (2015) combined FTA and MCS approaches to assess the reliability of a micro-grid with a substantial amount of clean energy integration. The reliability of the photovoltaic (PV) subsystem was observed to decrease significantly, reaching only 20% reliability after approximately 5 years of operation. This highlights the importance of monitoring subsystem performance over time. Each subsystem's essential components were determined by the analysis. Strategies to improve the overall system's reliability can be developed by identifying which components are most important. Enhancing the reliability of these crucial elements is vital for optimal system functionality. A Mean Time to Failure (MTTF) of roughly 58.35 years was obtained for the entire micro-grid system from the 500,000 iterations of the simulations. This metric provides a useful estimate of the expected operational lifespan of the system.

Benabid et al. (2018) employ three probabilistic safety analysis (PSA) methods such as FTA, Reliability Block Diagram (RBD), and MCS to examine the reliability of electrical power supply systems under different redundancy scenarios. MATLAB is used to implement the RBD and MC methodologies, while RiskSpectrumPSA® software is used for the FTA. These techniques are employed to assess and enhance the reliability of electrical power supply systems, particularly when considering different redundancy scenarios. They compared the results obtained from applying these methods to three different case studies. It finds that all three methods yield similar results in terms of the system's failure probability, validating the reliability modeling approach used in the study. Moreover, the results demonstrate that increasing the number of redundant components in the power supply system improves its reliability. However, the study also highlights that this improvement comes with trade-offs, such as higher costs and an increased probability of common cause failures, where multiple components fail due to a shared cause.

Bian et al. (2009) discusses the application of FTA combined with MCS to evaluate the reliability of an Autonomous Underwater Vehicle (AUV) system. The study begins by introducing the traditional FTA method, which is used to model the failure of the AUV as the top event in the fault tree. The research aims to quantitatively analyze the AUV's reliability by constructing a fault tree and using MCS to simulate the system's behavior. They developed a simulation model of the AUV's fault tree using MATLAB. Through this digital simulation, they derive the system's life distribution function, which helps in understanding the overall reliability of the AUV. Additionally, the analysis provides insights into the importance of basic components within the system, including both basic unit importance and mode importance. The findings not only give a thorough understanding of how every component influences the system's reliability, but they also offer helpful guidance for enhancing system maintenance and design.

A novel approach for assessing the economic viability of Condition-Based Maintenance (CBM) tactics in unmanned systems is presented by Southgate et al., (2024), with an emphasis on addressing the high initial costs and particular operational difficulties of these systems. Employing a blend of Modular Dynamic FTA (MDFTA) and MCS, the research evaluates the return on investment of several CBM approaches via an Unmanned Surface Vessel (USV) case study. The results highlight the significance of strategically choosing components for CBM implementation, as they show that monitoring non-critical components can lead to higher returns on investment. For firms looking to enhance maintenance procedures and boost system reliability, the study's broad approach offers ample flexibility for conducting extensive sensitivity analysis.

Glaude (2020) investigates how the Anthropocene era, especially global warming, has affected environmental risks. It focuses on two major groundwater threats: the emergence of thermokarst lakes in permafrost conditions and seawater intrusion that contaminates wells with salt water. The study quantifies the probabilities of these risks using FTA and MCS. Under climate change scenarios, the risk of seawater intrusion is significantly increased, and there is a high likelihood of thermokarst lake formation and subsequent talik development. The results underline how critical it is to act quickly to reduce the dangers' potential to cause irreparable environmental harm.

Pamungkas & Dirhamsyah (2019) conducted a study focusing on the Nagan Raya steam power plant in Aceh, owned by PT. PLN (Persero), which experiences frequent failures due to a six-month overhaul maintenance schedule. They aimed to evaluate the reliability of the plant and optimize preventive maintenance scheduling using MCS for nine critical components in the boiler section. The simulation results suggest that maintenance intervals for these components should range from 40 to 86 days, with reliability percentages between 31% and 41.87%. Specific findings include a 40-day maintenance interval for the cyclone separator in boiler unit 1 with a 34.45% reliability and an 86-day interval for the PA fan in boiler unit 2 with a 37.89% reliability. These results highlight the need for tailored maintenance strategies to improve the overall reliability of the plant's operations.

In recent years, several literature reviews have examined FTA from various perspectives. For instance, Javadi et al. (2011) used FTA to assess the reliability of power systems by examining how individual or combined lower levels can lead to the TOP event. Halme & Aikala (2012) present an approach to enhancing maintenance strategies using FTA for real-time reliability and failure probability assessment in industrial systems. This approach focuses on dynamically updating the fault tree based on real-time data related to root causes and events. By integrating dynamic information, such as anomalies, service actions, and cumulative loading, the system can continually recalculate the probabilities of fault tree events and interactions. Mahmood et al. (2013) looked at how fuzzy set theory may be used to extend FTA. They covered its principles, uses, and benefits over more conventional FTA techniques. Ruijters & Stoelinga 2015 concentrated on several FTA-related topics, such as tools, analysis, and qualitative and quantitative modeling. Then, Kabir (2017) summarized FTA, its extensions, and other dependability analysis techniques. The difficulties posed by ambiguity in FTA-based risk assessment techniques were discussed by Yazdi et al. (2019). Aslansefat et al. (2020) distinguished between static and DFTA while reviewing FTA modeling, analysis, and tools.

History of DP

DP is a station-keeping method that utilizes onboard thrusters, automatically controlled to maintain the position or heading of a floating structure. The thrusters or rudders generate propulsive force that counteracts the combined effects of wind, waves, and currents, allowing the structure to remain within predetermined tolerances at a specific location above the sea floor and on a designated heading (Chas & Ferreiro, 2008). Essentially, DP allows a ship to maintain a relatively fixed position above the ocean floor without the use of anchors. This is achieved by employing two or more propulsion devices, which are controlled by systems such as gyrocompasses, satellite navigation, and inputs from sonic instruments located on the seabed and the vessel itself (Holvik, 1998). A DP system is an assembly of equipment designed to facilitate this process. Its primary function is to keep the vessel within acceptable limits at a given position, along a defined track, and with a set heading.

The system must be capable of handling transient conditions such as changes in external forces, sensor or position signal failures, and hardware malfunctions. In addition to maintaining position, the system also aims to reduce fuel consumption and minimize wear on the thrusters (Cavanagh, 1997).
The offshore hydrocarbon exploration and production sector makes extensive use of DP systems on ships and other floating structures. Additionally, the DP system is becoming more and more well-liked in other sectors of the economy, such as the Navy and cruise lines. Deeper waters offshore were being rapidly explored for oil toward the end of the 1950s and the beginning of the 1960s. It was becoming more and more difficult to use anchors, thus a new strategy was needed. To test whether their position could be maintained without anchors while drilling in three thousand meters of water, Willard Bascom came up with the idea to attach thrusters on the CUSS 1.
Figure 1 shows the "CUSS1." It was the first drillship in the contemporary definition of the term. It was the first vehicle to employ DP and had four rotating thrusters, one at each corner. Manual controls were used to adjust the engine speed and direction from a central point.

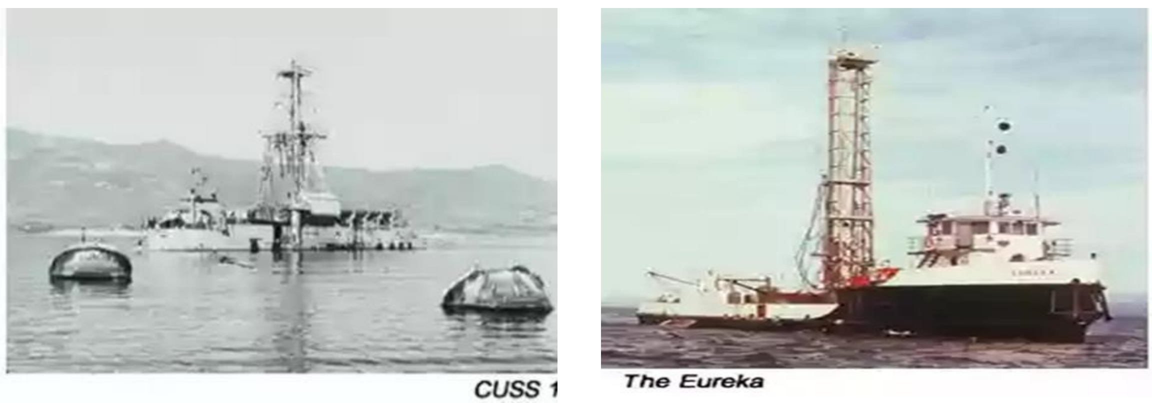


Fig 1: First Dynamically Positioned Ships (Shatto, 2011)

The Eureka was the first ship to employ automatic position control as shown in Figure 2.1. Hughes Aircraft designed and fabricated the control machine, which was based on Honeywell process controllers. To control yaw, sway, and surge, one of each controller was utilized. An oscilloscope was used to visualize the position as a dot, derived from a "tilt meter" that determined the angle at which a taut cable had reduced a large weight to the floor of the ocean. A gyrocompass was used to determine the heading (Shatto, 2011). In the early 1960s, PID controllers were standard components of the earliest DP systems. Advanced control methods were introduced starting in the mid-1970s, utilizing Kalman filter theory and linear optimum control (Samad & Annaswamy, 2011).

DP System Classification

Position-keeping capability loss has consequences that dictate how reliable the DP system needs to be. Higher consequences are indicative of a more stable DP system. The kinds of failures that must be considered dictate the kinds of equipment and their impacts (DPVDPG, 2011). IMO defines three DP equipment classes that provide varying levels of station-keeping reliability (Shatto, 2011). Equipment Class 1 allows for the possibility of position loss due to a single failure in any active component or system. In Equipment Class 2, position loss is not anticipated from a single failure in an active component, assuming that static components are adequately protected and reliable. Failures in Class 2 can involve active components such as generators and thrusters, as well as unprotected static components such as cables or pipes. Equipment Class 3 covers all the same criteria as Class 2 but also includes potential failures within watertight compartments or fire zones due to incidents such as fire or flooding. The classes are designed to correspond with the potential consequences of losing position. For DP2-class vessels, redundancy of all active parts including generators, thrusters, switchboards, and remote-controlled valves is essential. DP3 requires not only redundancy of active and often static components but also physical separation of these components. The IMO's equipment classes and redundancy criteria have formed the basis for the DP regulations established by major classification societies (IGSODP, 2009). Notably, DP rules and guidelines stipulate that DP vessels must be able to maintain position following a single failure long enough to safely conclude ongoing operations (DPVDPG, 2015).

DP System Principles

The wind, current, and waves are some of the environmental forces the vessel must contend with when it is in open water. Task-dependent forces such as cables, pipes, anchors, tow ropes, or fire monitor reactions may also apply to task-specific vessels. The ship also experiences moments produced by the propulsion system on board. Every factor acting on the ship is unpredictable and affects its velocity distinctly. External forces continuously affect the vessel's heading, position, and speed. The DP control system receives the data from a position-reference system, which measures these variations. Additional information from the environmental reference system is incorporated into the roll, pitch, wind force, and direction values adjustments to guarantee precise control and stability. The DP control system calculates the forces the thrusters need to generate to manage the vessel's movement. As illustrated in Fig 2, the

DP vessel positions itself within the desired degrees of freedom (represented by orange arrows) by using its propulsors (green arrows) to counterbalance the environmental forces (red arrows).

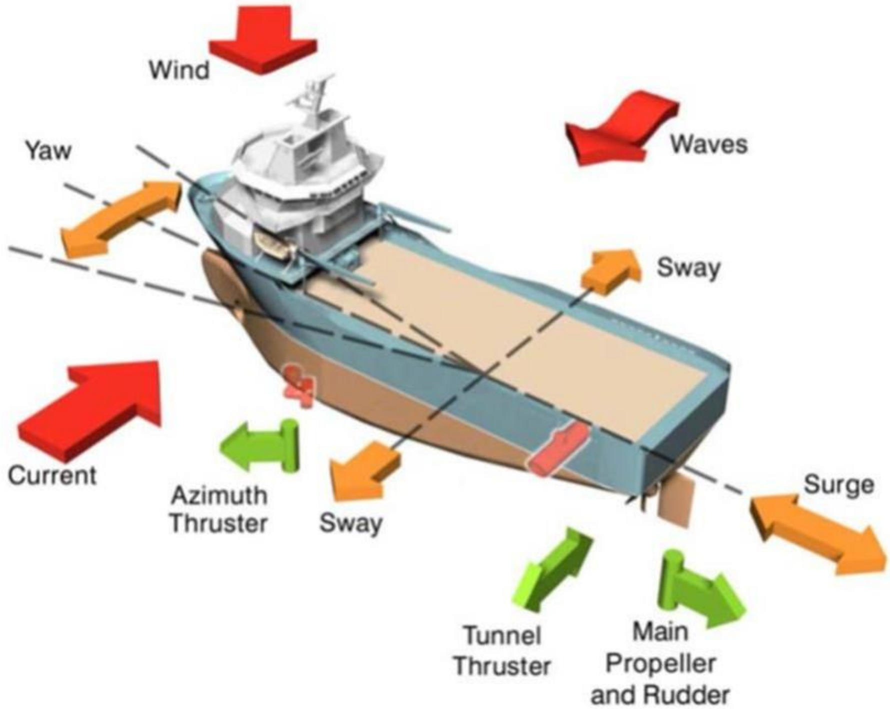


Fig 2: Forces exerted on a vessel in a DP (Løkling et al., 2022)

Within the horizontal plane, the DP system regulates the vessel in three degrees of freedom: yaw, sway, and surge. In addition, the ship can move in three vertical directions: roll, heave, and pitch. Although the pitch and roll motions are not under the control of the DP system, the system needs to know about them for the position-reference system to adjust for them. Only the DP addresses the automatic management of surge, sway, and yaw. According to Chas & Ferreiro (2008), yaw is determined by the vessel's heading, whereas surge and sway are connected to the position of the vessel.

To comprehend the design philosophy of the DP system, one must establish the three fundamental principles that form its foundation: Capacity, Redundancy, and Reliability. A DP vessel's ability to maintain its position under certain operational and environmental conditions is known as its "DP capability." DP capability assessments determine the maximum weather conditions in which a DP vessel can maintain its position and heading, based on the proposed thruster configuration.

Redundancy refers to having multiple ways to complete a critical task (DPVDPG, 2011). While redundancy and reliability are often related, they are not the same. In DP systems, redundancy, or single failure tolerance, is achieved by incorporating redundant systems. The redundancy criteria outlined in DP class rules are designed to create fault-tolerant systems that prevent a single failure from causing a loss of position. However, these rules often overlook the vessel's ability to continue fulfilling its industrial objectives (DPVDPG, 2015).

The likelihood that a product can carry out a necessary function under specified circumstances for a certain amount of time is known as Reliability (DPVDPG, 2011). DP vessels ought to maintain a high enough degree of station-keeping reliability. The reliability of a DP vessel is influenced by several factors, including the expertise of the engineers who design and built it, the proficiency of the crew and management who operate and maintain it, the quality of the equipment used, and the reliability of the suppliers involved (DPVDPG, 2015). The levels of reliability are not specified in the DP rules and recommendations.

The division of thrusters, generators, and auxiliary services into groups significantly impacts the vessel's worst-case failure and, consequently, its post-failure DP capacity. According to DPVDPG (2015), the failure that has the biggest impact on station-keeping capabilities is the worst-case scenario. An FMEA assessment usually identifies the worst-case failure. A fault in a major propulsion motor or one of the main bus bars sections is the worst-case single fault in terms of class criteria DP2 or 3. For instance, the loss of the starboard bus bar section, which would result in the loss of three thrusters, would constitute the worst-case failure of the offshore supply vessel as shown in Fig 3.

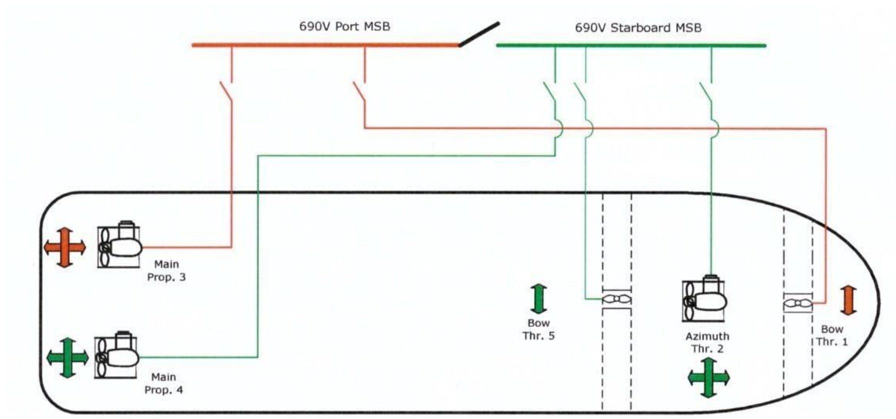


Fig 3: Example of vessel redundancy concept (Elo & Kyngas, 2008)

5. DP System Structure

The main subsystems that make up the DP systems are listed as follows (Chas & Ferreiro, 2008):

i. Control System
ii. DP Reference System
iii. Environment Reference System
iv. Propulsion system
v. Power system

As seen in Fig 4, each system is made up of different parts, sensors, and tools needed to complete the task.

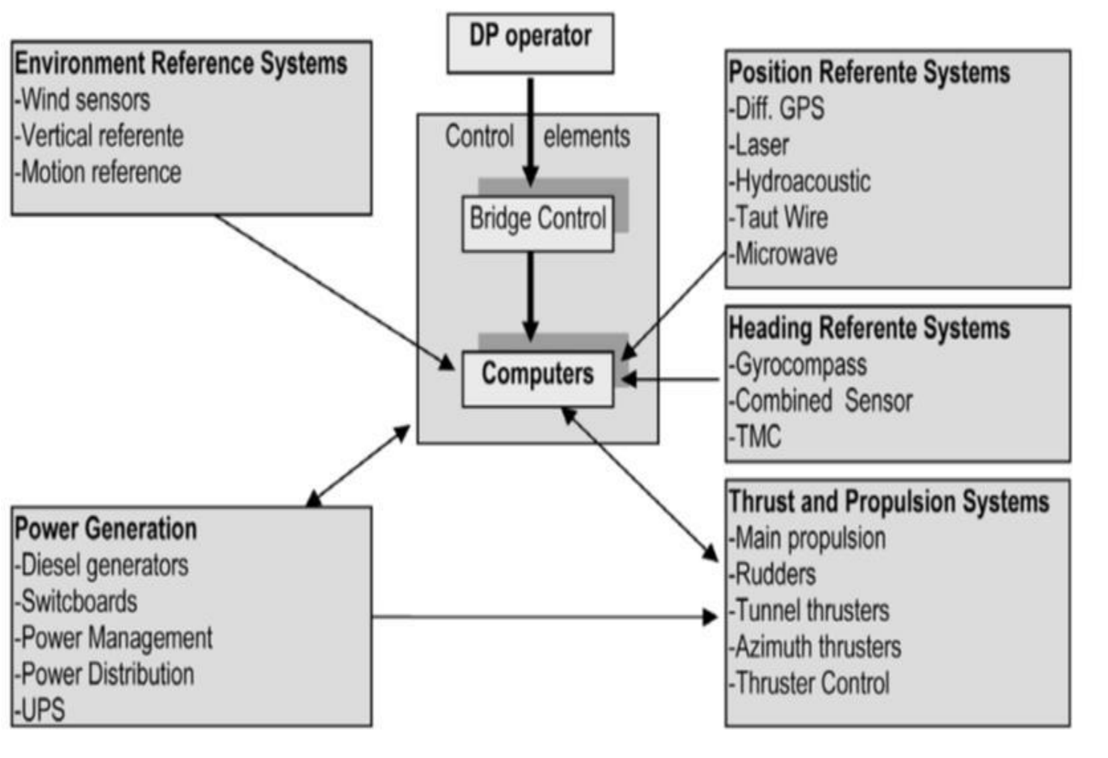


Fig 4: Schematic diagram of the DP system (Oil Field Team, 2020).

This schematic diagram in Fig 4 illustrates the core components and operational flow of a DP system, highlighting the interaction between various subsystems necessary for maintaining a vessel's position and heading. The DP operator oversees the system, which is controlled through a bridge interface that connects to the central computer. The computer processes inputs from several reference systems: environmental sensors (e.g., wind, vertical, motion), position reference systems (e.g., GPS, laser, hydroacoustic), heading reference systems (e.g., gyroscope, combined sensors), and thrust and propulsion systems (e.g., main propulsion, rudders, thrusters). Additionally, power generation systems, including diesel generators and power management units, support the overall operation. This integration of components enables the DP system to maintain stability and positioning in real-time, even under changing environmental and operational conditions (Chas & Ferreiro, 2008).

The DP control system receives data from position and heading reference sensors, environmental reference sensors, and operator commands to maintain the vessel's position and heading. Following an analysis of the input data, DP computers instruct the propulsion systems to station the vessel. A system for power generation provides the necessary power.

Control System

DP computers are the general term for the processors running the DP control program. Computer installations can be single, dual, or triple, depending on the DP vessel's class notation. In addition to dynamic location, many more vessel management functions can be incorporated into modern systems that communicate via intranets or local area networks (LANs). The DP control computers in every DP vessel are solely responsible for performing the DP function. A 'simplex' DP control system, consisting of just one computer, lacks redundancy. In the event of an online system failure, a dual or two-computer system provides redundancy and automatically switches over to the backup system to maintain operation. Usually installed on DP3 boats, a triple or "triplex" system offers an additional layer of redundancy as well as the possibility of 2-out-of-3 voting. The DP system interface, often referred to as the control console or operator station, enables the DP operator to send and receive data. The console is equipped with control buttons, switches, lights, alarms, and display screens. Key operational parameters are displayed to ensure the thruster system, DP control system, and power systems are functioning correctly. All essential information for the safe operation of the DP system should be readily accessible, with the option for the operator to request additional details when needed. In a well-designed DP control station, the thruster panels, communications systems, and control panels for the position reference systems are strategically and ergonomically placed around the DP control console for optimal operator efficiency.

DP Reference System

DP requires continuous, accurate, and reliable position information. DP Reference Systems (DPRS) come in a variety of forms; a vessel's role determines the position measuring devices to use (GDPV, 2000). There are two types of DPRS: absolute and relative. The geographical position of the vessel is provided using an absolute system. A relative system is used to provide the vessel's position with respect to a non-fixed reference. Several kinds of position measurement apparatus can be included in a DPRS. Although one form of location reference may be utilized, two or more types are typically required for reliability. A voting mechanism can be utilized to aggregate the position values and apply the proper weighting when many DPRS are available online. It is just checked, filtered, and used if only one DPRS is enabled. As seen in Fig 5, there are currently five primary kinds of location reference systems in use aboard DP boats.

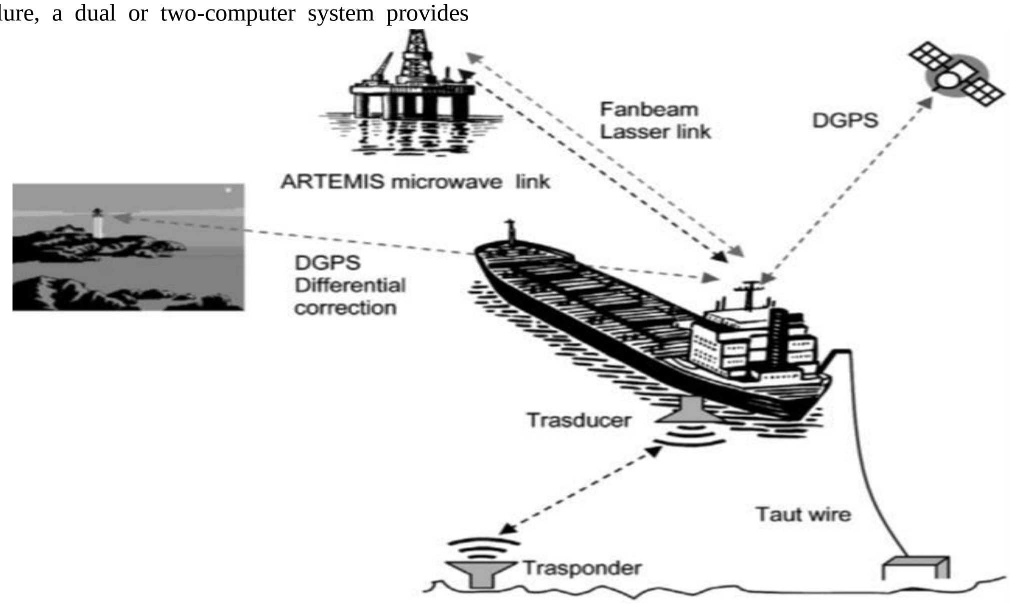


Fig 5: Different kinds of systems for referencing positions (Chas & Ferreiro, 2008)

i. Taut Wire: The position can be determined by lowering a depressor weight to the seabed and measuring the difference in the wire's angle between a fixed point on the vessel and a fixed point on the seabed. The accuracy of this system depends on several factors, such as water depth, mooring tension, the wire's angle relative to vertical, and the strength of the tide (Chas & Ferreiro, 2008).

ii. Radio-based DPRS: This determines the vessel's position by measuring the absolute distance and relative angle between the vessel and the reference object using radio waves. The systems Artemis, RadaScan, and RADius all operate based on this principle (Chas & Ferreiro, 2008).

iii. Differential Global Navigation Satellite System DGNSS: The standard term for satellite navigation systems that provide global coverage and autonomous geographic positioning is GNSS (Global Navigation Satellite System). To enhance the accuracy of GPS data, differential corrections are often applied to GNSS measurements. The most popular GNSS mode for usage in offshore vessel operations is unquestionably Differential Global Positioning System (DGPS). The precision range for determining the geographical position of the vessel is between two and five meters. In 95% confidence zones, some service providers quote a possible positioning accuracy of 0.5–1 m (FMVST, 2001). When precise location between moving vessels is necessary for vessel operation, a relative DGPS system is employed. The first vessel tracks its position with a conventional DGPS. In addition to receiving GPS data from the first vessel via an Ultra High Frequency (UHF) link, the second vessel also receives GPS data on its receiver. After comparing the two positions, the second vessel calculates a range and bearing that it then feeds into the DP system (GDPV, 2000).

iv. Hydro-acoustic Position reference (HPR): HPR operates on a similar principle to radio wave systems above water, providing positioning by placing transponders on the seabed and a transducer within the ship's hull (Alstom, 2000). However, a key drawback is its susceptibility to noise from thrusters or other acoustic equipment, and it has limited effectiveness in shallow waters (Chas & Ferreiro, 2008).

v. Laser-based systems: Two major laser-based DPRS commonly used are CyScan and Fanbeam. Both systems latch onto one, many, or all the targets on the structure, and they must maintain their positions from there. Range and bearing are measured by sending and receiving light pulses (GSPS, 2017). Fig 6 represents the failure modes of a DPRS (IEC, 2014).

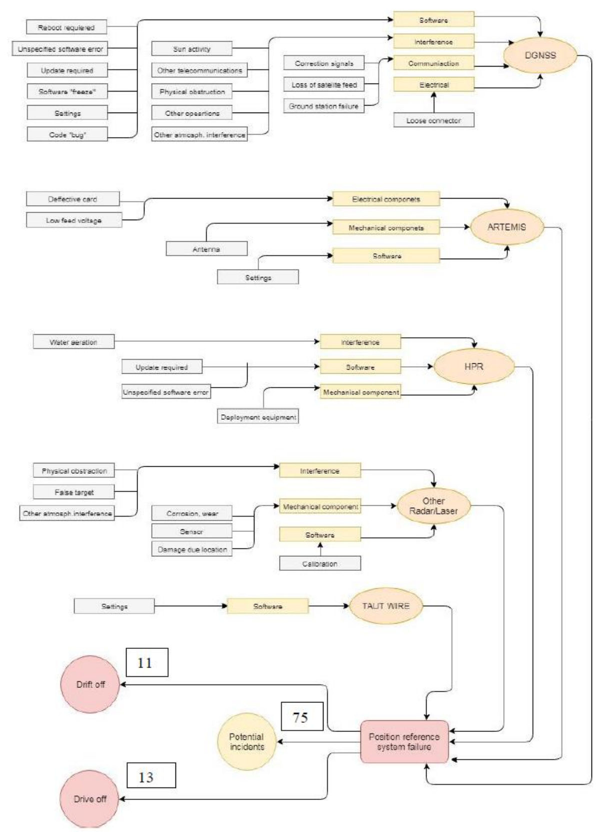


Fig 6: Incidents caused by “Reference system” failure (Pil, 2018)

Environment Reference System

The environmental factors, such as wind, current, and waves, operating on the vessel are measured by an environment reference system. The systems are made up of sensors that provide the DP system with environmental data. The sensors on the vessel are:

i. Gyrocompass: A gyrocompass is utilized for accurate heading control in DP systems.

ii. Vertical Reference Unit (VRU): The VRU measures the difference between the "local" vertical and the vessel's reference plane. Although a DP system does not control a vessel's movement along the heave, roll, or pitch axes, accurate pitch, and roll measurements are essential for providing precise compensation to certain position-measuring devices.

iii. Anemometer/Wind sensor*:* An instrument used to measure the wind's direction and speed is called an anemometer. On a vessel, wind is a primary source of disturbance. Through altering thruster demands, position control can be enhanced by the wind's speed and direction.

iv. Doppler Log: The vessel's speed over the bottom is measured using the Doppler log. It makes use of sound and the Doppler Effect, which is caused by a moving sound source with a modified reflected frequency that changes in relation to the sound source's speed (Alstom, 2000).

Propulsion System

The propulsion system is essential to the vessel's overall operation, particularly its capacity to maintain position. While most medium-sized and large displacement vessels are now powered by diesel, some still have thrusters that are driven by hydraulics or direct drive (FMEAs, 2016). On dynamically positioned vessels, thrusters typically come in four types (FMEAs, 2016):

i. Conventional propellers with rudders

ii. Tunnel thrusters

iii. Azimuthing thrusters

iv. Azipod thrusters

The conventional means of propulsion for a vessel is a propeller. Propellers can be set up as single or dual units. Propellers can be further classified as fixed-pitch propellers (FPP) or controllable-pitch propellers (CPP). Propellers can generate thrust in both directions, but only 40–60% of that can be generated in the opposite direction because of the way the blades are shaped and the effect of the hull (Alstom, 2000). Rudders work in tandem with the propeller to give the boat sway force. When side thrust is needed, rudders are typically regarded as ineffective. For enhanced maneuverability, DP vessels equipped with traditional shafted propulsion will use stern tunnel thrusters. The ship's bow and/or stern are equipped with tunnel thrusters. These give a turning moment and allow the vessel to be moved sideways. Thrusters can be CPP or FFP types, just like a primary propeller. Tunnel thrusters are only considered effective at very low speeds and when positioned as far below the waterline as possible.

Azimuth thrusters can spin, whereas tunnel thrusters are confined within the tunnel and are only capable of providing thrust in one direction. Within 360^0, the push direction can be adjusted by turning the thruster. Thrust magnitude can be controlled either by adjusting the pitch (for CPP) or by varying the speed (for FPP with a variable speed drive). Azimuth thrusters are positioned to minimize interference with one another and to prevent damage from coming into contact with the seabed. Moreover, they could be retractable. An entire propulsion system hung beneath the ship is called an azipod. An electric motor, with its drive end fastened to a fixed-pitch propeller, powers the pod. The ability to rotate the azipod through 360^0 offers excellent maneuverability. Figure 7 represents the failure modes of a DP system for a propulsion system.

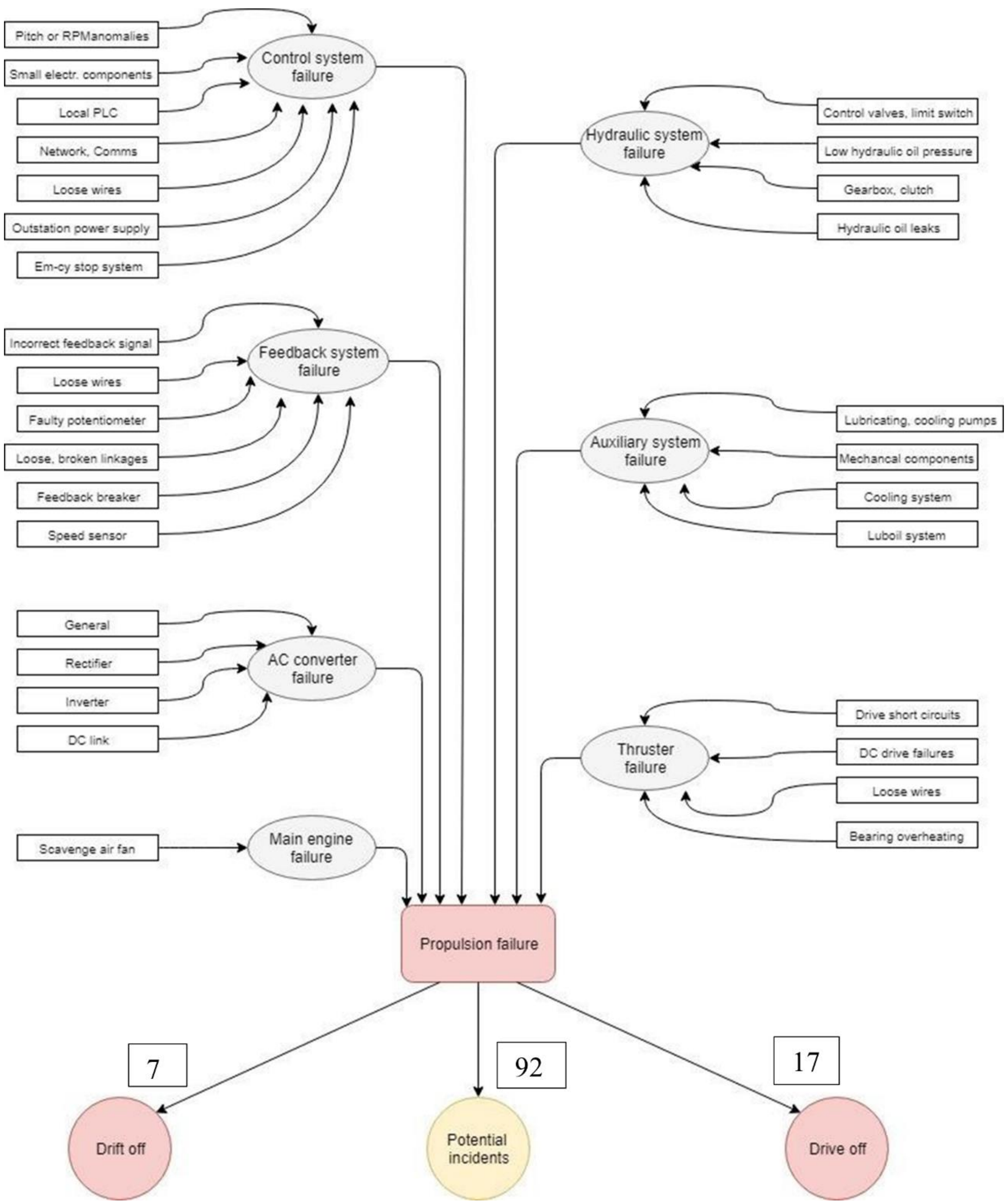


Fig 7: Incidents caused by "Propulsion system" failure (Pil, 2018)

Power System

The reliability of the power system is essential for effective DP operations. Power is needed to support the thrusters, all auxiliary systems, the DP control elements, and the reference systems. Today's offshore installations and vessels are designed to comply with various environmental standards that place a premium on air emissions. Marine Diesel Oil (MDO) is used by most offshore support vessels. Because MDO is ready to use, it is also favored. Piston engines are typically utilized for installations of a moderate scale. Electrical propulsion is commonly integrated into the design of larger DP-operated offshore oil and gas production vessels, as well as semi-submersible units (Sørfonn, 2007). The thrusters are the primary consumers of the generated power. The operating mode of the system and the surrounding variables determine the power requirement when it is in operation. Because of this, DP vessels' power systems need to be adaptable and able to withstand brief power surges. The applicable regulations for the mandatory classification notations on the vessel must also be followed by the power systems. The arrangement of all necessary services, including cooling, fuel, air, and lubrication systems, for generators and their prime movers must follow the vessel's DP notation.

Power must be safely transported to customers after it is produced. Modern vessels' electrical systems necessitate a complex Power Management System (PMS) and considerable usage of power electronics. The purpose of a PMS is to regulate and track the generation and use of electricity within a ship. Switchboards, consumers, and generators powered by engines are all under system control and observation. The PMS minimizes downtime by quickly restoring power in the event of an electrical system malfunction. The generators on a conventional diesel-electric arrangement provide the electricity (generator driven by diesel engine). The number and configuration of the generator sets are determined by the DP notation requirements and the specific operational capability demands.

The offshore support vessel power system typically consists of four generator sets connected to a single bus bar. These generator sets provide power to the thruster electrical drives via transformers. Frequency converters manage speed control for the thrusters. As shown in Fig 8, the bus bar can be divided into two sections by opening the bus tie, allowing for the required redundancy in the power system. Because of their significance and susceptibility, power systems must meet high requirements for redundancy and reliability. Different components in a vessel's power system are prone to various failure modes as shown in Fig 9.

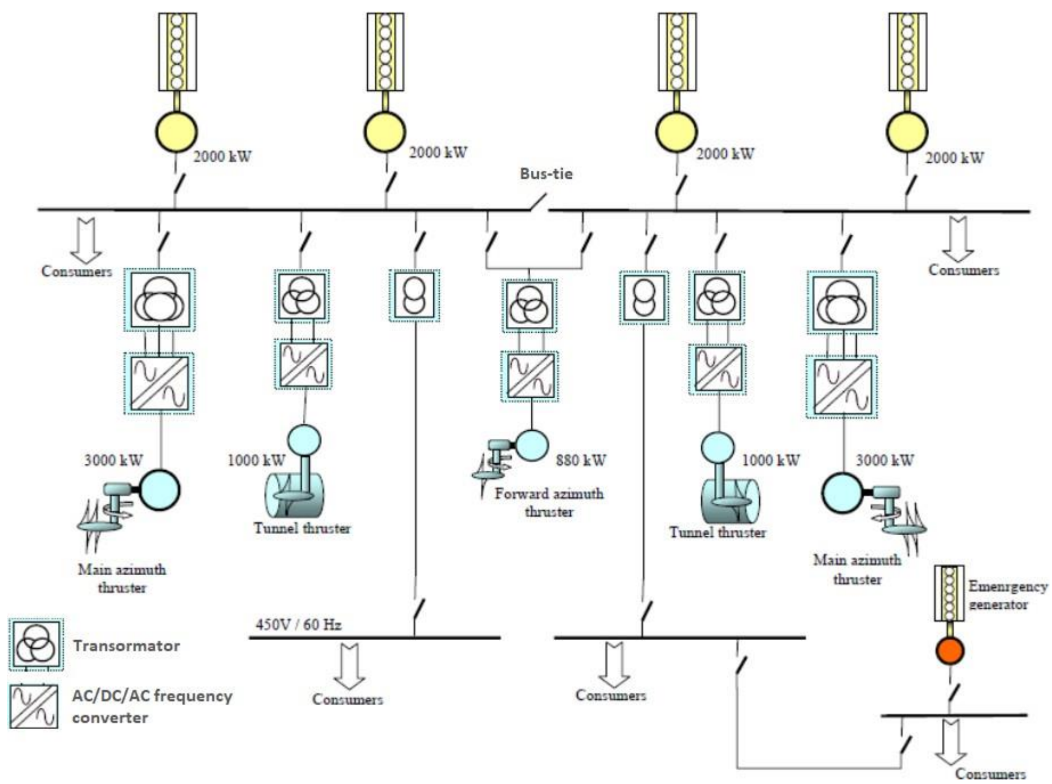
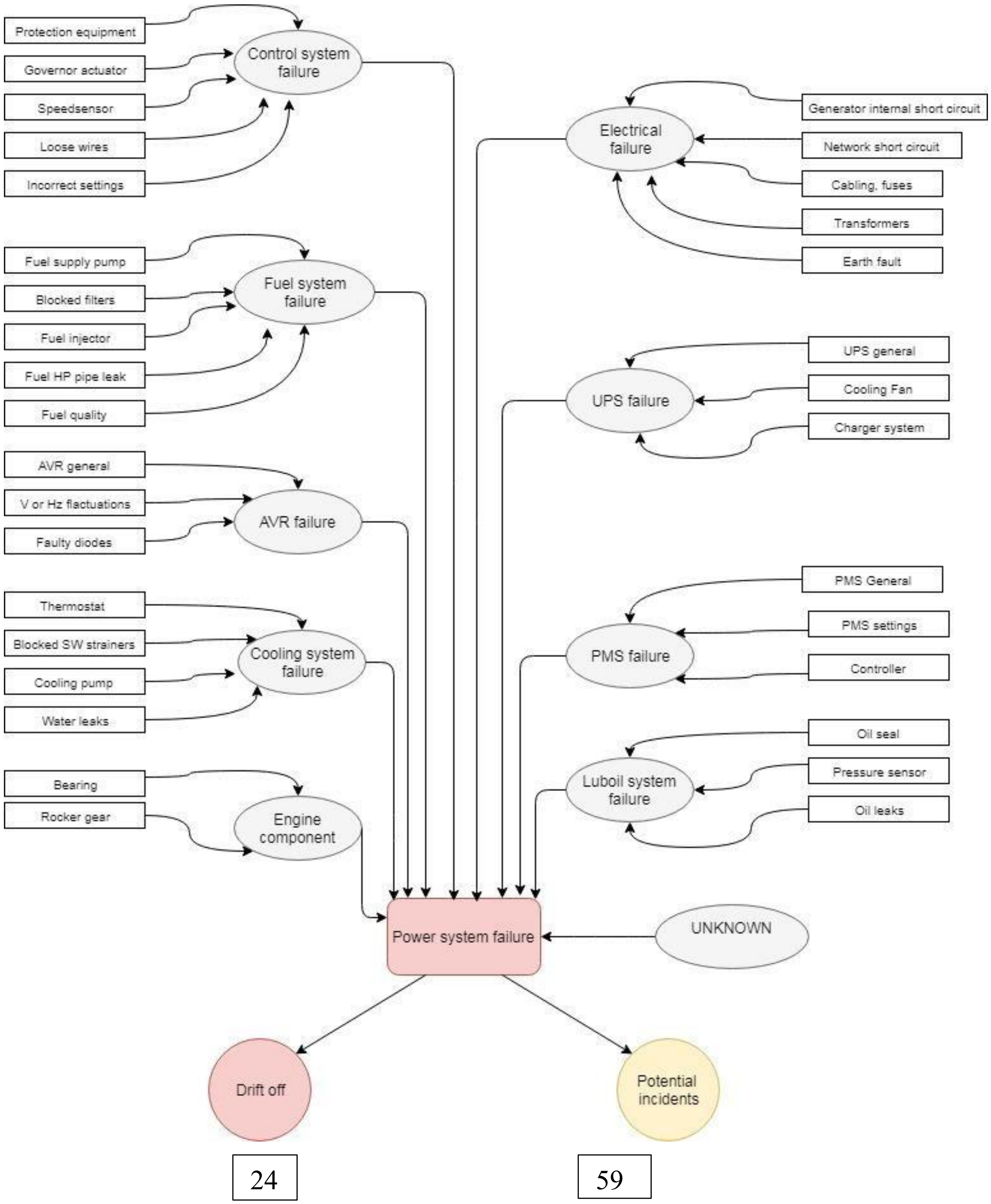


Fig 8: A simplified one-line diagram illustrating the power system of the DP vessel (Sørfonn, 2007).

Fig 9: Incidents caused by "Power system" failures (Pil, 2018)



Monte Carlo Simulation

A numerical method for resolving mathematical problems by simulating random variables is the MCS method. Although there is no universal agreement on an exact definition, the most common explanation of a MC-like technique is that it uses chance to solve computational problems. In general, they can be used for numerical problems or situations that are inherently probabilistic (Ocnasu, 2008). Whenever there is no suitable analytical method for studying high-dimensional nonlinear systems, MCS methods are frequently the only viable option. In an industrial setting, they are employed to investigate the spread of uncertainty or to characterize the response to a random excitation. In general, they can be used for numerical issues or situations that are inherently probabilistic (Lynda, 2012). Because it allows access to several factors that are unavailable through other approaches and produces incredibly detailed analyses of the systems under study, MCS is an immensely intriguing technique. The simulation only displays the dominant states, regardless of the hundreds of thousands of states in the system under study, hence it is unrestricted by the number of states of random and deterministic phenomena in the same model. All recognizable system features and operations can be inserted and simulated by it. Using its behavior model, MCS is used to generate stories about the system, perform random draws of the input variables (the system's state), and statistically assess the output variables (Lynda, 2012). Reliability indices of an actual physical system can be determined by collecting data on the frequency of failures and repair times. The MCS approach simulates the failure and repair history of the system and its components using probability distributions for the duration of component states (Dabrowska, 2019). Once the simulation is run, data are collected, and statistical inference is applied to estimate reliability indices. There are two primary methods for MCS: Random Sampling and Sequential Simulation. In Sequential Simulation, random numbers and probability distributions of variables representing component state durations are used to generate a sequence of events. In random sampling, probability distributions of component states and random numbers are used to select states. In sequential simulation, time can be represented in two ways: (1) the "next event" or asynchronous timing method, and (2) the fixed interval method, also known as synchronous timing (Dabrowska & Soszynska, 2018). In the fixed interval method, the system state is updated, and time advances in fixed steps. In the next event method, time progresses to the occurrence of the next event. Real implementations may use various combinations of these timing controls. While the sampling method is generally faster than the sequential method, it is most suitable for cases where component failures and repairs are independent. This research focuses on applying the sequential method for reliability analysis.

Fault Tree Analysis

In 1962, under a contract from the US Air Force Ballistics Systems Division to evaluate the Minuteman Intercontinental Ballistic Missile (ICBM) Launch Control System, H.A. Watson developed the first version of FTA at Bell Laboratories (Mohammad et al., 2011). FTA has since become one of the most widely used methods for causative analysis in risk and reliability studies. It is a failure analysis technique that employs Boolean logic to combine multiple lower-level events into an analysis of an undesired state in a system. This method is primarily used in safety engineering to quantitatively determine the likelihood of safety hazards.

FTA is a graphical design method that serves as an alternative to reliability block diagrams, with a broader scope and distinct features. Unlike reliability block diagrams, FTA is a logical, top-down approach that focuses on events rather than components. One key advantage of this method is that it emphasizes failures, which are generally easier to identify and analyze than non-failures since failures tend to occur in more ways (Mohammad et al., 2011). FTA typically centers around a significant malfunction or catastrophic event, known as the "top event," which is depicted at the top of the fault tree diagram. The process begins with qualitative analysis, identifying the different combinations of events that can lead to failure. This is followed by quantitative analysis, which estimates the probability of the top event occurring. Failure rates are usually calculated using verified historical data, such as the average time between failures of systems, subsystems, and components. FTA is a valuable design tool for identifying potential failures and preventing costly design changes. It is also useful as a diagnostic tool for estimating the likelihood of system failure and is widely used in failure analysis of engineering systems and operations.

Conclusion

DP systems are integral to modern offshore operations, particularly in the oil and gas industry, as they provide precise station-keeping capabilities in deep and challenging marine environments. However, the complexity of these systems introduces significant reliability and safety concerns, making robust risk assessment and failure analysis essential. This paper has explored the application of MCS and FTA methods in enhancing the reliability and safety of DP systems.

Through an in-depth review of current research, we have highlighted that both MCS and FTA offer complementary strengths. MCS provides a probabilistic approach to simulating the behavior of DP systems under various failure scenarios, allowing for a detailed assessment of system reliability over time. On the other hand, FTA offers a structured top-down methodology for identifying and analyzing the causes of system failures, focusing on critical events that could lead to the loss of position or system malfunction. By integrating these two techniques, operators and engineers can gain a comprehensive understanding of the failure modes, predict potential points of weakness, and implement proactive measures to mitigate risks. The studies reviewed in this paper demonstrate that while DP systems have made significant technological advancements, failures are still possible due to the complex interplay of technical, human, and environmental factors. These failures, whether in power, propulsion, or control systems, can lead to severe operational consequences, including drive-off and drift-off incidents. Therefore, ongoing risk assessments using advanced tools like MCS and FTA are crucial to improving the fault tolerance, redundancy, and overall safety of DP systems. Furthermore, the review suggests that the future of DP system reliability will increasingly depend on the integration of real-time data analytics, improved fault detection algorithms, and enhanced operator training programs. By focusing on early detection of failures and better understanding the impact of human and environmental factors, the industry can further reduce the likelihood of catastrophic failures.

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