TABLES

REFERENCES

BIBLIOGRAPHY

ABBREVIATIONS

ABS	AMERICAN BUREAU OF SHIPPING
AC	ALTERNATING CURRENT
AFC	APPROVED FOR CONSTRUCTION
AGP	ADVANCED GENERATOR PROTECTION
AI	ASSET INTEGRITY
AODC	ASSOCIATION OF OFFSHORE DIVING CONTRACTORS
API	AMERICAN PETROLEUM INSTITUTE
ASOG	ACTIVITY SPECIFIC OPERATIONAL GUIDELINES
AVR	AUTOMATIC VOLTAGE REGULATOR
BOP	BLOW OUT PREVENTER
BV	BUREAU VERITAS
CFD	COMPUTATIONAL FLUID DYNAMICS
CMF	COMMON MODE FAILURE
CP	CONTROLLABLE PITCH
CPP	CONTROLLABLE PITCH PROPELLER
DGNSS	DIFFERENTIAL GLOBAL NAVIGATION SATELLITE SYSTEM
DGPS	DIFFERENTIAL GLOBAL POSITIONING SYSTEM
DNV	DET NORSKE VERITAS
DP	DYNAMIC POSITIONING
DPCS	DYNAMIC POSITIONING & CONTROL SYSTEMS
DPO	DYNAMIC POSITIONING OPERATOR
DPS	DYNAMIC POSITIONING SYSTEM
DPVOA	DYNAMICALLY POSITIONED VESSEL OWNERS ASSOCIATION
DSV	DIVING SUPPORT VESSEL
EARTH	GROUND
ECR	ENGINE CONTROL ROOM
ER	ENHANCED RELIABILITY
ESD	EMERGENCY SHUTDOWN SYSTEM
F & G	FIRE & GAS
FAT	FACTORY ACCEPTANCE TEST
FMEA	FAILURE MODES AND EFFECTS ANALYSIS
FMECA	FAILURE MODE EFFECT AND CRITICALITY ANALYSES
FOG	FIBRE OPTIC GYROS
FPP	FIXED PITCH PROPELLER
FPSO	FLOATING PRODUCTION STORAGE OFFTAKE
FSVAD	FLAG STATE VERIFICATION & ACCEPTANCE DOCUMENT
FW	FRESH WATER
GA	GENERAL ALARM
GNSS	GLOBAL NAVIGATION SATELLITE SYSTEM
GPS	GLOBAL POSITIONING SYSTEM
GROUND	EARTH
HAT	HARBOUR ACCEPTANCE TEST
HAZOP	HAZARD AND OPERABILITY
HDOP	HORIZONTAL DILUTION OF POSITION
HIL	HARDWARE IN LOOP
HMI	HUMAN MACHINE INTERFACE

HSE	HEALTH, SAFETY AND ENVIRONMENT
HSI	HUMAN SYSTEM INTEGRATION
HV	HIGH VOLTAGE, GENERALLY VOLTAGES OVER 1000 VOLTS
HVAC	HEATING VENTILATION AIR CONDITIONING
I/O	INPUT/OUTPUT
IAN	INERTIAL AIDED NAVIGATION
IEC	INTERNATIONAL ELECTROTECHNICAL COMMISSION
IJS	INDEPENDENT JOYSTICK
IMCA	INTERNATIONAL MARINE CONTRACTORS ASSOCIATION
IMO	INTERNATIONAL MARITIME ORGANISATION
IRM	INSPECTION REPAIR AND MAINTAINABILITY
LBL	LONG BASELINE
LCI	LOAD COMMUTATED INVERTER
LLRC	LOW LOSS REDUNDANCY CONCEPT
LRS	LLOYDS REGISTER OF SHIPPING
LUSBL	LONG ULTRASHORT BASELINE
LV	LOW VOLTAGE, GENERALLY VOLTAGES BELOW 1000 VOLTS
MOC	MANAGEMENT OF CHANGE
MODU	MOBILE OFFSHORE DRILLING UNIT
MOU	MOBILE OFFSHORE UNIT
MRU	MOTION REFERENCE UNIT
MSC	MARITIME SAFETY COMMITTEE
MTBF	MEAN TIME BETWEEN FAILURE
MTS	MARINE TECHNOLOGY SOCIETY
MTTR	MEAN TIME TO REPAIR
NMD	NORWEGIAN MARITIME DIRECTORATE
OIM	OFFSHORE INSTALLATION MANAGER
OSV	OFFSHORE SUPPORT VESSEL
PA	PUBLIC ADDRESS
PLC	PROGRAMMABLE LOGIC CONTROLLER
PMS	PLANNED MAINTENANCE SYSTEM
PRS	POSITION REFERENCE SYSTEM
PSU	POWER SUPPLY UNIT
PWM	PULSE WIDTH MODULATION
QCV	QUICK CLOSING VALVE
RAO	RESPONSE AMPLITUDE OPERATOR
RCA	REDUNDANCY AND CRITICALITY ANALYSES
RCU	REMOTE CONTROL UNIT
RESTRICTED EARTH FAULT PROTECTION	DIRECTIONAL EARTH FAULT PROTECTION
RIO	REMOTE INPUT OUTPUT
ROV	REMOTELY OPERATED VEHICLE
RPM	REVOLUTIONS PER MINUTE
SAT	SEA ACCEPTANCE TEST
SCE	SAFETY CRITICAL ELEMENTS
SIL	SAFETY INTEGRITY LEVELS
SIMOPS	SIMULTANEOUS OPERATIONS
SMO	SAFEST MODE OF OPERATION
SOLAS	SAFETY OF LIFE AT SEA

STCW	STANDARDS OF TRAINING CERTIFICATION AND WATCH KEEPING
SW	SEAWATER
TAGOS	THRUSTER AND GENERATOR OPERATING STRATEGY
TAM	TASK APPROPRIATE MODE
TCPC	TRAINING, CERTIFICATION & PERSONNEL COMPETENCE
THD	TOTAL HARMONIC DISTORTION
TTT	TIME TO TERMINATE
UKCS	UK CONTINENTAL SHELF
UPS	UNINTERRUPTED POWER SUPPLY
USBL	ULTRA SHORT BASE LINE
VAr	VOLT AMPERE REACTIVE
VCB	VACUUM CIRCUIT BREAKER
VFD	VARIABLE FREQUENCY DRIVES
VRU	VERTICAL REFERENCE UNIT
VRU	VERTICAL REFERENCE UNIT
WCF	WORST CASE FAILURE
WCFDI	WORST CASE FAILURE DESIGN INTENT
WSOG	WELL SPECIFIC OPERATIONAL GUIDELINES

1 INTRODUCTION

1.1 PURPOSE

1.1.1 This document has been generated by the MTS DP Technical Committee and has been provided to industry as a guidance document to aid in the design of DP Vessels.

1.1.2 This document is not meant to replace any rules, regulations or guidelines that are in existence. It is a compilation of experiences, practices and information gleaned from various sources in industry, some of which are not in the public domain. It is expected that compliance with applicable Class Rules will be ensured..

1.1.3 It is acknowledged that DP Class notation is governed by Class Rules which cover DP equipment and addresses redundancy requirements. However, these rules do not address the industrial mission of the vessel nor the overall performance and operational capability. Consequently vessels designed to obtain a DP Class Notation alone may not achieve the post worst case failure capability that could potentially be achieved by establishing and adopting philosophies that minimize loss of positioning capability after failure and enhance reliability.

1.1.4 Note:-LRS and DNV offer a means to compare DP vessel performance through the use of PCR and ERN numbers.

1.1.5 This is not intended to be an all encompassing document covering all aspects of DP vessel design. It attempts to provide guidance on a number of themes which have not been adequately defined by DP Class Rules or are subject to interpretation. Incorporating the guidance provided in this document during design should result in a vessel with enhanced capability to perform its industrial function and which meets Class Rules for the desired DP Class Notation.

1.1.6 Enhanced vessel capability as implied in this document means a more fault tolerant/fault resistant DP system which minimizes loss of positioning capability post worst case failure. This in turn translates into greater operational uptime and the ability to carry out its mission within a larger operating envelope.

1.1.7 The focus areas of this document have evolved from industry experience of technical failures. Addressing these vulnerabilities during design will result in a robust vessel capable of conducting its industrial mission. Exposure to environmental conditions is addressed by focusing on capability and sizing of thrusters and power plants. Technical failures are addressed by designing fault tolerant and fault resistant systems. Some technical faults require operator intervention to prevent escalation. Ergonomics and ‘decisions support tools’ aid effective operator intervention.

1.1.8 Implementation of the Guidance during design phase rather than later in the life cycle is expected to lower the cost of a ’fit for purpose‘ DP vessel.

1.1.9 The guidance provided in this document is not directed at any particular category of DP vessel. It is intended to apply to any Class 2 or Class 3 DP vessel operating in support of offshore oil and gas activities. The principles may be implemented as appropriate on Class 1 DP vessels. Examples include MODUs, MOUs, construction and logistics vessels where dynamic positioning is used for, or aiding, station keeping.

1.2 GENERAL GUIDANCE

1.2.1 The guidance provided in this document is intended to aid in the design of a fault tolerant, fault resistant DP vessel. It is intended to apply to any class of DP vessel operating in support of offshore oil and gas activities. The goals of the guidance are to:

1. Prevent loss of position
2. Prevent loss of redundancy

The objectives of the above are to meet class requirements and obtain operational uptime.

1.2.2 The industrial mission of DP vessels varies. Examples as follows:

1. DP MODUs
2. Project construction vessels
3. logistics vessels

1.2.3 Fault tolerant power systems can be achieved by the use of sophisticated protective functions or by configuring the power plant as two or more independent systems (open bus). Design should always facilitate effective open bus operations.

1.2.4 It is acknowledged that the level of sophistication and complexity required to achieve fault tolerance, fault resistance and uptime for DP MODUs and project construction vessels are likely to be higher than that applied to logistics vessels due to the nature of their industrial mission.

1.2.5 Diesel electric DP logistics vessels are also expected to be fault tolerant and fault resistant. Operational uptime on DP may not be the driver given the nature of their industrial mission. Acceptable levels of station keeping reliability and fault tolerance can be achieved using less sophisticated redundancy concepts.

1.2.6 It should be recognized that power plants need a larger level of integration than other components of DP systems. Care should be exercised in the concept and design phase of power systems to clearly establish the needs of the industrial mission, requirements of the Regulatory/Classification bodies and to define the system for all aspects of the project life cycle.

1.2.7 All vessels should be operated within their post failure DP capability as determined by their Worst Case Failure.

1.3 LAYOUT OF THE DOCUMENT

1.3.1 This document consists of two parts. Part 1 is a management guide explaining why each theme is important. Part 2 contains additional details on how to address these themes along with anecdotal examples.

1.3.2 The level of detail in the sections on power (generation, distribution and power management / vessel management) is deliberately and consciously greater than that provided in other sections. A well thought through power system design delivers a robust and capable vessel and enhances the ability of the vessel to perform its industrial mission. Note that the term ‘power system’ includes auxiliary systems and related pipework.

2 DEFINITIONS

2.1 GENERAL

1. **Reliability:** The probability that an item can perform a required function under given conditions for a given time interval.
2. **Redundancy:** The existence of more than one means of performing a required function.
3. **Full redundancy:** A system comprising two or more redundant elements each of which is capable of performing the function.
4. **Partial redundancy:** A system containing three of more redundant elements which are capable of performing the function in combination (e.g. Any two-out-of-three)
5. **Availability**: The ratio of the total time a functional unit is capable of being used during a given interval to the length of the interval.
6. **Single fault tolerance:** The ability of a system to continue its function, following a single failure, without unacceptable interruption.
7. **Independence:** With reference to main machinery such as generators and thrusters. Auxiliary and control functions should be provided in a manner that makes the machinery as independent as practical to minimize the number of failures that can lead to the loss of more than one main item of machinery
8. **Separation:** With reference to systems or equipment intended to provide redundancy. Reduce the number of connections between systems to reduce the risk that failure effects may propagate from one redundant system to the other.
9. **Physical separation:** With reference to DP Class 3 vessels, fire and watertight subdivisions required to support the worst case failure design intent in respect of DP 3 failure criteria.
10. **Monitoring:** Alarms and indications required to reveal hidden failures. Monitoring should be of a design and implementation that positively identifies a fault or degradation of functionality in the system e.g. lack of flow not just loss of pressure.
11. **Critical redundancy:** Equipment provided to support the worst case failure design intent.
12. **Non critical redundancy:** Equipment provided over and above that required to support the worst case failure design intent. Its purpose it to improve the reliability and availability of systems.
13. **Industrial Mission:** The industrial mission is the primary operational role of the vessel, typically applicable to MODUs and Project and Construction vessels. (e.g. Pipe-lay/Heavy-lift). (Note Industrial mission by definition for Logistic Vessels is to support logistics)
14. **Diversity:** The property of introducing differences into redundant elements to avoid common mode, common cause failures. Different levels of diversity are possible such as specifying different manufacturers for redundant GNSS systems. Even greater diversity can be achieved through orthogonality which requires redundant elements to operate on different principles.

15. **Orthogonality:** With reference to redundant systems the secondary means of providing a function should be based on completely different principles to reduce the risk of common mode failures. (e.g. Gyros-spinning mass versus Fiber Optic Gyros (FOG), anemometers (ultrasonic versus mechanical).

16. **Differentiation:** A method to avoid common mode failures by introducing a change in personality of redundant systems based on the same principle. (e.g. use of Inertial Aided Navigation (IAN) on one of the two redundant GNSS systems)

17. **Suitability:** In this document 'suitability' pertains to the vessel having the appropriate position reference sensors to undertake its industrial mission.

18. **Position/heading keeping:** The ability of the DP system to maintain a desired position or heading within the normal excursions of the control system and environmental conditions.

19. **Loss of Position:** The vessel's position is outside the limits set for carrying out the industrial activity in progress as defined in the WSOG/ASOG.

20. **Thruster Phaseback:** A method utilized to temporarily reduce power consumption following an event, to stabilize the power plant and avoid a black-out.

21. **Critical Activity Mode of Operation (CAMO):** This is generally a tabulated presentation of how to configure the vessel's DP system, including power generation and distribution, propulsion and position reference systems, so that the DP system, as a whole is fault tolerant and fault resistant. The CAMO table also sets out the operator actions should the required configuration fail to be met. The term Safest Mode of operation (SMO) has been previously used to describe CAMO.

22. **Systematic failure:** Failures due to flaws in the system. Systems subjected to the same conditions fail consistently.

23. **Wear out:** Specific class of failure when an item of limited life has worn out.

24. **Random failure:** Failure due to physical causes such as corrosion, thermal stressing. Statistical information can be derived from historical data.

25. **'Task Appropriate Mode' (TAM) is a risk based mode:** Task Appropriate Mode is the configuration that the vessel's DP system may be set up and operated in, accepting that a failure could result in effects exceeding the worst case failure such as blackout or loss of position. This is a choice that is consciously made. This mode may be appropriate in situations where it is determined that the risks associated with a loss of position are low and where the time to terminate is low. (Not to be confused with Thruster Assisted Mooring)

26. **'Active redundancy':** Redundancy wherein all means for performing a required function are intended to operate simultaneously.

27. **WCFDI:** The worst case failure design intent (WCFDI) describes the minimum amount of propulsion and control equipment remaining operational following the worst case failure. The worst case failure design intent is used as the basis of design. Single fault tolerance is to be achieved by the provision of redundant systems.

28. **Time to Terminate:** This time is calculated as the amount of time required in an emergency to physically free the DP vessel from its operational activity following a DP abort status and allowing it to be maneuvered clear and to proceed to safety.

3 DP VESSEL DESIGN PHILOSOPHY

3.1 RESPONSIBILITIES

3.1.1 This document is intended to be a design philosophy guide. However, it is important to note that carrying the process of the design concept to completion of a vessel involves many stakeholders. Consequently, it should be recognized that the contracting philosophy employed at each level of design and the various disciplines involved directly affect both the design and execution of the design.

3.1.2 Whether the contract is turnkey “design and build” or the owner presents a fully developed and reviewed design complete with owner furnished equipment to the shipyard, the fact remains that oversight of the process as a whole is a key factor in the success of the design.

3.1.3 Regardless of the contracting philosophy the key disciplines and stakeholders in the process remain the same. The responsibilities of each stakeholder for a given project should be clearly defined by contract, communicated to, and understood by all parties involved in the design and execution of the design. The following list attempts to provide a high level description of the scope of design responsibilities for the various stakeholders; it does not address financial responsibilities:

1. **Senior Management:** The owner’s senior management is responsible for the project charter, which should clearly define the mission parameters for the design. The charter should include the basis of design. Strict guidelines should be incorporated for management of change to mitigate scope creep.
2. **Project Team:** The owners project team will vary depending on the type of contract, however there are common skill sets required on the team including project management, engineering and administration. While each contract will differ, it is important to state that it is the responsibility of the owner to adequately staff the project in order to diligently oversee the entire design process as well as the implementation of the design.
3. **Naval Architects / Designers:** Naval architects and designer are responsible for the conceptual design. The naval architect does not provide detailed engineering or systems designs. In general the naval architect provides hull form drawings, scantlings, conceptual general arrangement drawings, and reports such as weight estimates, hull friction, stability, etc. The Naval architects drawing must be translated by others into detailed production design drawings.
4. **Flag State:** The flag state administers the rules adopted by legislation for the flag state. In general these rules are mainly Health, Safety and Environment and manning related. Flag state rules will normally enforce international conventions such as IMO, SOLAS and Marpol. While some flag states have extensive design codes in place, it is not uncommon for flag state rules to defer to one of the class society’s codes for design criteria.

5. **Class Society:** Class societies establish design codes, review and certify adherence to the codes during design, review the vessel while it is being built and tested, and ultimately certify that the completed vessel complies with their rules. Class societies do not have any governmental authority other than that which may be granted by a flag state. They developed first as a method of providing insurers with technical reviews of vessels to determine whether a vessel was safe and fit for the purpose it was designed for.

6. **Shipyard:** While there are many forms of shipyard contracts and many levels of ability within shipyards throughout the world, it must be noted that the shipyard generally either does or subcontracts the detailed design. With the exception of a complete design and build contract, the shipyard works from a conceptual design by others. The shipyard must interpret the design from the naval architects, various systems designers and vendors, produce detailed designs across disciplines, then fabricate and assemble the hull and systems per the design. Ultimately, the design must be tested as a completed system per the basis of design.

7. **Integrator:** Regardless of the contracting philosophy, the equipment specified by the design must be integrated into a system. It should be noted that when the term “Dynamic Positioning System” is used it refers to the fully integrated vessel systems. There are numerous disciplines, vendors, flag state requirements, class society requirements and design basis requirements that must be integrated into a fully functional, ‘fit for purpose’ system. The integration process must be closely monitored from the basis of design through to the delivery of the vessel. Design/system reviews at identified points with participation by relevant stake holders could facilitate the integration process.

3.2 RELIABILITY OF STATION KEEPING

3.2.1 Reliability and redundancy should not be considered as synonymous. DP class rules have redundancy requirements stipulated to achieve fault tolerant systems and meet the objective of not having a single failure leading to a loss of position. They often do not address the ability of the vessel to continue its industrial mission.

3.2.2 For the purposes of this document the properties of redundancy and single fault tolerance are considered to be synonymous. It is acknowledged that this interpretation is not universal.

1. Often, redundancy is interpreted as having two items of equipment required to perform a function with no consideration given to ensuring that the redundant unit can take over from the failed unit without unacceptable interruption of the function.
2. Similarly, there may be no consideration of how to prevent a fault in one redundant element affecting the operation of others.
3. The above factors should be taken into consideration during design and avoided by incorporation into specifications.
4. The terms ‘redundancy’ and ‘single fault tolerance’ are used interchangeably throughout this document.

3.2.3 DP vessels should have a sufficient level of station keeping reliability. Reliability is a product of the quality of the equipment and suppliers selected, the competence of the engineers who design and build the DP vessel and the competence of the crew and management who maintain and operate it.

3.2.4 Redundancy does not in itself guarantee a sufficient level of reliability leading to overall availability. It can contribute to availability if the redundant elements themselves are sufficiently reliable. DP rules and guidelines do not specify a level of reliability. When mentioned it is in the context of the consequences of loss of position.

3.2.5 The vessel's availability to work can be related to the probability of losing fault tolerance. The vessel's industrial mission should determine what overall level of reliability should be attained to achieve the required vessel availability. Higher vessel availability can be achieved by the application of non critical redundancy and attention to reliability. A robust design can provide high reliability and availability and this should be the primary objective of any design process. . Vessel build specifications that make reference to Class rules alone without explicitly addressing Industrial mission requirements and robust design may not achieve the above goal.

3.2.6 This goal may not be achieved if the only objective is compliance with class rules.

3.2.7 Requirements for single fault tolerance must be satisfied in any design to comply with the rules.

3.2.8 This guidance document only deals with design.

The guidance provided in this document is intended to assist with delivering a robust design capable of:

1. Preventing loss of position
2. Preventing loss of redundancy

This is expected to result in a vessel that meets class requirements and delivers the desired availability to carry out its industrial mission.

3.3 DP EQUIPMENT CLASS

3.3.1 IMO Marine Safety Committee Circular 645 (MSC 645),'Guidelines for Vessel's with Dynamic Positioning Systems', 1994 is intended to provide an international standard for dynamic positioning systems. This document defines three DP equipment classes which are intended to provide different levels of station keeping reliability which can be matched to the consequences of loss of position. The three equipment classes are defined by the effect of failure and the nature of the failures which must be considered.

3.3.2 IMO MSC 645 does not address the industrial mission of the vessel.

3.3.3 The equipment class of the vessel required for a particular operation should be agreed between the owner(s) of the vessel and their respective customer based on a risk analysis of a loss of position. Some Coastal States imposes minimum DP Equipment Class requirements for activities carried out within their domain.

3.4 DP EQUIPMENT CLASS 1

3.4.1 Loss of position may occur in the event of a single failure.

3.5 DP EQUIPMENT CLASS 2

3.5.1 Loss of position is not to occur in the event of a single fault in any active component or system. Normally static components will not be considered to fail where adequate protection from damage is demonstrated and reliability is to the satisfaction of the administration. Single failure criteria include:

1. Any active component or system (generators, thrusters, switchboards remote controlled valves, etc).
2. Any normally static component (cables, pipes, manual valves, etc) which is not properly documented with respect to protection.

3.6 DP EQUIPMENT CLASS 3

3.6.1 A single failure includes:

1. Items listed for class 2, and any normally static component are assumed to fail.
2. All components in any watertight compartment, from fire or flooding.
3. All components in any one fire subdivision from fire or flooding.

3.7 CLASSIFICATION SOCIETY DP NOTATION

3.7.1 Each of the main classification societies produces its own DP rules which align to different degrees with the requirements of IMO MSC 645.

3.7.2 Classification society rules are generally updated twice a year and are not applied retrospectively.

Table 3-1 Class Equivalent Notation

IMO	Class 1	Class 2	Class 3
DNV	DYNPOS-AUT DPS 1	DYNPOS-AUTR DPS 2	DYNPOS-AUTRO DPS 3
ABS	DPS-1	DPS-2	DPS-3
LRS	A	AA	AAA
GL	DP1	DP2	DP3

3.7.3 This document only considers requirements for Equipment Class 2 and Equipment Class 3. Several classification societies offer other notations. Examples of these additional notations are DNV's DYNPOS ER (Enhanced Reliability) and Germanischer Lloyd's DP3 (DP2)

3.7.4 DYNPOS ER allows greater freedom in the use of features and functions intended to improve post failure station keeping capability. For DYNPOS AUTR and DPS 3, it is accepted that a vessel with DYNPOS-AUTRO or DPS 3 notation can have alternative configurations complying with the requirements of DYNPOS AUTR or DPS 2. No additional notation is given but compliance is visible through the approved FMEA.

3.7.5 Germanischer Lloyd's DP3 (DP2) allows a DP vessel to have a dual DP notation with different worst case failure design intents and post failure DP capabilities created by applying the failure criteria for both DP2 and DP3.

3.8 FUNCTIONAL REQUIREMENTS

3.8.1 In order to meet the single failure criteria it will normally be necessary to provide:

1. For equipment class 2 - redundancy of all active components.
2. For equipment class 3 - redundancy of all components and physical separation of the components.

3.9 TIME TO TERMINATE

3.9.1 DP rules and guidelines require only that DP vessels be able to maintain station following a single failure for long enough to safely terminate the work in progress.

3.9.2 Different industrial activities have different termination times and this may influence the design of the DP system and choice of operating configuration. For example, in certain drilling activities the drilling rig can disconnect fairly rapidly and move off station in a controlled manner. In other activities a much longer time to terminate is required. Diving support, Pipelay, umbilical-lay and heavy lift activities may have longer time restrictions in some cases.

3.9.3 Industrial missions that inherently require longer duration time to terminate should consider designs that limit loss of thrust, post failure. Fuel service tank capacity thermal capacity of cooling systems or provision of HVAC are factors that could influence achieving the desired duration necessary for time to terminate.

3.10 MITIGATION OF FAILURES

3.10.1 DP rules and guidelines generally require that equipment intended to provide redundancy is available immediately and with a minimum of operator intervention. Classification societies interpret this differently and some DP notations require that the vessel must be able to hold position with the main machinery that remains operational following the worst case failure. Others accept that standby machinery may be brought online automatically. The requirement for all redundant machinery to be ‘active redundancy’ was sometimes relaxed in the case of seawater cooling systems. This was reasonable if the time taken for temperatures to reach critical levels was long. As interpretation of rule requirements changes over time it is important to clarify such issues at the redundancy concept development stage to avoid delay and rework at a later date.

3.10.2 Operator intervention can be considered as part of the failure mitigation process. In a limited number of cases operator intervention may be accepted provided there is sufficient time for the operator to act before the failure effects escalate to unacceptable levels and there are clear alarms and indication to identify the fault. ‘Drive off’ is an example of a failure effect where operator intervention is likely to be required. Unambiguous instruction and procedures should be developed for all cases where operator intervention is part of the failure mitigation. Training and drills should also form part of the confidence building measures designed to ensure the failure can be safely mitigated by operator intervention.

3.11 REDUNDANCY CONCEPT AND WORST CASE FAILURE DESIGN INTENT

3.11.1 The worst case failure design intent describes the minimum amount of propulsion and control equipment remaining operational following the worst case failure. The worst case failure design intent is used as the basis of design. Single fault tolerance is to be achieved by the provision of redundant systems. Adequate holding capability is to be achieved by provision of adequate remaining power and thrust.

3.11.2 The redundancy concept is the means by which the worst case failure design intent is achieved and should be documented as part of the preliminary design process. This is highlighted and emphasized as it determines the ability of the vessel to undertake critical activities associated with its Industrial Mission in the desired range of environmental parameters.

3.11.3 The redundancy concept and post failure DP capability should take into account the long term loss of a major item of machinery such as a generator or thruster. This is not a requirement but will aid in system availability and operational uptime for a wider range of environmental conditions. It adds flexibility in maintenance and improved efficiency. It should also be possible to account for long term unavailability in the consequence analysis.

3.11.4 Design should precede ordering of capital equipment. Long lead times for equipments such as engines or thrusters may preclude this. Features and design attributes of such pre-purchased items may influence design development and needs to be accounted for in the development of the redundancy concept.

3.12 AVAILABILITY AND POST FAILURE DP CAPABILITY

3.12.1 System availability and post failure capability strongly influences the ability of the vessel to undertake its industrial mission in a range of environmental conditions. This influences operational uptime.

3.12.2 The Worst Case Failure Design Intent (WCFDI) is the basis of DP vessel design. The Worst Case Failure is the failure that has the greatest effect on station keeping capability. A successful DP vessel design is one where the WCF achieved is less than or equal to the WCFDI. The WCF is used in the DP control system online consequence analyzer.

3.12.3 The philosophy espoused within this document strives to limit loss of thrust capacity post worst case failure. In the discussion that follows, redundancy depends on systems being available in both number and capacity to produce the required post worst case failure DP capability.

3.12.4 The redundancy concept can have a very significant impact on DP vessel design and there are several variations on how to provide a fault tolerant system. In general terms the redundancy concept is based on power and propulsion systems that are independent in respect of single point failures. That is to say no defined single point failure in one independent system will disrupt the operation of the other. Independent systems can be designed to provide full or partial redundancy.

3.12.5 An independent system is said to provide full redundancy if it can develop the necessary surge, sway and yaw forces required to maintain position and heading in the defined post worst case failure environmental conditions.

3.12.6 An independent system is said to provide partial redundancy if it can only provide the necessary surge, sway and yaw forces in combination with another independent system. For example, all independent systems may be able to provide equal surge, sway and yaw forces but more than one independent system is required to produce the level of thrust required by the defined post worst case failure DP capability. The redundancy concept must ensure that suitable combinations of systems are available following any defined failure. Alternatively one independent system may develop alongships thrust and the other athwartships thrust, thus redundancy is required in each axis.

3.12.7 The simplest diesel electric redundancy concepts have two fully redundant power and propulsion systems each capable of maintaining position and heading if the other fails. More complex designs make use of multiple systems each providing partial redundancy such that the vessel can maintain position with all combinations of independent systems that survive any defined failure. For example, a vessel with three systems can hold position with any two of the three systems available.

3.12.8 An advantage of redundancy concepts based on multiple independent systems, each providing partial redundancy, is that provided each system can develop surge, sway and yaw forces and has all necessary services required to support DP it is possible to consider these systems as providing full redundancy in reduced environmental conditions. Thus a DP system with three independent power and propulsion systems can still be considered fault tolerant if only two of the three systems are available and may be able to continue DP operations in this degraded condition if environmental conditions allow. However, it is important to establish this as a design objective as it is possible to create redundancy concepts based on partially redundant system which do not remain fully redundant with reduced capacity when one system has failed.

3.12.9 The use of multiple independent systems offers other advantages. A vessel with four independent systems can in theory remain fault tolerant up to 75% power compared to one with only two systems which can only operate up to 50% power. Thus the design based on multiple independent systems can have smaller machinery for the same post failure DP capability or use the same machinery and have a greater DP capability.

3.12.10 The redundancy concept has a strong influence on machinery sizing. Design should ensure adequate margins to accommodate increased demand for power and thrust associated with development of the detailed design.

3.12.11 A basic redundancy concept and WCFDI should be developed as a precursor to design and before orders are placed for long lead items (e.g. engines and thrusters to ensure the correct ratings are ordered.) Designers and naval architects will have established the amount of thrust required. The equipment required to provide the stipulated uptime in the expected range of operating conditions will determine the required post worst case failure DP capability. The redundancy concept will determine how that post failure DP capability is provided by establishing the number of generators and thrusters available after worst case failure. This is likely to be an iterative process influenced to some extent by the equipment that can be purchased in the expected development and construction timescale. See also Section 3.11.4.

3.12.12

3.13 EXTERNAL FACTORS

3.13.1 When considering the type of failures that can occur it is normal to consider the vessel and its DP related equipment. Influences external to the vessel can also initiate failures in the vessel's power plant and control systems. Typical external influences that must be considered include:

1. Uncommon environmental effects:
    a. Sudden squalls.
    b. Winter storms.
    c. Hurricanes
    d. Typhoons.
    e. Micro-bursts.
    f. Waterspouts.
    g. Solitons.
2. Seawater - fouling - aeration – contamination.
3. Combustion air – contamination.
4. Ventilation – contamination.
5. Fuel - contamination - microbial – water.
6. Position reference signal path (Sea and Sky).
7. Lightning.

3.14 KEY ELEMENTS OF DP SYSTEM PERFORMANCE

3.14.1 There are two key elements in DP performance:

1. Holding capability.
2. Reliability.

3.14.2 **Station keeping capability:** Is the ability of the vessel to maintain position and heading in defined environmental conditions.

3.14.3 **Component reliability:** As used in this document is the choice of individual elements of equipment or software for prolonging Mean Time Between Failure (MTBF).

3.14.4 Redundancy is provided to give the required level of reliability and comply with classification society requirements for fault tolerance. Holding capability gives the expected uptime in the intended area of operation. Redundancy applied to ensure there is no loss of position following a single fault is defined as critical redundancy. Additional equipment intended to ensure the vessel remains fault tolerant following a single failure is defined as non critical redundancy.

3.15 KEY ELEMENTS OF REDUNDANT SYSTEMS

3.15.1 There are three key elements in any redundancy concept:

1. Performance.
2. Protection.

3. Detection.

3.15.2 **Performance:** Holding capacity is fundamental to the design process. Appropriate engineering studies establish the amount of installed thrust and power generation for the environmental ranges the vessel is designed to operate in.

3.15.3 When establishing thrust requirements for ship shaped hulls, designs should not be overly reliant on keeping the bow into the weather as the design basis. This has proven inadequate in many cases, as heading often cannot be changed fast enough to follow changes in wind direction. The design should account for operations that might require a non-optimal heading including a beam environment. Experience has shown that DP MODUs, designed to cope with 70 knots of wind on the beam (zero waves or current) in an intact condition, have proved to have adequate capability to undertake operations in most environments. This is a good rough check.

3.15.4 At system and component level all equipment must be capable of its rated performance to ensure fault tolerance.

3.15.5 **Protection:** Fault tolerant systems based on redundancy require protective functions to prevent faults in one redundant system being coupled to others by way of common connections or equipment. The design should ensure all necessary protective functions are provided. Operator intervention should not be considered a protective function.

3.15.6 Protective functions exist in many different systems including DP control, automation and power generation. The drivers for applying protection may be compliance with Class Rules, safety, equipment protection or in support of the redundancy concept. Addition of a protective function should not conflict with DP redundancy. Where conflicts exist, a solution should be developed to satisfy all requirements.

3.15.7 **Detection:** Equipment intended to provide redundancy must be available in both number and capacity. The design must include means to detect reduction in capability or unavailability. Redundant components should be immediately available and with such capacity that DP operations can be continued for long enough to safely terminate the work in progress.

3.16 COMMUNICATING AND SUPPORTING THE REDUNDANCY CONCEPT

3.16.1 Once the preliminary redundancy concept has been developed it is important that it be communicated to all stakeholders and understood. As a minimum the stakeholders should include:

1. Shipyard.
2. Classification societies.
3. DP control system provider.
4. Automation system provider.
5. Power system provider.
6. Propulsion system provider.
7. Integrators if applicable.
8. FMEA contractor.

9. Vessel owner's site team.
10. Crew.
11. Charterer if applicable.

3.16.2 Interface issues between various vendors should be carefully managed. Responsibility for this may lie with the shipyard or owner's team depending on the nature of the contract. Responsibility should be clearly defined, identified and made visible.

3.16.3 It is important to concurrently develop vessel specific Inspection, Repair and Maintenance (IRM) procedures, operating procedures, guidelines and reference materials such as DP Operations Manuals to develop and support the redundancy concept. Supporting documentation may include Activity / Well Specific Operating Guidelines (A/WSOG) and Thruster and Generator Operating Strategy (TAGOS).

3.17 CONNECTIONS BETWEEN REDUNDANT SYSTEMS

3.17.1 Experience suggests that common connections between systems intended to provide redundancy create the paths by which a fault in one redundant system may affect another independent system. Some connection points are unavoidable such as remote control systems, and may be beneficial to the design. Where common points exist between redundant systems, risk assessments on impacts of failure propagation should be carried out, documented in the FMEA and adequately mitigated.

3.18 MULTIPLE POWER PLANT CONFIGURATIONS

3.18.1 Diesel electric plant design should incorporate configuration flexibility to cope with equipment unavailability. (e.g. failures or equipment taken down for maintenance) However, it is important that the effect of such reconfigurations are understood as some may not be redundant. Major configurations should be identified and analyzed in the vessel's DP system FMEA to prove the DP system remains redundant. Fault tolerance of configurations should be made visible and understood by the crew. Where there is configuration flexibility in the design, the Critical Activity Mode of Operation (CAMO) should be clearly defined in addition to other Task Appropriate Modes (TAM) for use on DP with any additional risks made visible. For example, some task appropriate modes may rely more heavily on protective functions than others.

3.18.2 It may not be practical to consider every possible variation particularly in vessels that have complex power distributions systems and some classification societies state that the vessel is only considered to comply with their requirements for the DP notation when operated in one of the configurations analyzed in the approved FMEA. Vessels with complex power distribution systems should consider the most likely configurations that the vessel will be operated in and have them analyzed in the FMEA. If there is a need to operate in a configuration that is not addressed in the FMEA, it may be necessary to supplement the FMEA with additional analysis and tests to confirm the level of redundancy provided by the intended configuration. This will be required if verification of class compliance is required.

3.19 CRITICAL AND NON CRITICAL REDUNDANCY

3.19.1 Class rules require DP systems to be redundant with the primary objective of achieving no loss of position. However, redundancy in itself does not guarantee a particular level of reliability. Loss of fault tolerance could cause operational issues impacting the industrial mission of the vessel. Where aspects of the design are identified as being of lower reliability or there is a need to ensure higher availability it may be beneficial to provide redundancy over and above that required to meet class requirements.

1. Critical redundancy is defined as equipment required to ensure the vessel is single fault tolerant. To remove such equipment would either remove the DP system's fault tolerance entirely or reduce its post failure DP capability.
2. Non critical redundancy is equipment intended to provide greater availability.

3.19.2 If redundant elements are highly reliable, there is no need for non critical redundancy but it can be usefully applied to allow maintenance or in cases where it is uneconomical or impractical to increase the reliability further.

3.20 AUTONOMY AND DECENTRALIZATION

3.20.1 Modern DP vessels are complex machines with several layers of automation. Experience suggests that there are benefits to be derived from making generators and thrusters independent in the provision of auxiliary support services and control functions. Designs should be resistant to internal and external common cause and common mode failures. Designs in which the control function has been decentralized are considered to be more fault tolerant. In such designs, each major item of machinery is responsible for making itself ready for operation and ensuring that all necessary services are online. In general, control system failure effects are less likely to exceed loss of the associated engine or thruster. It can be more difficult to prove that the effects of failures in centralized systems do not exceed the worst case failure design intent. This is an important consideration when choosing a control system topology for fault tolerant systems. There is still a requirement for a remote control system in decentralized designs but the functions of this control layer are limited to scheduling and remote manual control.

3.21 ORTHOGONALITY, DIVERSITY AND DIFFERENTIATION

3.21.1 Diversity is a desirable property in the design of fault tolerant systems based on redundancy. Different degrees of diversity are possible such as choosing equipment from different suppliers or using different principles of operation (orthogonal design).

3.21.2 In the field of reliability engineering the term orthogonal design indicates that a completely different method has been used to provide redundancy from that used as the primary method. Orthogonality by design reduces the risk of common mode failures in redundant systems compared to systems using identical redundant elements.

3.21.3 DP class rules require orthogonality in measurement methods used for position references. A minimum of three position references are required for DP class 2 and DP class 3. Two of these three should be based on different measurement principles.

3.21.4 It is good practice to have orthogonality in sensors such as gyros, anemometers and MRUs. Different measurement principles (orthogonality) offers the greatest advantages but where this is not practical a diversity of manufacturers is desirable.

3.21.5 Differentiation can reduce the risk of common mode failures. Differentiation can be achieved on redundant position reference systems operating on the same principle by combining one of the position references with position information from an inertial navigation systems to create Inertial Aided Navigation (IAN). (e.g. dual DGNSS or dual acoustics). IAN changes the characteristics of how the reference behaves and minimizes the probability of both (IAN and non IAN) systems being rejected.

3.22 COST EFFECTIVE RISK REDUCTION

3.22.1 When the redundancy concept is developed there will be a number of failures that have a severity equal to the worst case failure design intent (WCFDI). Design should focus on minimizing the number of failures equal to the WCFDI. These failures should be reviewed to determine whether a cost effective improvement can be made. When considering cost benefit analysis it is the lifecycle cost that should be considered including the penalties for non availability. For example, the worst case failure design intent for a particular vessel accepts that three out of six generators may be lost as the result of a single failure. The design is such that this failure effect may occur because of a main switchboard bus bar failure or because a 24Vdc power supply fails. Given the relative probabilities of failure it may be cost effective to provide a second 24Vdc power supply or possibly one for each generator. This would reduce the severity of the failure effect associated with the 24Vdc supply system.

3.23 ENHANCING CLASS MINIMUM STANDARD

3.23.1 Classification society rules are generally intended to provide a minimum technical standard. The Industrial mission and desire to achieve greater availability may influence vessel owners to exceed the minimum requirements and improve reliability, operability and maintainability. Vessel owners should be aware that any such improvements to the DP system need to be expressly agreed in the shipyard contract for the vessel. The default position for shipyards is to meet class requirements. Where the owner wishes to apply a different worst case failure design intent to some aspect of the redundancy concept over and above that required by class this needs to be agreed to and reflected in the contract. If the shipyard contract only requires the design to meet class requirements the additional features may not be provided. For example, the redundancy concept for a DP class 3 vessel may accept that that three of six generators are be lost because of an engine room fire but the owner wishes to limit the effects of technical failures to loss of a single engine or thruster. Class 2 DP rules allow all generators to be located in a single space. Many vessel owners prefer to have two or more engine rooms. Such arrangements limit the risk from crank case explosions and engine room fires and other risks such as flying debris.

3.23.2 A fully automatic blackout recovery system is not a class requirement. Main class rules and SOLAS have requirements for some degree of automatic restart of electric power systems but for a DP vessel it may be unwise to rely on this to ensure a full blackout recovery system is provided. A fully automatic black out recovery system can be supplied by all the major marine automation providers and should be specified by vessel owners. Modern blackout recovery systems can typically restore thrust in less than one minute from blackout. DYNPOS ER has higher requirements for automatic blackout recovery compared to traditional DP notations.

3.23.3 The classification society may limit its plan approval process to proving compliance with the worst case failure arising from application of the failure criteria defined in the rules appropriate to the DP notation being sought (e.g. fire or flooding). The FMEA and proving trials should cover the redundancy concept and worst case failure design intent at all levels in addition to addressing class requirements. The contract with the shipyard should expressly stipulate this. Consideration could also be given to stipulating the choice of FMEA vendor if the owner or charterer has a preference. Class will accept an FMEA commissioned or carried out by the shipyard.

3.24 INFLUENCE OF THE VESSEL'S INDUSTRIAL MISSION

3.24.1 Dynamic positioning is provided to allow the vessel to carry out its industrial function such as drilling, pipe laying, or heavy lifting. In diesel electric designs based on the power station concept, the electric power systems supply all power for propulsion, hotel, auxiliary systems and the consumers associated with the vessel's industrial mission. There may be competing requirements for power between station keeping and the industrial function. This needs to be defined and carefully managed to ensure the propulsion system has access to the power it needs to prevent loss of position in the range of environmental conditions the vessel is operating in. The requirements of the industrial consumers may dictate or favor a particular power plant configuration. Such configurations should not conflict with the redundancy concept or compromise the industrial mission.

3.24.2 Rules for DP notations are intended to ensure a satisfactory level of station keeping integrity. They do not specifically address the vessel's industrial mission so it is important when specifying the DP system to ensure that it has all the appropriate features and functions required to carry out its mission effectively. For example, number and type of position reference systems should be appropriate to the type of work to be carried out. In the case of multi purpose DP vessels, design should consider systems appropriate to all types of work that may be required of a vessel.

3.25 REGULATORY REQUIREMENTS

3.25.1 Although IMO MSC 645 is intended to provide an international standard, compliance with this standard or rules for DP notations do not guarantee compliance with other regulatory requirements imposed by flag and coastal states. For example, requirements related to environmental legislation such as emission control may be difficult to reconcile with requirements for active redundancy contained in DP rules (DYNPOS ER differs from traditional DP notations in this respect). Operating large diesel engines at low load levels is inefficient and may not achieve the gas temperature required for exhaust gas scrubbers to work efficiently. Asymmetric thruster loading of independent power systems may assist to some extent. Thruster bias can similarly be used to increase load levels which consumes more fuel. It is a challenge to reconcile a scheme that requires burning more fuel with an environmentally conscious policy.

3.25.2 A low loss worst case failure design intent allows the power plant to be much more heavily loaded than the class minimum of a two way split. This is of benefit in the efficient operation of pollution control equipment. A larger number of smaller generators can assist in addressing this issue. If the power consumers related to the vessel's industrial mission are large these can be used in such a way that the power plant is operated efficiently provided there are effective means to shed load when power is required for station keeping either as a result of deteriorating weather or partial power plant failure.

4 CAPABILITY

4.1 INITIAL DESIGN PROCESS

4.1.1 It should be recognized that Classification Rules or Regulations do not specify the station keeping capability of DP vessels.

4.1.2 The first step in the design process is to establish the desired capability and is typically stipulated by the owner. Achieving the required capability is an iterative process during design and should be carried out to establish amount of thrust and power to be installed. The following should be taken into consideration:

1. Industrial Mission of the vessel.
2. Objectives to be achieved (Operational uptime, limiting loss of post failure thrust capability).
3. Environmental parameters under which the Industrial mission is to be undertaken.
4. Transit capability desired.
5. Limitations imposed by:
   - Hull form (impacts on wind and current drag coefficients, thruster to thruster and thruster to hull interaction).
   - Environment (current inflow and impact on thrust).

4.1.3 A robust iterative process as described above should result in well designed vessel with matched power plant (station keeping and industrial mission requirements being met) capable of accomplishing its industrial mission.

4.1.4 The Holding Capability of a vessel is depicted in capability plots. IMCA M 140 addresses specification for capability plots.

4.1.5 Online capability plots are capable of being provided by DP equipment manufacturers. This is a desirable feature and should be specified.

4.2 CAPABILITY PLOTS

4.2.1 The station keeping capability of a DP vessel is not covered by any rules or regulations. It is typically determined or specified by the owner of the vessel. The capability, however, must be demonstrated by submittals to the classification body. Upon approval, the capability documentation will become a part of the vessel's operating manual and describes the limits of operation of the vessel.

4.2.2 The station keeping capability of the DP vessel is typically presented as a set of polar plots indicating the performance of the vessel under certain environmental and, in some cases, operational conditions. The environmental conditions include the forces due to wind, current and waves. Capability plots should take into account changes in the wind or drag coefficients caused by execution of industrial functions. e.g. pipe tension, heavy lift drag, hawser tension, etc.

4.2.3 A capability plot is an analytical presentation of the vessel's performance during station keeping operations while exposed to external forces - environmental forces such as wind, current, and waves - as well as external force generated by industrial mission of the vessel. Capability plots do not indicate the excursions of the vessel. They represent analysis of the equilibrium of the steady-state forces and moments of the vessel and establish the static holding capabilities. A dynamic time-domain simulation is not required by the classification societies.

4.2.4 If an alternate centre of rotation (other than centre of gravity / centre of vessel) is contemplated as a means to undertake the industrial mission, capability plots should be developed for this condition for both intact and post worst case failure scenarios.

4.3 ENVIRONMENTAL FORCES

4.3.1 The plots should be generated for environmental events controlling the limits of DP operations that are likely to occur at the anticipated sites of operation. Maximum predicted combinations of current and wind speed with associated wave height and period should be considered.

4.3.2 The classification societies require that the plots should be generated assuming that the environmental forces are imposed on the vessel collinearly and concurrently.

4.3.3 It may be necessary to generate capability plots that consider other combinations of wave and wind direction specific to the area of operation.

4.4 THRUSTERS

4.4.1 The thrusters generate the counter forces necessary to establish the force equilibrium. A realistic assessment of the actual thruster net forces acting on the vessel is a prerequisite for accurate polar plots.

4.4.2 The following should be considered when assessing actual thruster net forces:

1. The basic thruster performance data should be based on sound hydrodynamic principles, not on marketing considerations.
2. The thruster data used for generating capability plots at different current inflow velocities should be based on performance curves for that inflow velocity. Using bollard pull data which is usually based at zero inflow velocity leads to inaccuracies.
3. The potential impact of current inflow on thrusters that are not aligned with inflow should be considered.
4. The thruster performance data provided is usually for open water conditions. Thruster data used for station keeping calculations should account for thruster to hull interaction losses. The magnitude of the losses is a function of the hull shape, thruster location, degree of tilt of the propeller or nozzle axis, etc.
5. ‘Barred zones’ prevent thrust in defined sectors. These zones can be created in the DP control system software to address issues associated with thruster wash for azimuthing thrusters. Such barred zones may result in reduced capability. Typically, the arc of this sector is small and the associated losses are a few percent of the nominal thrust.

4.5 CAPABILITY PLOTS FOR INTACT AND FAILURE CASES

4.5.1 Capability plots should be developed for multiple cases based on the specific vessel configuration. The following cases are offered as an example.

1. Intact - All thrusters are available.
2. Failure mode 1- One thruster not available (selecting the worst case).
3. Failure mode 2- Two thrusters not available (selecting the worst case).
4. Failure mode 3 - Worst Case Failure Design Intent.

4.5.2 Other thruster configurations may be investigated if warranted.

4.5.3 Capability plots should consider the influence of the power plant,(including limitations if any) and power available to the thrusters not just rated capacity.

4.6 PRESENTATION OF CAPABILITY PLOTS

4.6.1 Capability plots should be easy to understand, comprehensive and informative.

4.6.2 Several types of static plots are common in the industry. Dynamic plots are a recent phenomenon, this section addresses static plots.

4.7 BASIC PLOTS

4.7.1 This is the most common type of plot. It presents the maximum (only) capability of the vessel under certain environmental conditions and intact/failure modes and could be used during the preliminary design phase.

4.7.2 Typically, one environmental criteria (e.g., current velocity) is selected for the plot, together with intact or failure mode data. The resulting plot indicates the maximum station keeping capability of the vessel for the remaining environmental forces (e.g., wind and associated waves for a given, predetermined relationship between wind velocity and waves) over an environmental force incident angle of 0-360 degrees. These types of plots are valid only for the assumed relationship between wind velocity and wave data and consequently apply only for one particular operational region.

4.7.3 These plots typically do not consider the influence of the power plant. It is recommended that an iterative process be carried out to validate the basic capability plots once the power plant design is available. The validity of these plots depends upon the accuracy of the power plant data which is in turn dependent on knowledge of the capacity and efficiency of all components of the power plant and thruster drives.

4.8 COMPREHENSIVE PLOTS

4.8.1 These types of plots allow an individual input of wind, current and wave data (in magnitude and direction) and display the power required for the thrusters over 360 degree heading angle of the vessel. These plots allow the selection of optimum heading angles, and indicate the exact power levels for the thrusters which is a valuable tool for the optimized operation of the vessel. The validity of these plots depends upon the accuracy of the power plant data which is in turn dependent on knowledge of the efficiency of all components of the power plant and thruster drives.

5 MODELING

5.1 SCOPE OF MODELING

5.1.1 Modeling as referenced in this section addresses pertinent topics related to design in the following areas:

1. Naval Architecture.
2. Power and Safety Systems.
3. Operability Parameters.

5.2 NAVAL ARCHITECTURE

5.2.1 Modeling in Naval Architecture can be accomplished in the following three ways:

1. Modeling by example (prior example - build like before).
2. Analytical modeling.
3. Hull form modeling.

5.3 MODELING BY EXAMPLE

5.3.1 Prior example is the simplest modeling technique. In this method an existing design with validated performance characteristics is used. Prior example could be effective when replication allows cost and schedule benefits without compromising the performance of the industrial mission.

5.3.2 Designing by prior example may preclude opportunities for improvement. When opportunities for improvement are pursued as an objective, it should be accompanied by a robust MOC process. It is important to consider the impact in differences between applications and avoid replicating any inherent weaknesses in the design.

5.4 ANALYTICAL MODELING

5.4.1 Use of analytical modeling, early in design, facilitates delivery of a robust vessel. Advances in computing technology have resulted in effective tools capable of aiding design decisions (e.g. Computational Fluid Dynamics (CFD), optimization of tilt of azimuthing thrusters)

5.4.2 Analytical modeling could be used as a technique to aid in establishing preliminary thrust requirements for further iterations in the design cycle. (Station keeping capability)

5.5 HULL FORM MODELING

5.5.1 Hull form modeling for DP vessel design is suggested when:

1. Validation of Analytical Modeling data is warranted.
2. Novel hull forms or prototypes are being considered.

5.5.2 Hull form modeling is accomplished at:

1. Test Basins

2. Wind tunnels (to establish wind and current drag coefficients)

5.5.3 Hull form modeling for non prototype/ non novel vessels, as the primary means of establishing station keeping performance, delivers limited value due to cost, scaling factors, and availability of alternate means of establishing equivalent data.

5.5.4 Information availability on station keeping performance is usually the driver to initiate hull form modeling. This information can be established by analytical modeling.

5.6 POWER AND SAFETY SYSTEMS

5.6.1 **Power systems:** Advances in computing technology have facilitated the ability to accurately model power plants:

1. Stability.
2. Harmonics.
3. Resonance.
4. Protection coordination.
5. Short circuit withstand capability.
6. Load analysis.

5.6.2 Adopting these techniques in the design phase enables delivery of a fault tolerant/fault resistant system capable of meeting station keeping requirements and the industrial mission of the vessel.

5.6.3 **Safety systems:** Advances in computing technology have facilitated the ability to use modeling as an effective technique to:

1. Analyze Major Events (e.g. gas dispersion studies)
2. Safety Integrity Levels (SIL) (Establishing and analyzing Cause and Effects Matrix for ESD systems, ability to carry out “what if analysis”)

Modeling techniques mentioned above provide design support and can be carried into operations by facilitating decision support.

5.7 OPERABILITY PARAMETERS

5.7.1 The ability of the vessel to carry out its industrial mission is dependent on the respective vessel motions in addition to its station keeping capability. The optimum heading for reducing thrust for station keeping may not be the optimum heading to be within the limits for motions to carry out the Industrial mission. Modeling to establish RAOs (Response Amplitude Operators), during the iterative design process for determining thrust requirements, aids in decisions such as evaluating the benefits of additional thrust versus potential mission uptime

5.8 PRIOR EXAMPLE

5.8.1 Prior example is the cleanest form of modeling. It is effective when performance expectations are met and relies on replication in the following areas:

1. Vessel hull form.

2. Range of environmental conditions.
3. Industrial mission.

5.8.2 It offers the following advantages:

1. Costs for engineering and design are far less.
2. There is high probability that it will work and perform to expectations.
3. Reduced construction time if replication is extended to the yard and project team.

5.8.3 Care should be taken to avoid replicating mistakes.

5.8.4 There are many issues that can make use of prior example inappropriate. For example, a change of mission, deeper water, mixing of drilling and construction functions and most of all advancing technology.

5.9 ANALYTICAL MODELING

5.9.1 Analytical modeling is an effective tool to aid design.

5.9.2 There are well established techniques and equations that allow calculation of wind drag, wave drift force and current drag on a vessel from all directions. Guidance on calculation is provided in API RP 2 SK and can be used to calculate the thrust requirements for a DP vessel. These values are used as the starting point for DP control system tuning. Final values are established as the result of the tuning effort.

5.9.3 The ability to carry out numerical analysis has been enhanced by the use of modern computers. Numerical analysis can be used to model dispersion of thruster wakes and losses from all forms of the Coanda effect. Such modeling has aided in the optimization of the tilt down angle for thrusters to minimize loss of thrust.

5.10 PHYSICAL HULL FORM MODELING

5.10.1 Test basins were the only established form of physical hull form modeling until the advent of wind tunnels. After accounting for scale and viscosity, testing of a small model of a large hull in a wind tunnel can yield comparable results to test basin.

5.10.2 Test basins are generally used to establish:

1. Expected vessel motions in different sea states including green water impacts.
2. Expected speed in different sea states.

5.10.3 Test basins have been used to validate DP station keeping capability. The intent was to measure how tightly the vessel is able to hold position on DP using a particular DP control system. While this is a question asked by those new to DP, the results (test basin and full scale test) have shown that most DP control system can maintain position to within a meter in calm weather and a few meters in rough weather. That is up to the point where the available thrust is exceeded when the vessel will drift at a rate proportional to the exceedence of the weather against the available thrust.

5.11 POWER SYSTEMS

5.11.1 Advances in computing technology have facilitated the ability to accurately model a power plant. As a minimum, the following studies should be included:

1. Transient stability - The ability of generators to remain in synchronism following power system transients.
2. Harmonics and resonance - To confirm levels of power system harmonics remain within acceptable values.
3. Protection coordination - The ability of a protection scheme to isolate a fault at source.
4. Load analysis - To confirm all power sources are capable of supplying the expected load.
5. Short circuit withstand and breaking capacity of switchboards and switchgear.

5.11.2 It should be noted that power system studies for class notation do not necessarily cover the full range of failure modes that may be experienced.

5.11.3 The faults listed below are some examples that may not be addressed from the perspective of maintaining continuity of electrical supply.

1. Over voltage, under voltage.
2. Over frequency, under frequency.
3. Earth fault.

5.11.4 Requirements from class, if any, are focused on protecting personnel and equipment and do not address the needs of the industrial mission.

5.11.5 Addressing the full range of power plant failure modes in appropriate studies during the design phase aids delivery of a fault tolerant/ fault resistant system capable of meeting the station keeping needs and the industrial mission of the vessel.

5.12 OPERABILITY PARAMETERS

5.12.1 The ability of the vessel to carry out its industrial mission is dependent on vessel motions in addition to its station keeping capability. The optimum heading for reducing thrust for station keeping may not be the optimum heading to restrict vessel motions to the maximum allowed for the Industrial mission. Modeling to establish RAOs during the iterative design process of determining thrust requirements, aids in decisions evaluating benefits of additional thrust to increase potential mission uptime.

5.12.2 Umbilical lay vessels experience similar issues. In this case the governing factor is restrictions on vessel heading rather than vessel motions.

6 MANAGEMENT OF CHANGE IN DESIGN (MOC)

6.1 REQUIREMENTS FOR MOC

6.1.1 A robust Management of Change Process should be established at the concept phase, implemented systematically and followed diligently throughout the Project life cycle. The MOC process should be in place prior to finalizing the redundancy concept for the vessel. Any changes to the redundancy concept should be subjected to the MOC process.

6.1.2 Integrity of the MOC process should be maintained, communicated and used effectively. All stakeholders should have ownership in the process. Rationalization of changes by specific disciplines should be avoided as changes may impact other disciplines.

6.1.3 Any changes to the redundancy concept should be subjected to the MOC process.

6.1.4 Changes to the redundancy concept are relatively rare but when they occur they can have a broad effect on vessel design. For example:

1. Changes to the vessel industrial mission.
2. Changes to the desired post failure capability of the vessel that changes the redundancy split say from a two way split to a four way split (to reduce the impact of the worse case failure).

6.1.5 MOC should identify all the design changes required so that the vessel’s revised design will comply with the new redundancy concept.

6.1.6 Changes in the design that violate the redundancy concept are more common. Diligent application of the MOC process could aid in avoiding such violations.

6.1.7 Configuration changes to DP control systems and other equipment with software (e.g. automatic power management systems) are particular examples of failure to apply the. MOC process.

6.2 MOC EXAMPLES

1. Vessel moves to a new work location where a different setup is required for the acoustic position references to accommodate SIMOPS with several vessels (Wide band). Failure to control the change in working location under the MOC process could result in degraded position reference status in that location.
2. A drilling vessel was originally equipped with two DGNSS. Modifications were made to add several more DGNSS without understanding the consequence of relying so heavily on the DGNSS as a reference to the detriment of the hydro acoustic references.
3. To solve an unrelated reliability problem, a thruster drive manufacture adds an under-voltage trip to a thruster variable speed drive without fully understanding the consequences for the redundancy concept. This modification removed the drive’s voltage dip ride through capability leading to multiple loss of thrusters when short circuit fault occurred in the power distribution system.
4. An ESD system was fitted to a MODU without a systems engineering approach resulting in a design which introduced single point failures. A blackout occurred when the ESD system failed.

5. Operational impact of working in shallower water depth not understood and appropriate barriers (equipment and procedures) not implemented.

7 THRUSTERS

7.1 PRINCIPLES

7.1.1 Thrusters as referenced in this section means propulsion to achieve:

1. Transit.
2. Station keeping using dynamic positioning.

7.1.2 Designers of DP vessel propulsion systems should incorporate the following principles in design:

1. Robustness.
2. Reliability.
3. Simplicity.
4. Redundancy.
5. Efficiency.
6. Maintainability (routine and intrusive IRM).
7. World Wide Operations (temperature ranges, ice).

7.2 PROPULSION CHOICES

7.2.1 Propulsion system choices are mainly threefold:

1. Azimuthing propulsors & cycloidal.
2. Fixed direction propulsors.
3. Vessels using a combination of fixed and azimuthing propulsors.

7.2.2 When choosing propulsors during the design phase, the following should be taken into account:

1. Reliability.
2. Service intervals.
3. The industrial mission (station keeping versus transit requirements).
4. Desired hydrodynamic aspects.
5. Number of thrusters with respect to post failure thrust capability and ability to exercise control in surge, sway and yaw axis..
6. Location and geometric arrangement.
7. Installation and maintainability methodology over life cycle of vessel - Service access (keel haul, dry dock, retractable).
8. Influence of the hull form.
9. Drive system.
10. Control of thrust.
11. Regulatory requirements for dry docking of vessels with tail shafts.
12. Draught restrictions.

7.2.3 The impact on the Industrial mission and the stated objectives due to a loss/reduction of thrust following a failure event should be recognized and carried through all phases of the design cycle. Particular attention is to be bestowed on:

1. Seals.
2. Auxiliary systems (principles of independence to be followed).
3. Ease of maintenance.
4. Specification and testing of key components (e.g. gears).
5. Impacts of vibration.
6. Introduction of vulnerabilities to thrusters not in use during transit.
7. Life extension of components and thruster.

7.2.4 Incorporating non critical redundancy into identified elements of the propulsion systems could aid in mission uptime. Robust FMEA/FMECA techniques can aid in identifying such key elements.

7.2.5 There has been a noticeable reduction in failure rates of thrusters since the introduction of variable frequency drives (VFDs) with fixed pitch propellers. VFDs facilitate fast phase back capability, a key feature to prevent power plant instability.

7.3 DESIGN BASIS CRITERIA

7.3.1 A DP vessel is subjected to environmental forces such as wind, waves, and current. In order to maintain a certain position, these forces have to be counteracted by the vessel's propulsors.

7.3.2 The dynamically positioned vessel has to be able to provide the forces required to execute maneuvers in surge, sway, and yaw. The total forces must be controllable in magnitude from zero to full power, and in direction through 360 degrees.

7.3.3 A variety of propulsor options are available to generate thrust for station keeping.

7.3.4 The propulsion system of a typical DP vessel has to be developed to comply with the following mission requirements:

1. Transit over extensive distances.
2. Optimum speed (typically12-14 knots for ship-shaped vessels and 5-7 knots for semisubmersibles).
3. Station keeping for extended time periods.

7.3.5 The following **design basis criteria** should be applied by the designers of the propulsion system:

1. Robustness.
2. Reliability.
3. Simplicity.
4. Redundancy.
5. Efficiency.
6. Maintainability of systems without outside support or dry docking.

7.4 PROPULSION CONCEPTS

1. Azimuthing propulsors.
2. Fixed direction propulsors.
3. Hybrid concepts utilizing a combination of azimuth thrusters and fixed-direction thrusters.

7.4.1 The characteristics of propulsors are outlined in the table below:

Table 7-1 Propulsor Characteristics

TYPE	APPLICATION	ADVANTAGES	DISADVANTAGES
Propulsors with fixed direction of thrust			
In-Line Conventional propulsion systems	Used widely for transit as well as station keeping (providing thrust in longitudinal direction) on ship shaped DP vessels (OSV's, diving support vessels, pipe-laying vessels, older generation of drill vessels)	Simple, reliable, robust and proven system. Very low maintenance, highly efficient for DP when equipped with ducted propellers	Requires reverse gear or CP propeller to change direction from AHEAD to ASTERN. Additional thrusters needed for transverse thrust forward and aft. Efficiency reduced in reverse operations
Transverse Tunnel Thrusters	Installed in the bow and/or stern of vessels to provide transverse thrust and forces for yaw manoeuvres	Simple installation inside a transverse tunnel in the hull. Well protected; hydrodynamically smooth uniform operation; long life	Mediocre performance (depending on length of the tunnel, tunnel exit/entrance configuration). For fixed pitch propellers, reversing of the sense of rotation is required to change the direction thrust. No access for maintenance. Removal/installation requires drydocking in most cases; may lose thrust during heavy motions of the

TYPE	APPLICATION	ADVANTAGES	DISADVANTAGES
Ducted transverse thrusters	Installed below the hull, forward and aft to provide transverse thrust; mostly installed in retractable containers. Bi directional ducts and propellers generate equal amounts of thrust in both transverse direction. Many successful installations on first generation DP drill vessels	High performance in both directions. Simple and robust design. Access for maintenance after retracting the assembly	For fixed pitch propellers, reversing of the sense of rotation is required to change the direction of the thrust.
Propulsors with directional control of thrust			
Azimuth thrusters	Most popular thrusters applied for transit as well as stationkeeping for DP MODU's (Mono hull and column stabilized) Typically installed under the bottom of the hull thus increasing the draft of the vessel, Smaller ship shaped DP vessel (OSV's etc) uses azimuth thrusters installed in the skeg of the vessel (above the base line). Installation forward requires retractable azimuth thrusters to minimize draft during transit	Reliable proven designs, High performance. Bottom mounted thrusters are accessible for maintenance after underwater removal, No drydocking required for maintenance. Containerized azimuth thrusters:- This thruster is installed in a watertight container which encloses the drive motor and the auxiliary systems. The entire container is retractable to a position above the waterline at which servicing the thruster is feasible. This is the optimum installation for DP application if achievable.	Underwater installation and removal complicated and time consuming. Requires support vessels in many cases. Retractable azimuth thrusters (without containers) are mechanically complex, expensive, require a high degree of maintenance. Access typically only during dry-docking. Custom dock preparations necessary
Voith Schneider propellers (VSP)	A very special type of propulsor applicable for DP operations. It is a	The VSP is an ideal propulsor for DP combining the propeller characteristic of a	The mechanical complexity, high costs, and maintenance of a large diameter seal, limit the application to low draft vessels

TYPE	APPLICATION	ADVANTAGES	DISADVANTAGES
	cycloidal propeller operating on a vertical axis.	controllable pitch propeller combined with control of the direction of thrust through 360 degrees. Allows step less control of thrust in magnitude and direction. Can be supplied with integral active anti-roll system.	and usually for specialized applications.

7.5 LOCATION AND GEOMETRICAL ARRANGEMENT OF THE PROPULSORS

7.5.1 The layout of the thrusters should be such that effective thrust can be generated in surge, sway and yaw in both intact and post worst case failure conditions. Effective thrust capability is dependent on the lever arms. This should be taken into consideration during the design phase. Location of thrusters should be optimized and is dependent on the hull geometry.

7.5.2 For a monohull, the most onerous criteria for the assessment of the DP capability of a vessel are its performance when exposed to environmental forces from the beam direction. A vessel which excels in this condition typically performs well in any other situation. Care should be exercised when assessing DP capability of a vessel where a portion of the thrust is required to carry out the industrial mission (for example thrust to overcome bottom tension on a S-Lay pipe lay vessel.

7.5.3 For effective counter forces against wind, the size (capability) of the thrusters should be approximately proportional to the windage area at the area of installation. In other words, a vessel with a high superstructure forward requires the installation of adequately sized thrusters forward. Failure to follow this basic design philosophy introduces the potential to lose station in conditions where the wind velocity and direction is shifting rapidly (numerous instances of occurrence in the Gulf of Mexico).

7.6 THRUSTER-THRUSTER INTERACTION

7.6.1 In order to minimize negative effects caused by thrusters interacting hydro-dynamically with each other, the distance between thrusters should be maximized to the extent feasible.

7.7 THRUSTER- HULL INTERACTION

7.7.1 The operation of a thruster in the vicinity of a body such as the vessel's hull may result in interaction effects resulting in a reduction of effective thrust. The tilting of the nozzle or (better) of the propeller axis several (optimum approximately 7 to 8 degrees) reduces the interaction losses noticeably. In addition, this also reduces the thruster-thruster interaction losses.

7.8 HYDROPHONE INTERACTION

7.8.1 For DP vessels equipped with acoustic equipment installed under the hull, an interference of the thruster wake (jet) and the hydrophones should be avoided.

7.9 MINIMUM NUMBER OF THRUSTERS

7.9.1 The number of thrusters should be determined by:

1. The ability to develop forces in surge, sway and yaw post worst case failure.
2. Classification society requirements for redundancy post worst case failure.
3. The desired post failure DP capability for the industrial mission.
4. Maintenance considerations - maintaining redundancy for both intact and post worst case failure conditions when a thruster is taken out of service for IRM. For example, a scenario where a vessel with a four thruster configuration where power distribution is such that two of them come off each switchboard. When one thruster is required to be taken out of service - post worst case failure capability is reduced to one thruster and vessel may not be able to maintain station.

7.10 THRUSTER HANDLING REQUIREMENTS OVER LIFECYCLE

7.10.1 The choice of handling options should be made during the design phase taking into account the industrial mission over the lifecycle of the vessel. A variety of handling options are available:

1. For below hull azimuthing thrusters, the underwater mountable and removal feature should be considered if dictated by the industrial mission. Handling aids should be designed for the range of environmental conditions contemplated for this activity.
2. Thrusters installed in capsules which are retractable inside the hull allow access for minor repairs, e.g. service to the propeller shaft seals.
3. Access to non retractable thrusters may require dry docking the vessel or provision of special arrangements to facilitate intrusive maintenance (for example habitats) or special docking arrangements to allow lowering of the thrusters inside the dock.

7.11 BASIC THRUSTER HYDRODYNAMIC ASPECTS

7.11.1 Thruster design requirements for DP operations may conflict with those of transit:

1. Thrusters for station keeping are normally designed to operate in zero or low velocity inflow conditions. Optimizing the thruster design for this condition leads to a thruster with a large propeller diameter turning at a relatively low rpm. Thrusters exclusively applied for station keeping should be designed with these features.
2. Thrusters for transit are normally designed to operate at high inflow velocities leading to propellers with smaller diameters turning at higher rpm.
3. For applications which require the thrusters to provide thrust for station keeping and for transit operations (e.g. DP drill vessels, DP OSVs), the thrusters should be designed for the best compromise between the two operating scenarios.

7.12 THRUSTER DRIVE SYSTEMS

7.12.1 Thruster drive systems can be:

1. Electric motors - AC induction, synchronous, DC (less frequently used).
2. Hydraulic motors.
3. Direct drive by diesel engine.

7.12.2 Electric motor driven thrusters are most common in DP service. Thrusters that are driven directly by diesel engines are common in logistics vessels. Some vessels are outfitted with thrusters powered by hydraulic motors.

7.12.3 Most modern day electric motors for thrusters are powered by AC variable speed drives. The characteristics of these drives are a good match to the characteristic of a propeller. The drive system is capable of delivering a constant maximum power over a certain rpm range of the motor (approximately + 10 to 15% of the base rpm). This feature is similar to the field weakening feature of older DC/SCR controlled systems; however, it utilizes simpler components (i.e. motors) and operates at higher efficiencies.

7.12.4 A thruster drive system for a DP semisubmersible, for instance, can be designed to deliver maximum power to the thruster over the entire operating range of the vessel. In this case, the thruster propeller pitch is selected for bollard pull. By increasing the rpm (by field weakening), full power is available even at a transit speed of 5 to 7 knots.

7.12.5 For a typical DP monohull vessel, the operating range is too large to utilize the field weakening effectively. The propeller pitch has to be optimized between bollard pull and transit to deliver an effective thruster.

7.12.6 Thrusters (or in-line main propellers) with fixed pitch propellers driven directly or through a reduction or reverse/reduction gear by Diesel engines are not able to control the lower part of the engine rpm below the engine's minimum idling rpm, which is approximately 40% of the rate rpm. Operating the diesel engine in this range with the clutch leads to high wear of the clutch and is not desirable. Where thrusters are driven by diesel engines, control of thrust in magnitude and direction (ahead/astern) is best achieved by a controllable pith propeller (see also below: Control of Thrust).

7.13 CONTROL OF THRUST

7.13.1 Thrusters in DP service must provide controllable thrust from zero load to full load in stepless increments. This can be achieved through control of the propeller pitch or the speed of the propeller

7.13.2 Controllable pitch (CP) propellers: Before the introduction of devices allowing the control of the rpm of electric motors, this was the predominant method of thrust control. The complexity of the mechanical pitch control and its inaccessibility for service caused many failures of these systems in the past.

7.13.3 Thrusters of fixed pitch design, driven by electric motors controlled by variable speed drives are more common. This approach has increased the mechanical reliability of thruster systems.

7.13.4 The exception is thrusters (including in-line main propulsion systems) which are driven by diesel engines. The characteristic of the diesel engine and its inability to control the rpm over the full operating range generally excludes a direct (or geared) drive of a thruster with a fixed pitch propeller. CP propellers and slipping clutches have been used for lower power applications.

7.14 THRUSTER VARIABLE SPEED DRIVES

7.14.1 **General:** The voltage source Pulse Width Modulation (PWM) convertor is the most common type of variable speed drive installed for DP propulsion systems and is used with asynchronous (induction) motors. Induction motors are highly reliable. This type of drive is able to convert power at fixed voltage and frequency to power at variable voltage and frequency using power electronic switches. This type of drive may have a rectifier front end or an active front end.

7.14.2 Load Commutated Invertors (LCI) drives are also available. These are current source convertors and are used with synchronous motors for higher power applications.

7.14.3 DC drives for propulsors are typically based on fully controlled rectifiers driving shunt excited motors. DC drives are cheap and are still used in some propulsion applications for this reason. It can be difficult to make DC drives fully fault tolerant as they are prone to commutation failure associated with power system transients. The dc motor has reliability issues and more onerous maintenance requirements than ac motors.

7.14.4 **Reliability:** Variable speed drives have adequate reliability but several failures in the lifetime of a vessel can be expected. Modular design allows rapid repair if a stock of critical spares is maintained. Reliability may be influenced by environmental conditions. Elevated temperatures and salt-laden atmospheres reduce reliability and consideration should be given to installing the drives in a clean air conditioned compartment.

7.14.5 **Failure modes:** Modern variable speed drives generally fail to zero speed. It may be necessary to make special arrangement to test the failure modes of internal control loops due to perceived risk of damage. For this reason it may be advantageous to conduct such testing at FAT when technical expertise is available to support the testing. DC drives may fail to zero speed or full speed in some designs. Failure to full speed (significantly increased thrust) is generally not accepted in DP rules and guidelines and should be addressed appropriately in the design.

7.14.6 **Water cooling:** Many modern drives use water-cooling to conduct away significant amounts of unwanted heat from power electronic devices. Rupture of water cooling systems within the drive cabinet can develop into a short circuit fault on the main power system which may have failure effects of greater severity than loss of the drive itself. Design should carefully consider the robustness and failure modes of the cooling water system. Hose terminations may need careful attention. It may be beneficial to monitor cooling water system flow. Some variable speed drives use high purity de-ionized water. The cooling water system will typically contain instrumentation intended to confirm the purity of the cooling water. The control systems for these cooling water skids may carry out various checks on restoration of power which may delay starting of the thruster. These features should be considered when developing blackout recovery functions.

7.14.7 **Obsolescence:** Design should consider obsolescence of power electronic technology. This issue should be discussed with the variable speed drive manufacturer.

7.14.8 **Field weakening:** This is a feature that allows the thruster motor to run 10 to 15% over base speed for certain applications. It may be useful in transit applications and should be discussed with the thruster and variable speed drive manufactures at the design stage.

7.14.9 **Ride through capability:** This is an essential feature in any variable speed drive to prevent unwanted tripping of the drive on power systems transients. Vessels intending to operate the power plant as a common power system should be able to confirm the ride through capability of their drives by testing. Failure to achieve sufficient ride through capability can result in the loss of all thrusters leading to loss of position. Parameterization can have significant influence on a variety of drive functions and care should be taken not to defeat the ride through capability by inappropriate selection of parameters or other settings. It is important to consider auxiliary systems such as cooling water and hydraulic pumps as these also require ride through capability. In some cases it may be possible to achieve this by automatic restart if this method is accepted by the classification society rules for the DP notation being applied for.

7.14.10 **Thruster starting sequence:** The thruster blackout recovery sequence should be carefully designed to optimize starting time reliability. There may be a number of permissive, interlocks and safety shutdowns which can be configured. However, it is important that these are active only when necessary. For example it may not be necessary to make cooling water flow a start permissive as the drive will later shut down on over temperature if the pumps fail to start. A large number of permissives may reduce the reliability and extend the recovery sequence. In a blackout recovery situation auxiliary systems may become available at different times depending on the operation of the blackout recovery function. If the drive control system delays starting until auxiliaries become available, the time taken to make the thruster ready for DP can be excessively long or the starting sequence may fail.

7.14.11 **Regeneration:** Some propulsion systems are designed to regenerate significant quantities of power back to the power system during braking maneuvers. Design should ensure this regenerated power can be handled safely without risk of tripping generators on protective functions. Propulsion systems based on torque control typically do not produce regenerated power. Consideration can also be given to using dynamic braking resistors rather than regeneration as a means of dissipating energy from the propeller. The effect of inflow on starting should be considered. During blackout recovery thruster propellers may be turning due to inflow. Drives without regeneration capability may experience starting problems if the drive is not capable of starting with the propeller turning in forwards or reverse rotation. If one or more thrusters fail to start then blackout recovery may be compromised. Most drives are capable of starting on-the-fly but the issue of starting with inflow should be clarified with the manufacturer.

7.14.12 **Drive operating quadrants:** Selection of operating quadrants depends on the choice of propulsor. Most modern azimuthing thrusters have single quadrant drives which do not reverse direction and do not intentionally regenerate power to the bus. Control issues associated with low levels of environment are generally resolved by using thruster bias. There may be other applications where regeneration and / or the ability to reverse thrust direction without azimuthing are desirable and these should be considered in the design and discussed with the drive and thruster manufacturers. It is important to note that some thrusters are not rated mechanically for significant amounts of reverse thrust.

7.14.13 **Speed and torque control:** Most modern variable speed drives operate on the torque control principle using a mathematical model of the motor. However speed control and torque control may still be options for the DP control loop and the advantages of each should be discussed with the DP control system manufacturer. Some DP control systems switch from Torque (Force) control to Speed control at low RPM. Careful design of the switching function is required to ensure a bump-less changeover.

7.14.14 **Auxiliary systems:** Auxiliaries such as cooling water pumps and fans should be powered from same source as drive main power. Pre-charging and pre-magnetizing power may be required before the main breaker is closed. The design should carefully consider the need to provide these power sources during normal operation and for blackout recovery. Control power should be provided from a UPS. The main input to the UPS should be from the thruster auxiliary system power supply. A backup power supply to the UPS input should be arranged from the emergency switchboard.

7.14.15 **Protection settings:** Variable speed drives typically have a large number of protective functions designed to protect the drive from damage. Design should carefully review these protective functions to confirm that they do not defeat the redundancy concept or reduce drive availability to unacceptable levels. It should be noted that some drives require local reset following activation of protective functions. This can significantly increase the time required to restart a thruster and design should consider providing a remote reset function.

7.14.16 **Fast phaseback:** This feature is provided in most modern variable speed drive systems. It allows the thruster to shed load rapidly in response to falling bus frequency which indicates that the generators are in overload. The phaseback function attempts to maintain an acceptable bus frequency during overload conditions. This method of load shedding has several advantages:

1. **Independence:** Each drive makes the decision to shed its load independently of the others reducing the risk of control system failure leading to the loss of more than one thruster.
2. **Continuity:** This function allows time for the power system to recover by connecting standby generators. Phaseback is reduced as the power plant recovers.
3. **Integrity:** By basing the phaseback function on frequency rather than power the integrity of the load shedding function is not dependent on an assumed generator capacity. Thus the system will act in response to failures that cause the generators to lose power such as fuel or combustion air problems.
4. **Maximum capacity:** Systems based on maintaining acceptable bus frequency provide access to whatever power is available from the plant even if generators are only capable of reduced capacity.
5. **Load acceptance:** The phaseback system can compensate for poor load acceptance in modern medium speed diesel engines. This may be required if the step loads associated with power system faults are greater than the load acceptance rating of the engines.

7.15 MAINTAINABILITY AND MAINTENANCE OF THRUSTERS

7.15.1 The consequences of unavailability of thrusters can be extreme. Design should facilitate uptime, availability and ease of maintenance. The principles of non critical redundancy, detection, protection, and ergonomics should be incorporated in the design to facilitate maintenance, and achieve availability and uptime.

7.15.2 Thrusters should be designed for DP service. The consequences of equipment failure can be significant. For example, in the case of a DP drilling vessel, the financial losses caused by taking the vessel out of service to repair a leaking propeller shaft seal may easily exceed the value of the thruster.

1. The lubrication system should be equipped with a seawater indicator/alarm for early detection of leaks.
2. The lubrication system should allow retrieving samples of the lube oil from the lowest point of the gear housing.
3. Facilities should be provided which allow the lube oil to be changed easily while the vessel is at operating draught.
4. Auxiliary systems in the thruster room should be installed with easy access for service and exchange in mind.
5. As far as feasible, support systems (azimuth drives, lubrication systems, etc.) should be installed with redundant key components. If redundancy of the components is impractical, design should incorporate easy interchangeability as a feature (for example, hose connections instead of hard piping for hydraulic components). Provisions should be made for an adequate inventory of spares.

7.15.3 Experience has shown that occasional intrusion of seawater through the propeller shaft seal into the gear housing is unavoidable. An external filtration or purification system should be provided to remove seawater contamination from the lubrication oil for each thruster. Examples of filtration systems include lube oil purifiers and coalescing type filter arrangements.

7.15.4 A condition monitoring system should be considered for continuous surveillance of the condition of power train.

7.16 TESTING OF THRUSTERS

7.16.1 The thrusters should be subjected to thorough testing during the various states of manufacturing. Confirming thrust performance objectively after installation on the vessel is a challenge. Contractual stipulations should take this into consideration.

7.16.2 Estimation of thrust from a fixed pitch propeller is feasible by comparison of measurement of shaft speed with performance data.

7.16.3 Estimation of thrust from a controllable pitch propeller by measurement of pitch is difficult as it depends on the alignment of mechanical components in the hub.

7.16.4 The following are examples of thruster related equipment to be tested:

7.16.5 **Testing of the right-angle gear tooth contact:** This test is important for the assurance of the correct installation and adjustment of the gears. It also indicates errors in gear cutting or machining of the gear housing.

The test should be carried out by applying full, rated torque to the pinion shaft and providing a retarding force to the propeller shaft. The optimum indication for the contact tooth condition is achieved after one revolution of the propeller shaft. More revolutions may corrupt the contact patterns, and less than one full revolution may leave several potential errors undetected.

It is highly recommended to apply the (maximum) propeller thrust to the propeller shaft during this test. This creates a realistic simulation of the actual working conditions of the thrusters

7.16.6 **Functional component and subsystem testing of propeller shaft seals:** The consequences of a propeller shaft seal leak and the efforts and cost (direct and consequential) involved in servicing or replacing the seal are high. A factory bench test is recommended for large thrusters, particularly those equipped with mechanical type radial seals.

7.16.7 **Hydraulic systems for azimuth power, control and gear lubrication:** These systems should be tested for appropriate function and connection.

7.16.8 **Gear housing:** The gear housing should be air-pressure tested for tightness after final assembly.

7.17 VIBRATION MEASUREMENTS

7.17.1 The base vibration signature will assist in future troubleshooting and failure analyses. After completion of the sea trials, a base vibration measurement should be taken several locations on top of the thruster inside the thruster room. The results should be recorded and the location of the measurements should be marked for future repetition of the test and comparison of the results.

7.18 OPERATION OF THE THRUSTERS

7.18.1 **Number of thrusters in operation:** During station keeping operations, the highest overall efficiency for fixed-pitch propellers is achieved by running all thrusters.

7.18.2 **Propeller "windmilling":** The design of a right-angle gear thruster should consider the potential adverse effects of windmilling:

For example a drilling vessel with six thrusters is intended to undertake an extended transit one of the thrusters is unavailable. The vessel will be propelled by the remaining five thrusters and is expected to move at twelve knots. The failed thruster would be exposed to twelve knots inflow velocity, causing the propeller to windmill. This generates thrust in the opposite direction to the normal operating thrust. The mechanical design of the power train must be designed for this condition to prevent damage to bearings and gears. Addressing windmilling by braking the (high-speed, low-torque) pinion shaft is detrimental. It could cause the engagement of one pinion gear tooth with two gear wheel teeth. The turbulent action of the inflowing water to the propeller would cause a continuous rattling of the gear teeth and may lead to a failure.

7.18.3 Depending on the type of electric drive system, the windmilling action of the motor may generate current. The electric drive arrangement should be able to cope with this.

7.19 MECHANICAL DESIGN OF THE RIGHT-ANGLE GEAR THRUSTERS

7.19.1 **General:** The majority of electric thrusters are of the mechanical, right-angle gear box design. A few electric-direct drive thrusters are in DP service (podded thrusters).

Gear design factors, and the calculated life of the bearings should be key elements for the evaluation of the quality of thrusters. Gear design factors include:

1. Safety factor against pitting.
2. Safety factor against tooth breakage.

3. Safety factor against scuffing.

7.19.2 A further gear design factor is the application factor which is a function of the (input) drive system (either reciprocal action such as Diesel engines, or uniform action such as electric motors), and the (output) operational condition, i.e. the condition in which the thruster is operating (e.g. smooth water or heavy turbulence - probability of exposure to the turbulent wake of another thruster in the vicinity).

7.19.3 Guidance for the selection of these factors is given in DIN Standard 3991, and Klingelnberg Standard KN 3030. The rules of the classification societies typically reflect these standards.

7.19.4 The gears should be designed and rated to transmit the specified torque for unlimited life.

7.19.5 The minimum calculated L-10 life of the bearings should be specified as 30,000 hours. The L-10 life is defined in ISO 281:2000, ‘Standard for calculation of bearing ratings and life’. L-10 indicates the life that 90% of a large sample of identical bearings should achieve.

7.20 PROPELLER SHAFT SEALS

7.20.1 Propeller shaft seals are the weak point of the thruster design. It is said the failures of these seals have caused more downtime in the offshore industry than any other single component. It is of utmost importance that the seals including their support systems are selected for quality and proven performance and independent of cost considerations.

7.20.2 Axial (mechanical-type) seals as well as radial (lip-type) seals are used for large thrusters. The selection of seal type depends on factors such as draught of the vessel, the quality of the water in which the thruster is operating and personal preferences based on experience. For water contaminated with sand and silt, the mechanical seal is suggested due to the higher hardness of the seal surfaces.

7.20.3 Debris and fishing line contribute to seal failure. Design should incorporate mitigating measures such as streamlining the housing contour, attaching rope cutters to the propeller hub to protect seals from such exposure. The propeller-shafting-housing intersection should be designed to prevent debris and fishing line from entering the vicinity of the shaft seals. The rope guards should be designed for an extreme low clearance. A net protection ring with U-shaped cross-section may be attached to the forward end of the propeller hub.

7.21 THRUSTER PROPELLERS

The propeller material should be nickel-aluminum bronze for strength and ease of repair. Propellers should be manufactured, tested and balanced in accordance with International Standard ISO 484/1-1981 (E) Class I.

7.22 THRUSTER SELECTION CRITERIA

7.22.1 The following are examples of criteria that should be evaluated to assess thruster quality and performance as an aid to selection during the design phase.

1. Power to thrust ratio.
2. Maintainability.

3. L-10 life of the bearings.
4. Compliance with the specification and owner requirements.
5. Gear design factors such as:
   a. Safety factor against pitting.
   b. Safety factor against tooth breakage.
   c. Safety factor against scuffing.
   d. Application factor.

7.23 LIFE EXTENSION OF THRUSTERS

7.23.1 The following step should be considered to aid life extension of thrusters:

1. Protection of the gear housing with state-of-the-art epoxy compounds.
2. Installation of cathodic anodes at the outside of the thruster housing and at the nozzle.
3. Coating the inside of the nozzle shell plating with a corrosion-preventive compound. Design should incorporate features to facilitate renewal of the coating.
4. The nozzle should be equipped with openings for draining and filling.

SPECIAL APPLICATIONS

Certain vessels industrial mission is taking them into frontier areas where DP is being contemplated as a means of station keeping (e.g. Arctic Exploration).

Thruster designs will need to take into account specific requirements for operating in these environments (e.g. clogging of nozzles, ice loads and impacts on gears and appurtenances).

8 MARINE SYSTEMS

8.1 DESIGN OF MARINE SYSTEMS

8.1.1 The design of Marine systems supporting DP should follow the redundancy concept and WCFDI. Design of such systems should reflect the Industrial Mission and the objectives to be achieved. The benefits of incorporating design features of independence, segregation, critical redundancy, non critical redundancy and monitoring beyond Class Requirements should be assessed. These enhanced features should result in vessel that meets the objectives of its industrial mission and achieve the desired Class Notation.

8.1.2 Marine Systems as addressed in this section include:

1. Fuel oil system.
2. Seawater cooling systems.
3. Fresh water cooling systems.
4. Compressed air.
5. Lubricating oil systems.
6. HVAC and ventilation.
7. Remote controlled valves.
8. Water tight integrity /Subdivision Integrity.
9. Pipe work.

8.2 FUEL OIL

8.2.1 Fuel Oil systems should be designed to provide one per engine room or minimum of two for DP Class 2 and 3

8.2.2 There should be sufficient redundancy in the fuel transfer system to allow each engine room access to the vessel's entire fuel capacity following any single failure.

8.2.3 Actuators for Quick Close Valves should be installed on a per engine basis - any remote control system should fail safe in respect of position keeping.

8.2.4 Water content monitoring with remote alarms should be installed.

8.2.5 In addition to Class rule stipulated level monitoring, fuel level monitoring appropriate to the Industrial mission should be considered.

8.2.6 Fuel filter arrangements should be designed to facilitate changes without taking equipment out of service.

8.2.7 The design of the fuel system should facilitate isolation of services between station keeping and industrial functions if applicable.

8.2.8 Height of the day tanks for fuel should be designed to avoid dependence on emergency generator for black out/black start.

8.2.9 Co location of auxiliary systems supporting fuel systems should be avoided. Where segregation is chosen as a design principle, it should follow the redundancy concept.

8.3 SEAWATER COOLING

8.3.1 The design should incorporate redundancy in Sea chests and pumps in line with the redundancy concept and follow the WCFDI.

8.3.2 The design should facilitate isolation of services between station keeping and industrial functions if applicable.

8.3.3 Each engine room should have a sea water cooling system with one duty and one standby pump (interchangeable assignment). A high and a low sea chest will be provided and either can be selected. No single failure of an active component in the seawater system should lead to a loss position.

8.3.4 Two sea strainers will be fitted for each engine room seawater system with differential pressure alarms to identify the onset of severe fouling and it will be possible to remove one of the two sea strainers for cleaning with the seawater cooling system in operations.

8.3.5 Means to select the offline sea suction remotely should be provided.

8.3.6 Thruster seawater cooling system should follow the redundancy concept with one duty and one standby pump (interchangeable). One low and one high sea suction should be provided with two sea strainers and isolation valves to allow the thruster(s) to continue to operate while one strainer is being cleaned.

8.3.7 Engine room sea water cooling systems could be incorporated into the thruster seawater systems provided the redundancy concept is not contravened.

8.3.8 An effective anti bio fouling system should be installed to ensure the seawater cooling systems retain their efficiency between maintenance periods.

8.3.9 Temperature, flow and pressure monitoring (local and remote) should be an integral part of the design of sea water cooling systems.

8.4 FW COOLING

8.4.1 Fresh water cooling systems supporting station keeping equipment, per consumer, should be independent to the maximum extent feasible. Where independence is not part of the design philosophy, failure of the fresh water cooling system should not result in a failure mode worse than the WCFDI.

8.4.2 FW cooling systems for engines should consider use of engine driven freshwater pumps. Dual pumps should be provided in a duty / standby arrangement to improve availability.

8.4.3 Water makers should not introduce commonality in redundant FW circuits.

8.4.4 Flow and pressure monitoring (local and remote) should be an integral part of the design of fresh water cooling systems.

8.4.5 Fail safe condition for valves in FW system should fail as is.

8.4.6 Fail safe condition for Temperature regulating valves should be fail open.

8.5 COMPRESSED AIR

8.5.1 Compressed air is used for:

1. Starting air.
2. Control air.
3. General service.

8.5.2 Compressed air for starting engines should be independent to the maximum extent feasible. Where independence is not part of the design philosophy, failure of the system should not result in a failure mode worse than the WCFDI.

8.5.3 The above philosophy should be applied to general service air when used to support station keeping equipment.

8.5.4 Compressed air systems for DP related and non-DP related functions should be independent. Compressed air systems for DP related functions should follow the redundancy concept.

8.5.5 Control air and starting air may be taken from the same source provided any pressure drops associated with starting air do not affect the control function.

8.5.6 Where starting air is used for other purposes means should be provided to ensure the starting capacity required by class is protected against depletion.

8.5.7 Starting air system should be designed to allow simultaneously cranking, starting and connection of all diesel generators.

8.5.8 Control air for the thrusters may be derived from the associated engine room supply or locally. Loss of air supply to the thrusters should be alarmed and should have no effect on thruster operation.

8.5.9 Devices such as oil mist detectors should not have common mode failures such as common air supplies or crank case breathers.

8.5.10 Pressure monitoring (local and remote) should be an integral part of the design of compressed air systems.

8.6 LUBRICATING OIL SYSTEMS

8.6.1 Lube oil systems for engines should be associated with one engine only.

8.6.2 Facilities for storage, changing and disposing of oil may be on a per engine room basis but suitable interlocks should be provided to prevent inadvertent cross connections between engines which could lead to one engine sump being emptied and the other overfilled.

8.7 HVAC AND VENTILATION

8.7.1 Ventilation and HVAC for spaces containing equipment essential to DP should be designed to comply with the redundancy concept and failure should not have an effect exceeding the worst case failure design intent.

8.7.2 Consideration should be given to the use of temperature alarms for temperature critical spaces where cooling is essential to the correct operation of equipment, a backup temperature control system should be provided.

8.8 REMOTE CONTROLLED VALVES (DP RELATED)

8.8.1 All remotely controlled valves should fail in a manner that supports the redundancy concept. In general this will require double acting remote controlled valves which fail 'as set' unless required otherwise by Class.

8.8.2 Where any conflict arises between the requirements of Class and the redundancy concept a solution is to be developed to satisfy both requirements.

8.8.3 Consideration should be given to the need for remotely controlled valves for DP related equipment to operate reliably in challenging environments. The effects of technical failures, fire and flooding should be considered. Hydraulically operated valves may offer advantages in some failure scenarios

8.8.4 Monitoring of valve position of remote controlled valves should be based on feedback not command.

8.9 WATER TIGHT INTEGRITY/SUBDIVISION INTEGRITY

8.9.1 Design should incorporate features that will maintain watertight integrity/subdivision integrity of spaces containing DP critical equipment and be able to cope with inadvertent acts compromising integrity. Remote monitoring capability of such spaces is suggested.

8.9.2 Particular attentions should be directed towards hull penetrations associated with DP equipment. (e.g. hydro-acoustic transducers).

8.10 PIPEWORK

8.10.1 Failure of pipework associated with redundant elements passing through the same high risk area without adequate protection from mechanical damage and fire should not result in a failure worse than WCFDI.

8.10.2 Cross over valves where fitted between independent systems, to facilitate maintenance, should be provided with local and remote monitoring to indicate open/closed status.

Table 8-1 MTS Design for Auxiliary Services - Basis for Action, Cost Beneficial Risk Reduction

Systems	Independence	Separation	Monitoring	CR	NCR	CMF/CCF	X-OVER	IRM
Fuel supply	✓	✓	✓				✓	
Fuel Storage		✓	✓			✓	✓	✓
SW Cooling			✓		✓		✓	✓
FW Cooling	✓	✓			✓			
Starting air		✓	✓	✓			✓	
Control air	✓	✓	✓		✓			
Lubricating Systems	✓	✓						
HVAC and Ventilation		✓	✓	✓				
Remote Controlled valves		✓		✓				
Definitions								
Independence	Provide auxiliary service in a manner that makes thrusters and generators independent.							
Separation	Provide auxiliary service in a manner that supports redundancy & minimizes commonality – WCFDI.							
Monitoring	Provide monitoring to reveal loss of redundancy and common mode / cause failures.							
CR	Critical redundancy is sufficient i.e. supports WCFDI.							
NCR	Add non critical redundancy to improve reliability over that required for WCFDI.							
CMF/CCF	Pay special attention to common mode and common cause failures for internal and external sources.							
X-Over	Add normally closed crossovers for ease of maintenance.							
IRM	Pay special attention to maintenance requirements, and develop specific procedures.							

9 POWER GENERATION

9.1 ATTRIBUTES OF A ROBUST REDUNDANCY CONCEPT

9.1.1 DP class notation dictates the redundancy requirements. A robust redundancy concept has the following attributes:

1. Fully fault tolerant in relation to the defined failure criteria.
2. Main machinery is independent to the maximum extent feasible.
3. Redundant systems are clearly defined and well separated.
4. The division of systems into redundant groups is maintained throughout the design.
5. Low loss worst case failure effect.
6. Minimum number of failures leading to the worst case failure effect.

9.1.2 A robust redundancy concept should be rigorously applied to the design of the power generation system.

9.1.3 The design of the power generation system should take into account:

1. The Industrial mission of the vessel.
2. Power required to maintain station and perform the industrial mission in the desired range of environment.
3. The need to work efficiently in all required power plant configurations.
4. Power required to maintain station in the defined environmental limits in
   a. Intact condition.
   b. And post worst case failure.
5. The need for a robust blackout recovery system as a risk reduction measure
6. Any restrictions imposed by particular choice of main machinery

9.1.4 The key power system attributes that need to be considered during the design phase are:

1. Power, voltage, current, frequency and operating power factor.
2. Short circuit withstand capability.
3. Protection philosophy.
4. Power management.
5. Phase back of large consumers.
6. Regeneration from large consumers.
7. Starting of large consumers.
8. Load acceptance and rejection.
9. Load balance.
10. Voltage transient ride through.
11. Stability.

12. Efficiency.
13. Harmonic distortion.
14. Electromagnetic compatibility.
15. Maintenance requirements.
16. Environmental and pollution requirements.

9.1.5 The design effort should incorporate the necessary analysis and studies required to deliver a robust power plant, delivering effective capacity to undertake its industrial mission in the stipulated environmental conditions.

9.1.6 It should be recognized that Class Rules addressing the above attributes are minimum requirements for vessels and do not consider the industrial mission the vessel will be undertaking. The design philosophy should integrate the requirements of the Class Rules and the Industrial mission. This will translate into a more comprehensive and sophisticated design effort resulting in a more effective vessel.

9.1.7 Power generation design should deliver:

1. Flexibility (Optimize the number of generators in favor of flexibility for example six smaller generators rather than four larger ones).
2. Maximum independence and separation.
3. High availability.
4. Fault tolerance and fault resistance.
5. Continuity of supply of power.
6. Maximize post failure capacity.
7. Optimized Black Start requirements (minimize recovery time).

9.1.8 Design should consider the significance of the power plant in relation to the industrial mission of the vessel. Most modern DP vessels of medium to large size have a diesel electric power plant based on the power station concept. The power station concept is based on a centralized power generating and distribution system which provides power for all vessel power requirements including propulsion, industrial loads, auxiliary systems and hotel services.

9.1.9 Generators and thrusters are connected to two or more main switchboards to create independent power systems which are capable of maintaining position and heading in the event that one of the power systems fails.

9.1.10 **The design of the power plant should be based on a redundancy concept:** The redundancy concept describes the way in which each of the independent power systems supplies power for engine room services, thrusters and thruster auxiliary systems. The separation between these independent power systems is often referred to as the ‘split’ in the redundancy concept. A vessel with two power systems is described as having a ‘two-way’ split. A vessel with three independent power systems is described as having a ‘three-way’ split.

In good redundancy concepts the split between the power systems is clearly defined and there are few cross connections between systems. Where cross connections are unavoidable they should be easily identifiable. In these types of redundancy concepts, failures within each independent power system should only affect thrusters and generators in one of the power systems.

In poorly defined redundancy concepts the boundaries between each power system are more difficult to identify and there may be a larger number of shared components or connections. Vessels with this type of redundancy concept are susceptible to failures that could exceed Worst Case Failure Design Intent (WCFDI). Even if WCFDI is not exceeded, failure in one power system may affect generators and/or thrusters in the other power system and different combination of thrusters may be lost. Multiple failure permutations exist in such systems.

9.2 POWER SYSTEM ATTRIBUTES AND STUDIES

9.2.1 **General:** Alternating current power systems must operate within limits for voltage, current and frequency. Control systems on the generator continuously adjust the fuel admission and excitation levels to ensure each generator is running at the correct voltage and frequency and is carrying its proper share of the active and reactive power.

To maintain system stability:

1. The load on each generator must be the same and within the generator's rating. Asymmetric load sharing may be applied for maintenance purposes provided all necessary protective functions are in place to ensure system stability in this control mode.
2. Generator current must remain within rating to prevent the generator being tripped on over current.
3. When load is applied to the generators the application rate must be within the generator's load acceptance rating.
4. The worst case load rejection must not cause the generators to trip on over speed or over frequency.

System stability may be assisted by phaseback of larger consumers if the step load is caused by sudden loss of generating capacity exceeding the load acceptance.

9.2.2 **Harmonic distortion:** Modern power electronic convertors used for thrusters drives and other applications create harmonic distortion of the power frequency waveform.

Levels of harmonic distortion must be maintained within set limits to reduce the risk of equipment malfunction.

All these conditions must be met in both the intact case and after a fault has occurred.

Harmonic distortion of power frequency waveforms can be caused by:

1. Incorrect design of power systems.
2. Failures in variable frequency drives.
3. Failure of harmonic filters.
4. Loss of harmonic cancellation.

Harmonics can also be related to commutation notches from large rectifiers and contribute to overheating of service transformers.

High levels of harmonic distortion can have undesirable effects including failure of generator synchronizers, failure of control systems, noisy operation, overheating of machines and failure of ballasts in fluorescent lighting.

Harmonics are often a problem in large diesel electric power plants.

Measures such as phase shifting transformers, active front end rectifiers, and phase shifting transformers are used to reduce harmonic distortion to acceptable levels.

Harmonic filters can be unreliable. There have been known failures on DP vessels leading to severe short circuit faults and associated voltage dips and consequences.

Harmonic studies should be carried out to determine the worst case levels of harmonics in the intact condition and following the worst case failure of any harmonic reduction measures.

The system should be designed such that post failure levels of harmonics remain within acceptable levels or the power plant should be designed to operate at higher harmonic levels without malfunction.

Levels of harmonic distortion should be continuously monitored by the vessel management system and unacceptable levels should initiate an alarm.

Vessels that operate with the main switchboard busties open should only experience harmonics related to failure on one power system. However, some power system use phase shifting transformers with a different vector group on each side of the main busties to achieve additional harmonic cancellation. It is important that the harmonics remain within acceptable levels when the busties are opened and this harmonic cancellation effect is removed.

Some types of diesel electric power systems use phase shifting transformer between two bus sections to create a phase shift between the two power system voltage waveforms. When one power systems fails the 12-pulse rectifiers revert to 6-pulse operation. It is important to confirm that operation can continue for as long as required with the higher levels of distortion. Systems using this method should be designed for continuous operation in all defined bus configurations.

Guidance on acceptable levels of harmonic distortion is available from a number of sources including IEC 533. Protection relays and monitoring units are available to provide alarms or initiate actions on defined levels of harmonic distortion.

9.2.3 **Load balance:** The load balance indicates the load on the generators for various operations. It important that load balances acknowledges requirements for the DP system to have active redundancy i.e. ability maintain position with the machinery that remains available following the worst case failure. It is important that the load balance reflects the configurations that will be used for DP including SMO and TAM.

When the power plant is configured as a common power system all generators can feed all loads. There may be significant currents across the busties if loads are not equally divided up amongst the main switchboards.

It is important to balance DP loads and those associated with the vessel's industrial mission.

Failure to do this can create a design which cannot operate effectively with the busties open because one power system reaches capacity before the other preventing thrusters being utilized effectively.

Note: load balances are also required for other DP related energy sources such as UPS, transformers and DC power supplies.

9.2.4 **Voltage transient ride through:** Voltage transient ride through describes the ability of electrical consumers to continue in operation following a significant voltage excursion. Voltage transients can be caused by short circuit faults, voltage regulator faults and excessive regeneration from drives.

Many consumers such as variable speed drives and motors are supplied through electromagnetic contactors that are susceptible to voltage dips associated with clearing a fault elsewhere in the power system.

Unless all DP related consumers have the necessary voltage transient ride- through capability there is a risk of loss of all thrusters or blackout in DP vessels operating with a common power system. Typical issues related to voltage transients include:

1. VSDs DC link trips on over/ under voltage.
2. Insufficient under voltage release delay on feeders - For example service transformer feeders.
3. Drop out in contactors for pumps and fans.

9.2.5 **Voltage transient testing:** The voltage transient ride through capability should be proven by suitable analysis and testing including live short circuit testing and earth fault simulation on the main switchboards.

Careful development and planning is required to ensure such tests can be conducted safely with minimum exposure to people and risk of equipment damage. This type of testing has been carried out successfully on DP vessels with appropriate analysis, planning and execution. Such testing has revealed vulnerabilities and identified opportunities for improvement. Addressing any vulnerabilities and opportunities for improvement aids in delivering a robust power plant.

Such analysis and testing is recommended for DP class 3 vessels even if the power plant is operating with the main busties open especially if cable routes or collocation of non DP related equipment create a common point. A voltage transient could be experienced by all redundant power systems because of the effects of fire or flood damage to electrical equipment and cables.

Sufficient time should be allocated to carry out the required analytical modeling to enable execution of this test safely.

9.2.6 **Mitigation for effects of voltage transients:** The effects of voltage transients can be mitigated by:

1. The provision of UPSs for control power.

2. Suitable under voltage delay on circuit breaker opening.
3. Ride through power supplies on drives.
4. Kinetic buffering of thrusters.
5. Automatic restart of auxiliary services.
6. DC coils for MCC contactors.

9.2.7 **Resonance:** This is a condition which occurs when there is sufficient inductive and capacitive reactance in a power system to create a resonant frequency at or near one of the naturally occurring harmonic frequencies of the system.

Such an effect can cause a severe over voltage leading to equipment failure and blackout.

Resonance can occur if there are large capacitors on the system for filtering purposes etc.

The harmonic study can also be used to check for resonance.

9.2.8 **Transient stability:** Parallel generators are held in synchronism by the synchronizing torque developed from the bus voltage at the generator’s terminals.

During a severe short circuit fault the terminal voltage may drop close to zero causing generators to lose synchronism with each other.

Similar conditions may occur because of the crash synchronization of a generator, or two power systems. Inadvertent connection of a stopped generator may also cause severe disruption.

In marine power systems the generators are usually so closely coupled that the plant re-stabilizes when the short circuit has been cleared by the protection. A study should be performed to confirm this.

9.2.9 **Spinning reserve:** In discussion of marine diesel electric systems the term ‘spinning reserve’ is used to describe the difference between the system load and the online generating capacity. It does not include the capacity of standby generators.

It is good practice to maintain sufficient spinning reserve to cope with the worst case loss of power generating capacity without resorting to thruster phase back.

It may be impractical to carry sufficient spinning reserve to allow industrial consumers to continue without disruption and it may be acceptable to use load shedding functions to make power available for the thrusters. This method of power plant operation can only be considered as contributing to redundancy and included in the consequence analysis if the load shedding function is sufficiently reliable.

Studies should confirm the levels of spinning reserve required to provide active redundancy. Load dependent starting should be programmed to ensure such margins are preserved under all operating conditions.

9.2.10 **Short circuit withstand:** This is the property of electrical equipment that indicates that it is able to withstand the mechanical forces created by a short circuit fault.

The short circuit current increases with the number of generators or service transformers operating in parallel.

In low voltage power plant designs the maximum prospective short circuit current is sometimes greater than the withstand capability of the main switchboards. The power management system may be programmed to subdivide the power system to reduce the fault current available when the number of generators becomes too great.

In other designs service transformers are prevented from operating in parallel by system of interlocks. Device such as Is limiters (a type of fuse) can also be used to overcome such difficulties.

Whatever method might be employed to overcome the problems of high short circuit currents it is important that these are considered in relation to the redundancy concept and worst case failure design intent.

Classification societies require that short circuit calculations are carried out to ensure the prospective short circuit current does not exceed the rating of electrical equipment specified.

9.2.11 **Protection relay coordination:** Modern DP vessels intending to operate a diesel electric power plant as a common power system require a very sophisticated and comprehensive range of protection relays to prevent faults in one redundant power system affecting the operation and stability of others.

The type and settings of the protective functions must be carefully coordinated to ensure there are no conflicts and that faults are isolated as close as possible the source of the fault.

It is essential that protection relay coordination studies consider the need for protection to support the redundancy concept, industrial mission requirements, personnel safety and equipment protection.

9.3 GENERATORS

9.3.1 **Engines:** Generators for diesel electric power plants in medium and large sized DP vessels are usually powered by medium speed diesel engines. These engines are often highly turbocharged and have a number of features that can influence the DP redundancy concept. Features vary from engine to engine and from one manufacture to another even for engines of the same size and rating. It is important to understand any restriction imposed by these features. Engine attributes that should be considered in the design include:

1. Load acceptance.
2. Load rejection.
3. Starting time.
4. Load up time and emergency loading ramp.
5. Time on hot standby.
6. Minimum load and part load ratings.
7. Black start requirements.

9.3.2 **Load acceptance and rejection:** Load acceptance and rejection ratings define the step loading that can be applied to the diesel engine without unacceptable loss of cyclic regularity (frequency for a generator).

In modern medium speed diesels this figure varies with the load at the time the step is applied and is often worst at mid load. Figures of around 25% are not unusual in some engine types.

Care must be taken to ensure that failures in the power generation system which cause loss of multiple generators do not impose a greater step load than specified. Tests confirm that blackout can occur if this figure is exceeded.

In some designs it may be impractical to ensure this step loading cannot be exceeded and it is normal practice to relieve any fall in frequency using frequency based phaseback of large power electronic drives such as those for thrusters or drilling. A temporary reduction in the power consumption of these devices can rapidly relieve the load on the generator allowing it to maintain frequency and develop the required power. If this method of preventing cascade failure of generators is envisaged as part of a redundancy concept it is important to ensure that the frequency phase phaseback function in the drives is fast acting, stable, effective and proven at sea trials.

9.3.3 **Starting time:** Large engines may have restrictions on starting which extend their connection time. Some engines require slow turning after sitting stationary on cold or hot standby for an extended period. These pre-starting activities can extend connections times to the order of several minutes which is generally too long for DP requirements.

A connection time of 30s or less can usually be achieved but may require certain engine management functions to be incorporated in the power management system to ensure optimal engine readiness.

It is essential that starting time requirements are understood and agreed with the shipyard, engine manufacturer and power management system vendors. Interfaces and integration should be effectively managed.

9.3.4 **Load up time and blackout recovery loading ramp:** The engine manufacturer may impose restrictions on the rate at which load may be applied during normal operating conditions. Care must be taken to ensure that this load up ramp is suitable for the requirements of the DP controls system. The DP control system manufacturer may apply ramps in software to ensure the engines are not loaded up too quickly. A faster load up ramp may be agreed for blackout recovery - if this is the case then it will be necessary to provide the control options to utilize this in the power management systems.

Note: In the case of blackout recovery, the first generator to connect has to accept the load presented to it on reconnection of the distribution system. Significant hotel loads could contribute to this load. Design should consider this scenario and address appropriately. For example a service transformer that supports engine and thruster auxiliary systems as well as hotel services.

9.3.5 **Time on hot standby:** Some engines have limitations on how long they can remain on hot standby before they have to execute slow turn functions on start up.

Automation system manufactures may have standard functions designed to relieve this problem by starting the engines periodically and rotating them through a period of operation. Design should consider features of the engine and ability of the automation system to effectively address such features.

9.3.6 **Minimum load and part load ratings:** There may be restrictions of the minimum load at which a large engine can be operated. Low load running may result in build up of soot and other combustion products which reduce engine efficiency to the point where it cannot deliver rated load on demand.

Many power management and automation system providers have standard functions for engine conditioning but it is necessary to make sure that such requirements are included in the specification for the automation system.

In some type of load sharing systems the engine conditioning or 'base load' function may have to be provided by other means if the PMS does not perform the load sharing function. For example, digital governors may have an asymmetric load sharing function built in.

9.3.7 **Black Start Requirements:** Different types and sizes of engine have different requirements for black starting depending on how much time has passed since the engine was running or in hot stand by.

Some engine manufacturers stipulate that the engine must not be started without pre-lubrication. Others will allow starting without pre-lubrication for a defined time after pre-lubrication.

If pre-lubrication must be provided, consideration can be given to using air driven pre-lube pumps from the starting air supply. This is preferable to using the emergency generator.

Some engines may be very difficult to start if the jacket water temperature drops below a certain point. This is not usually an issue for blackout recovery if the engines have been running or the jacket water heaters are normally on during standby.

If the power plant cannot be recovered in a short time it may be advantageous to have alternative supplies for the jacket water heaters and pre-lube pumps from the emergency switchboard. This feature could be useful during the commissioning phase.

9.3.8 **Generators:** Generators for diesel electric power plant are typically salient pole brushless self exciting synchronous machines running at 720rpm or 900rpm, 60Hz. A range of voltages are available from around 440V to 13.8kV. 690V, 6.6kV and 11kV are the most commonly found ratings. Generators are available in a large range of power ratings. On medium and large DP vessels generator sizes typically range from around 2MVA to 10MVA and are normally installed in groups of 4, 6 or 8 depending on the size and type of DP vessel.

9.3.9 Note in this context the word 'generator' refers to the electric part of the generating set.

The impact of the following services on the redundancy concept need careful consideration when choosing a generator.

1. Excitation system.
2. Lubrication system.

3. Cooling system.
4. Facilities for alarms, monitoring and protection.
5. Neutral earthing.

Excitation support: Several types of excitation system are available for synchronous alternators and not all are suitable for use in marine diesel electric plants. Class requires that alternators are capable of delivering sufficient fault current to operate over current protection effectively during fault conditions and this may require the alternator to be provided with excitation support. The permanent magnet generator is the preferred method of providing this function. It has the advantage that it can also be used as an independent source of generator control power once the generator is up and running.

9.3.10 **Neutral Earthing (Grounding)** Main HV power distribution systems are normally unearthed but have a means of earth reference such as high resistance earth. LV power distribution is normally not earthed.

9.3.11 The size of the prospective earth fault current determines whether it is acceptable to have alarm and indication of earth faults only or whether they must be automatically isolated by tripping the faulty circuit.

High resistance earthing is normal on larger high voltage power distribution system. Class rules on cable insulation have changed and some classification societies allow the cable line to earth insulation to be rated for less than the line to line voltage which is the voltage experienced by the insulation following a ground fault. Adopting this approach requires that the earth fault protection operate almost immediately to relieve the stress on the cable insulation and this may not be compatible with the redundancy concept.

The HV cable earth insulation should be rated for the line to line voltage regardless of the method of earthing or fault isolation. This has negligible cost impact if specified upfront and is part of the bid spec.

Distribution systems may be earthed by neutral earthing transformers at the main switchboards or by neutral earthing resistors at the generator star points.

Earthing at the main switchboards provides a more consistent earth fault current unaffected by the number of generators connected. This is better for protection purposes.

9.3.12 **Generator control power:** It is good practice to make each generator independent in terms of control power. This can be done quite effectively when the alternator has a permanent magnet generator.

Providing control power battery systems for groups of generators inline with split in the redundancy concept is usually satisfactory for control purpose during starting and connection. Design should facilitate independence from the common battery supply once the alternator has excited.

9.4 FUEL CONTROL

9.4.1 **Load sharing:** In a diesel electric power system the engine governor controls frequency and load sharing. There have been a number of DP incidents attributed to governor faults.

Modern digital governors have advanced to the point where external trimming of load is not usually required. Operating parallel generators in uncorrected speed droop introduces the fewest common points and fewest failure modes of all the load sharing techniques.

Other examples of load sharing methods include:

1. Isochronous load sharing using analogue or digital load sharing lines.
2. Pseudo isochronous using external trimming of governor by the PMS (compensated droop).

The above two methods introduce additional failure modes which if not adequately militated against can result in blackout or loss of position incidents.

9.4.2 **Governor types and failure modes:** Governors can be forward or reverse acting. Reverse acting governors fail to full fuel which can be catastrophic for a DP power system.

Most modern DP vessels use digital forward acting governors for fuel control. These have proved to be a better choice in most applications.

The integral backup mechanical governor offered as an option by governor manufactures is of limited benefit to the DP redundancy concept. Such devices can introduce additional failure modes.

9.5 EXCITATION CONTROL

9.5.1 **The Automatic Voltage Regulator** (AVR) is used to maintain system voltage and reactive power sharing. It may also be involved in ensuring sufficient fault current is delivered for effective relay coordination.

AVRs that are operated in uncorrected voltage droop introduce the fewest common connections and failure modes for redundant systems. Design should take this into consideration.

External trimming of the AVR introduces additional failure modes and seldom offers benefits.

A few reactive power sharing schemes use sharing lines sometimes referred to as a cross current loop. These lines introduce further complexity in the control scheme and additional failure modes and are generally unnecessary in modern designs.

Most modern DP vessels use digital automatic voltage regulators.

9.6 SWITCHGEAR

9.6.1 **Switchboards:** Metal enclosed switchgear is normally specified for high voltage applications. Circuit breakers and contactors are used to connect generators and other loads. For 11kV and 6.6kV systems these can be vacuum circuit breakers or SF_6 type or may be air circuit breakers at lower voltages.

Switchboards should be arranged for full remote-manual and automatic control and be provided with all necessary alarms, controls and indications to allow local manual control of the power plant.

Switchgear can be arranged to fail ‘as set’ on loss of control power. This has advantages for DP redundancy provided there are other means of disconnecting circuits if required such as mechanical opening controls.

Note: Classification societies normally accept switchboards on the basis of type approval provided the prospective short circuit fault current is well within the rating of the switchboard.

If the calculation suggests it is close to the rating, full scale short circuit testing at a test facility may be required. This could have a significant cost and time impact. The cost effectiveness of specifying a switchboard with a higher rating should be evaluated.

Some classification societies require switch boards to have an arc proof rating for HV applications.

9.6.2 **Busties:** It is good practice to have a bustie circuit breaker at each end of a tie line connecting two switchboards, even if classification society rules only require one. For example as permitted in DP Class 2.

This is particularly important for safety reasons if the switchboards are located in separate switchboard rooms. There have been serious accidents associated with single bustie designs due to improper and ineffective isolation procedures.

Some classification societies enforce the requirements for two busties if the switchboards are in different compartments under main class rules or by interpretation of SOLAS.

9.7 POWER SYSTEM PROTECTION

9.7.1 **General:** Protection schemes for power systems are intended to protect life and limit damage to equipment. DP Class 2 and DP Class 3 vessels depend upon continuity of supply to essential consumers such as thrusters and auxiliary systems.

The protection scheme should be designed to ensure that faults are isolated at source and that failure effects do not exceed the worst case failure design intent.

Over current protection is the primary protection function and is intended to prevent overheating caused by high currents in cables and windings which may result in fire.

In diesel electric power plants for marine applications the main protection elements are:

1. Generator protection.
2. Bus bar protection.
3. Feeder protection.

Generator protection limits the effects of internal faults in the generator, to protect it from the effects of power system faults and protect the power system from the effects of generator faults.

Bus bar protection is intended to protect the switchboard against faults on the switchboard itself.

Feeder protection is designed to disconnect faulty circuits from the switchboard.

All protective functions are potential hidden failures which may defeat the redundancy concept by removing fault tolerance.

Critical protective equipment should be tested periodically, and equipment settings confirmed to match the approved protection and coordination study, to have a high degree of confidence that they will operate on demand.

Protective functions should be provided in such a way that spurious operation of the tripping functions should not produce a failure effect exceeding the worst case failure design intent.

9.7.2 **Arc detection:** Arc detection by optical means or by pressure wave detection has becomes a popular method of bus bar protection for high voltage marine power systems.

Arc detection offers advantage of very fast isolation of the fault. It does not depend on detecting the fault current. It does not require coordination with other protection as it positively identifies the location of the fault. It may be supplemented by over current protection to cover the possibility of a short circuit occurring without an accompanying arc.

9.7.3 **Over current detection:** This is the most basic form of protection and is applied at all levels in the power distribution systems for short circuit and over load protection.

Over current can be detected by current transformers, fuses, magnetic over current or bi-metal strips with heating coils. At the main power distribution levels 'protection-class' current transformers are used to provide digital relays with a signal representing the line current. Various current versus time curves are used to produce the required degree of coordination with other over current protection upstream and down stream.

Note: Protection class CTs may not provide the degree of accuracy required for instrument applications.

9.7.4 **Differential protection:** Differential protection is a form of over current protection based on summing the currents entering and leaving a node such as a switchboard, busbar or a generator winding.

Current transformers are used to monitor the current entering and leaving the zone to be protected. Provided there is no fault path within the zone the currents will sum to zero.

If a fault occurs this will no longer be true and a difference signal will be generated operating the over current trip on the circuit breaker.

Differential protection can be used to create zones around individual bus sections in a multi-split redundancy concept connected as a ring. With this arrangement only the faulty bus section is tripped and all other bus sections remain connected. This has advantages if some of the bus sections do not have a generator connected.

Differential protection schemes can have problems with high levels of through-fault current. That is current passing through a healthy zone on its way to a fault in some other zone. There have been problems with healthy zones tripping causing failure effects exceeding WCFDI. It is for this reason that some designers favor arc protection for this application.

The effectiveness of differential protection for bus bar applications is difficult to establish conclusively without conducting short circuit testing.

Differential protection is almost universally applied for the protection of generator windings on machines above about 1.5MVA.

9.7.5 **Directional over current protection:** Directional over current protection is sometimes applied for bus-bar protection. It is less expensive than differential, due to the reduced number of current transformers required to define a protection zone. Directional over current generally cannot be used with ring configurations as it depends on blocking the upstream circuit breaker from tripping.

9.7.6 **Earth fault protection:** The size of the power distribution system and the maximum prospective earth fault current influences the type of earth fault protection specified for marine system.

Low voltage marine power systems are often designed as un-intentionally earthed systems where the power system has no direct connection or reference to earth (vessel's hull). On these systems, earth faults are typically indicated by earth fault lamps or meters connected from each line to earth.

Intentional earth impedance should be considered in the case of high voltage systems. High resistance earthing of various types is generally employed.

All power systems are referenced to earth by way of the distributed capacitance of cables and windings. A significant earth fault current can flow even in unintentionally earthed HV systems.

The intentional earth impedance adds to the system charging current when an earth fault occurs and should be sized to provide an earth fault current three times that which would flow as a result of the capacitive charging current. This provides well defined current paths for protection purposes.

Earth fault protection for the main power system is sometimes based solely on time grading. The relay in the earthing resistor or earthing transformers for each bus will detect an earth fault at any point in the plant not isolated by a transformer.

Earth fault protection in the feeders is used to isolate a fault in a consumer. If the earth fault persists after the tripping time of the feeder the fault is assumed to be in the generators or on the busbars itself. At this point the protection driven from the neutral earthing transformers will trip the main busties to limit the earth fault to one bus or the other. Whichever neutral earthing transformer continues to detect an earth fault will then trip all generators connected to that bus. Losing a whole bus due to an earth fault in one generator is unnecessarily severe. Design should consider adding restricted earth fault protection to the generators.

9.7.7 **Over under voltage:** This protection element is often a class requirement. It assists in preventing equipment damage but does not contribute to redundancy concept directly.

There should be other protective functions to prevent the power plant reaching the point at which this protection operates. Over / under voltage protection is not selective and blackout is the likely outcome.

To prevent blackout in common power systems (closed bus), design should provide other protective functions which detect the onset of the voltage excursion and divide the common power system into independent power systems or isolate the sources of the fault before healthy generators are tripped (for example a faulty generator).

Operating the power system as two or more independent power system (busties open) provides protection against this fault.

9.7.8 **Over under frequency:** Under frequency can be caused by system overload and there must be means of preventing the power plant reaching this condition. Such functions are normally found in the DP control system, power management system, thruster drives and other large drives. Over frequency can be caused by a governor failing to the full fuel condition. This will cause a severe load sharing imbalance which can drive up the bus frequency to the point where several healthy generators trip on over frequency or reverse power. The failure scenarios are similar to those for over and under voltage as described above.

9.7.9 **Reverse power:** This protective function is applied to prevent a diesel generator that has lost power from becoming an unacceptable burden on other generators operating in parallel. If a generator with a fuel supply problem sheds the load it is carrying it will be motored by other generators. The power required to motor the faulty generator adds to the load on the healthy generators.

Although the reverse power trip is a useful function, it makes healthy generators vulnerable to being forced to trip on reverse power if a faulty generator takes all the load. In this failure scenario the healthy generators all trip on reverse power and the faulty set trips on some other protective function leading to blackout.

Vessels operating their power plant as a common power system should have a means to detect the onset of a generator fault which could have this effect and either subdivide the power plant into independent power systems or trip the generator that is creating the problem.

Operating the power plant as two or more independent power systems (busties open) provides protection against this type of failure.

9.7.10 **Field failure:** This protective function is designed to prevent a generator with field failure (under excitation) becoming an unacceptable reactive power drain on other generators. However, a generator may also fail due to over excitation. If this happens it may push the operating point of healthy generators into the tripping zone of their field failure protection leading to cascade failure and blackout.

Vessels operating their power plant as a common power system should have a means to detect the onset of a generator fault which could have this effect and either subdivide the power plant into independent power systems or trip the generator that is creating the problem.

Operating the power plant as two or more independent power systems (busties open) provides protection against this type of failure.

9.7.11 **Negative phase sequence protection:** Three phase synchronous generators can only tolerate a limited degree of imbalance in their line currents. Large single phase loads, faulty motors or broken conductors may cause a large imbalance which sets up a backwards rotating field in the generator causing overheating.

Negative Phase Sequence protection is used to trip any generator which has a line current imbalance larger than a defined percentage of the full load current. This protection function is not selective and there is a possibility that all online generators may trip in response to a large negative sequence fault.

Vessels operating their power plant as a common power system should have a means to either subdivide the power plant into independent power systems or trip the circuit (feeder, bus section or generator) that is creating the problem.

Operating the power plant as two or more independent power systems (busties open) provides protection against this type of failure.

9.7.12 **Advanced Generator Protection:** A number of electrical system vendors now offer some form of advanced generator protection. Although the name AGP originates with one particular vendor it has become the generic name for this type of protection.

This protection is intended to protect the power plant from blackouts caused by the common mode, common cause failures discussed above. It is able to detect the types of failures that standard generator protection relays cannot and trip a faulty generator before it can force other healthy sets to trip.

Any DP Class 2 or DP Class 3 vessels intending to operate their power plant as a common power system should be fitted with an appropriate and effective form of Advanced Generator Protection.

Advanced Generator Protection can be provided by systems that are:

1. Independent.
2. Centralized.

Designs based on independence provide each generator with its own dedicated protection function that is able to determine whether that generator is healthy or not. This type of system has another level of protection. If the AGP function in the faulty set is unable to trip itself, the AGPs in the healthy sets will all act to divide the common power system.

Designs based on centralized control usually function on the basis of comparison and voting. In this design a centralized control system attempts to identify which generator is faulty by comparing the operating points of several online generators and using a voting function to determine which generator to trip.

Independent systems are generally considered to be more robust than centralized systems using comparison / voting techniques.

9.8 SYNCHRONIZATION

9.8.1 **Generator synchronization:** Synchronization is the process of matching the voltage, frequency and phase of an incoming generator so that it connects smoothly to the power system at minimal load. Voltage matching is not usually necessary in marine power systems but frequency and phase must be tightly controlled.

The synchronizing process is normally controlled by an automatic synchronizer which takes over control of the generator's governor during the synchronizing process and adjust the speed of the generator to bring phase and frequency within defined limits. The relative speed of the incoming machine is set to ensure it takes a slight positive load on connection. When this has been achieved the synchronizer closes the generator circuit breaker and relinquishes control of the governor which then loads up the generator.

Connecting a generator out of sync can cause very severe power systems transients and these have been known to cause blackout in some cases.

Some marine power systems are robust enough to withstand a 'crash synchronization'. This can be demonstrated by mathematical modeling of the generator and bus bar currents which prove the generators will pull into synchronism before the transient current reaches the tripping point of over current protection.

Modeling of crash synchronization should be carried out for any DP Class 2 or DP Class 3 vessel intending to operate with the power plant configured as a common power system. Modeling may not be necessary if the FMEA can demonstrate that crash synchronization cannot occur because of a single failure. This can be difficult to prove in typical marine power systems.

In the case of vessels operating the power plant as two or more independent power systems, the effects of a crash synchronization are limited to one redundant power system.

Synchronizers may have problems connecting standby generators if the load on the power system is changing rapidly. Incidents of this type have occurred in the past. Such issues have been overcome by initiating a brief thruster command freeze during the synchronizing process.

Potential for failure to synchronize is common to power systems that are operated in both open and closed bus configurations. This scenario can be mitigated by ensuring sufficient spinning reserve and effective load shedding functions in each independent power system.

9.8.2 **Bus synchronization:** Bus synchronization is the process of connecting two independent power systems together. In this process the automatic bus synchronizers will raise or lower the speed of all generators on one bus to match the phase and frequency of the power system to which the incoming bus is to be connected. Failure scenarios are similar to those discussed under generator synchronization.

A suitable opportunity should be chosen to carry out bus to bus synchronizing to limit the consequences should a failure occur.

9.8.3 **Manual synchronization:** Classification societies require that there be an alternative means of connecting generators if the automatic synchronizers fail. A synchroscope with check sync function to supervise the manual closing command is the normal method of meeting this requirement.

The risks associated with manual synchronizing are not significantly different to those associated with automatic synchronization provided there is a check synchronizer.

9.8.4 **Breakout and inadvertent energization:** Inadvertent connection of a stopped generator may occur through maloperation, or a generator circuit breaker control system fault. This type of fault can also causes severe power systems transients with the potential for blackout. A running generator may also suffer a severe mechanical fault which may cause it to break synchronism and pole-slip.

Some marine power systems are robust enough to withstand this type of fault. Mathematical modeling of the protection response should be carried out to prove this for any DP Class 2 or DP Class 3 vessels intending to operate with the power plant configured as a common power system.

In the case of vessels operating with two or more independent power systems the failure effects should be limited to one power system.

9.9 INTERLOCKS

9.9.1 **General:** Dangerous power plant configurations should be prevented by design. Design should identify vulnerable configurations and effective mitigations should be implemented. Interlocks are a common mitigation.

All interlocks are potential hidden failures in much the same way as protection systems are. Critical interlocks should be tested non-destructively and periodically to confirm their effectiveness.

In power distribution systems with several voltage distribution levels it is important to carefully define the protection interlocking strategy to prevent faults on upper levels being back-fed by way of the lower levels and service transformers.

Classification societies may require that all interlocking is hardwired although it may be backed up by software equivalents in the VMS or PMS.

Hardwired interlocking that crosses the boundaries between systems intended to provide redundancy requires careful attention particularly in DP class 3 when it can provide a path for fault propagation.

Interlocks to prevent non redundant configurations which may compromise the redundancy concept by removing its fault tolerance are not a class requirement. These issues are usually dealt with by suitable checklists, consequence analyzers and criticality analyzers of various degrees of sophistication. Design should consider interlocks for preventing non redundant configurations to minimize vulnerabilities to human error or misinterpretation.

9.9.2 **Shore power:** Shore power connection points may be interlocked with the service transformers which supply the switchboard for hotel and auxiliary services.

The practice of inter tripping the service transformers if the presence of shore power is detected may introduce failure modes leading to loss of all thrusters or blackout if the interlocking / inter tripping fails or operates spuriously.

This failure effect can not be avoided by changes in power plant configuration (open / closed bus) and should be designed out.

9.9.3 **Short term paralleling and auto transfer:** Short term paralleling is the process by which a bustie between two switchboards may be closed for long enough to change oversupply from one service transformer to another.

The process may be automated to the point that the operator indicates to the VMS that it should change the supply arrangement and the process will be carried out without further operator intervention.

The design of such systems requires careful scrutiny to ensure they cannot disconnect both sources of supply, if the short term paralleling system has a hidden failure.

Such transfers, if needed, should be carried out during non critical DP operations whenever possible.

Some low voltage power distribution systems are designed to transfer a switchboard or consumer to another source of supply on loss of the normal supply.

Such systems should be designed in such a way that the transfer does not operate if the switchboard or consumer itself is faulty.

9.9.4 **Back feeding:** This term is used to describe the practice of back feeding the low voltage distribution level from the emergency generator. This can be a useful feature for maintenance purposes when the vessel is in dock and the main power plant is not operating.

Interlocks and intertrips associated with this arrangement needs careful scrutiny to ensure the redundancy concept is not defeated, if they fail or operate spuriously.

Classification societies normally require that use of the emergency generator for non emergency purposes is kept to a minimum and that the protection systems for back feeding are arranged to ensure continued operation of the emergency switchboard if there is a fault in a back-fed consumer.

Design should provide clear indication of emergency generator / switchboard status on the PMS power mimic to reduce the risk of putting to sea with the emergency switchboard in harbor mode.

9.10 PROTECTION AGAINST THE EFFECTS OF FIRE AND FLOODING

9.10.1 Classification society rules for DP Class 3 differ from each other and from IMO MSC645. Some classification societies require a higher standard of fire and flood separation than others.

9.10.2 **Physical separation of equipment:** The central tenet of DP Class 3 is that equipment intended to provide redundancy must be physically separated to protect against the effects of fire and flooding. Redundant equipment should be separated by A60 rated bulkheads or equivalent fire protection to A60 requirements.

Common points in the redundancy concept are created by co-location of equipment and cable routes. For DP class 3 there should be no co-location of DP related equipment.

It is not usual for industrial consumers to be fed from more than one redundant power system and effectively create a common point whether the busties are open or closed.

Where this type of design exists it is necessary to prove beyond reasonable doubt that the effects of fire and flooding at the common point cannot adversely affect the operation of all redundant power systems to which they are connected.

If many circuits from more than one power system enter a common space to provide auxiliary services for some part of the industrial function of the vessel there is a risk that fire and flood damage may create simultaneous or sequential faults which may divide the fault current available or extend the voltage dip applied to each power system.

This possibility should be considered in the protection relay coordination study and discussed in the DP system FMEA.

This issue can be avoided by supplying LV consumers from local Motor Control Centers rather than from main LV switchboards. This reduces the number of parallel cable runs into a single compartment. Thus, if the discrimination fails, the failure effect should be limited to loss of the MCC.

Supplying DP related and non DP related equipment from switchboards and MCCs supplied by separate service transformers largely negates the issues of extended voltage dips caused by sequential faults.

It is recommended that dual power supplies to the same space from redundant power systems be avoided if possible. If dual supplies are required, but only one feed is required at a time, then consideration should be given to carrying out the switching function at the main switchboards so that both cables are not live at the same time.

9.10.3 **Fire subdivisions:** All equipment intended to provide redundancy should be separated by bulkheads and decks of A60 rating or by two A0 bulkheads /decks with a low fire risk compartment in-between.

Watertight doors in A60 bulkheads need not be A60 rated but should have a melting point not less than 950°C. Combustible materials should not be located closer than 450mm from the door.

9.10.4 **Watertight subdivisions:** Equipment intended to provide redundancy should be contained within separate watertight and A60 compartments below the damaged waterline. As a minimum, the arrangement of watertight compartments should reflect the split in the redundancy concept and support the worst case failure design intent.

Consideration should be given to locating each thruster in its own watertight compartment. This is required by at least one classification society.

Watertight separation should be considered above the waterline when there is a risk of leakage from large bore pipe work, tanks or other sources.

9.10.5 **Cable and pipe routes:** Cable and pipe routes for equipment intended to provide redundancy should be physically separated by bulkheads of A60 rating. Where this is not possible cables may be run together in a single A60 rated duct where the only fire risk is from the cables themselves. This method should not be used in high fire risk areas such as engine rooms.

Means are to be provided to ensure the temperature of cables within ducts is maintained at or below the rating of the cable when operating at full power.

On open decks, cables in pipes that are separately routed are acceptable.

10 POWER DISTRIBUTION

10.1 DISTRIBUTION PHILOSOPHY

10.1.1 The design philosophy for the power distribution should:

1. Support the worst case failure design intent.
2. Be fully fault tolerant in respect of the defined failure criteria.
3. Follow the divisions in the redundancy concept which define redundant systems.
4. Maintain independence and separation.
5. Closely associate the power source of auxiliary systems for engines and thrusters with their respective main feeders.
6. Ensure the electrical protection scheme supports the redundancy concept.
7. Provide sufficient flexibility without compromising redundancy.

10.1.2 Failure modes in the power distribution should be minimized. Some of the common areas for vulnerabilities to be avoided are:

1. Single busties circuit breakers in DP Class 2 systems. Most classification societies accept a single switchboard being divided in two using a single bustie breaker. Consideration should be given to installing two bustie breakers.

   Note GL may require two circuit breakers between any two bus sections intended to provide redundancy.
2. Dependence on emergency switchboard / generator.
3. Voltage dips associated with short circuit faults.
4. Vulnerability to earth faults in deck equipment on DP distributions.
5. Poor regulation in service transformers.
6. Poor separation of DP and non DP related power consumers.
7. Control lines for interlocks, intertrips and protective functions which cross the divisions in the redundancy concept without adequate protection or selectivity.
8. Poor design of auto changeovers, backup supplies and common connections which can transfer faults.
9. Common backup supplies which span the divisions in the redundancy concept.
10. Co-location of services (DP and/or non DP related) fed from power systems intended to be redundant creates a common point under DP Class 3 failure criteria.
11. In DP Class 3 a common point is created by cable routes supplying non DP essential services where the route includes cables from power systems intended to be redundant.
12. Providing duty standby supplies for auxiliary systems confined to one redundant machinery group from power systems intended to provide redundancy.

10.2 MAIN POWER DISTRIBUTION

10.2.1 The main power distribution level in a diesel electric plant includes the switchboards to which the generators and thruster are directly connected. Power is typically generated at voltages of 690V, 6.6kV and 11kV depending on the size of the power plant. High voltage power generation is chosen because it reduces the required fault withstand rating of the switchboards and reduces the amount of copper required in cables to transmit the same amount of power. Most modern thruster drives operate at lower voltages so it is not uncommon for almost every consumer on an 11kV main power distribution level to be a service or drive transformer. At low voltages consumers may be connected directly to main.

10.2.2 The main power distribution should be arranged to reflect the split in the redundancy concept. Physical separation should be provided for DP Class 3 vessels.

10.2.3 Some classification societies still permit a single bustie between switchboards for DP Class 2. One bustie circuit breaker in each switchboard is the recommended arrangement. Some designs utilize a single bus coupler between two bus sections in the same switchboard. This arrangement is acceptable. The design should provide for two busties between separate switchboards, particularly if the switchboards are in different compartments.

10.2.4 **Low Loss Redundancy Concept (LLRC):** This is a term used to indicate that the redundancy concept is designed to reduce the amount of thrusters and generators lost as the result of single failure to as low values as practical. For example, many LLRCs adopt a WCFDI of one thruster and/or one generator or one fore and aft thruster pair.

10.3 AUXILIARY SYSTEM DISTRIBUTION

10.3.1 Design philosophy should strive to provide independence of main machinery such as generators and thrusters to the maximum extent feasible.

10.3.2 The distribution voltage for auxiliary systems is typically 480V. On vessels with 690V main generation level it is common to find larger motors supplied directly at 690V.

10.3.3 The split in the auxiliary power system should follow the split in the main power distribution system to match the worst case failure design intent. Switchboards for non DP essential services such as accommodation power and other hotel services need not be supplied with the same split or have only limited redundancy provided such arrangements do not compromise the industrial mission.

10.3.4 The auxiliary power distribution level is normally supplied from the main power distribution level by way of transformers. These service transformers should have an earthed screen between primary and secondary sides to reduce the risk of an over voltage failure on the secondary side caused by an internal fault.

10.3.5 The auxiliary power system provides all power for the pumps, fans and compressors used in the engine rooms, thruster rooms and other machinery spaces such as pump rooms.

10.3.6 Design should strive to closely associate supplies for auxiliary systems for engine and thrusters with the main feeder or incomers for those thrusters and generators.

10.3.7 In some applications, it is possible to feed auxiliaries from the high voltage incomer for a thruster by way of a dedicated step down transformer. This significantly improves the independence of the thruster drive. The rational for this arrangement is that if there is no main power, the auxiliary power is not required. It may also offer advantages in terms of reduced cabling for LV distribution.

10.3.8 Exceptions to the above philosophy that may need to be considered in design are:

1. Pre-charging circuits.
2. Cooling water pumps.
3. HVAC and ventilation.

10.3.9 Functions delivered by 1 and 2 are sometimes a perquisite for closing the main HV breaker to a variable speed drive.

10.3.10 HVAC and ventilation may be required for the comfort of engineers while the drive is shut down for maintenance. Consideration should be given to providing a normal supply from the drive auxiliary distribution and a backup supply from the main power systems. Control power UPSs for the drive and other thruster control systems should also be supplied in this manner.

10.3.11 The emergency switchboard is normally fed from the auxiliary power level. It is useful to have more than one feed to the emergency switchboard for flexibility. Difference in failure effects, if any, due to dual feed should be fully understood and documented in the FMEA.

10.3.12 Protection for auxiliary consumers usually consists of:

1. Short circuit.
2. Over load.
3. Earth fault - may be alarm only.
4. Under voltage - with suitable delay where required.

10.4 EMERGENCY POWER DISTRIBUTION

10.4.1 Dependence on the emergency switchboard for DP operations should be avoided.

10.4.2 The emergency switchboard may have several useful functions in a DP vessel in addition to its intended emergency role. Design should facilitate operation of the vessel with the emergency power system completely unavailable.

10.4.3 The emergency switchboard may provide the shore power connection point and be able to back feed the auxiliary power system in harbor mode.

10.4.4 The emergency switchboard should not be required for blackout recovery but may be utilized for longer term black start functions.

10.4.5 Every UPS and battery system should have a main power supply from an auxiliary system switchboard appropriate to the split in the redundancy concept and a backup supply from the emergency switchboard.

10.4.6 All changeovers should have sufficient interlocks and protection to prevent them transferring a fault from one supply to the other.

10.4.7 Failure of backup supply from the emergency switchboard to over voltage should also be considered. This should not be able to affect multiple consumers with backup supplies.

10.4.8 In DP Class 3 designs it may be more appropriate to carry out the switching functions at the switchboards such that only one supply is energized at a time. This prevents voltage dips occurring because of fire or flood damage at the common point created by the compartment.

10.4.9 In addition to all the emergency consumers and lighting required by SOLAS the emergency switchboard may also provide emergency power for certain functions associated with the industrial mission. This may require the emergency generator to be much larger than that found on merchant vessels. Emergency generators of 1MW or 2MW rating are not unusual.

10.5 RATING AND ROUTING OF CABLES

10.5.1 **Rating:** Classification society rules provide extensive guidance on the cable properties and ratings. In summary, cables should be rated for the line current and voltage they will carry, and the following should be considered:

1. Bend radius restrictions may be an issue particularly in HV designs.
2. Ambient temperature is a design consideration.
3. Cables must be de-rated if more than a certain number are grouped together due to the reduction in cooling effect when cables are bundled together.
4. Cable restraints to cable trays must be strong enough to withstand the mechanical forces created by short circuits.
5. Three core and single core power cables may be used as appropriate but single core cables require non-ferrous gland plates to avoid overheating created by eddy currents.
6. Cables for power and control functions should be installed with due regard to electromagnetic compatibility (physical separation requirements).
7. Voltage drop is to be considered.
8. Cables are to be marine approved types and at least flameproof.

10.5.2 Some classification societies may allow cables to be rated for a line to earth voltage lower than that experienced if design provides for automatic disconnection on detection of earth fault. To facilitate alignment with the redundancy concept, it is recommended that cables for DP vessels are rated for the full line to earth voltage that the insulation will experience under earth fault conditions.

10.5.3 **Routing:** In DP Class 2 vessels physically separate routes should be provided for cables to equipment intended to provide redundancy. The cables should be protected from mechanical damage. Cables for redundant systems should not be run together through high risk areas. Control cables for dual networks should be separated and protected from damage.

10.5.4 For DP class 3 vessels the same stipulations above apply but the separation between redundant cable routes should be of A60 rating. Two A0 bulkheads with a low risk compartment in-between are also acceptable. Where a common cable route is unavoidable, cables may be run in a single A60 rated duct provided the only fire risk within the duct is associated with the cables themselves.

10.5.5 Cable transits should not compromise the A60 rating of fire subdivisions. Cable transits should have properties equivalent to the subdivision that they are being used in and be able to withstand the maximum water pressure likely to be experienced.

10.6 SUPPLIES FOR DUTY STANDBY PUMPS

10.6.1 Duty and standby pumps should be provided to improve the availability of the system in the event of pump failure and not to maintain operation if one of the auxiliary switchboards fails. Therefore, the supplies for duty and standby pumps should come from the same side of the power distribution system in a manner that supports the worst case failure design intent. It may be advantages to provide power from different distribution boards for additional security and convenience.

10.6.2 The above philosophy is applicable when the auxiliary system to which the pumps belong serves only one redundant machinery group.

10.6.3 There are some class societies which accept designs in which the auxiliary system serves more than one redundant machinery group provided it has at least two pumps. In this case the pumps should be supplied from redundant power sources (opposite sides of the power system).

10.6.4 Shared auxiliary systems introduce commonality and are not recommended. Such a design may be accepted in the case of seawater cooling systems with appropriate and effective alarm and monitoring facilities.

10.7 TRANSFERABLE GENERATORS AND THRUSTERS

10.7.1 **Class requirements:** Carefully engineered transferable generators and thrusters are accepted by some classification societies. Designs that consider transferable generators and thrusters should be fault tolerant, fault resistant and follow a systems engineering approach.

10.7.2 Transferable or dual fed consumers are treated differently by different classification societies. In some DP notations thrusters of this type can be considered to contribute to redundancy as follows:

1. Thruster with changeover power supply which does not stop when the power supply is changed over.
2. Thruster which draws power continuously from two redundant supplies.

10.7.3 Care must be taken to ensure that faults cannot be transferred from one redundant power systems to the other because of faults in one system or in the dual fed consumer itself.

10.7.4 In the case of DP Class 3 vessels, the effects of fire and flood at the common point should be considered and designed such that there is no adverse reaction on either power system.

1. It is possible to cross check active power (kW) using a signal from a reactive power transducer (kVAr) and the product of current and voltage transducer signals to provide a kVA value.
2. It is possible to cross check circuit breaker status by noting whether current is flowing through the circuit breaker.

11.12.15 In the case of circuit breaker status contacts it is good practice to have one normally open contact and one normally closed contact that change state together. An indication of both contacts being in the same state should initiate an alarm. This alarm will be initiated when the circuit breaker changes state or when a line break is detected on closed contact. It is acknowledged that line break on an open contact will not be detected until there is a change of state. Design should provide line monitoring to facilitate immediate alarm initiation for line break.

11.12.16 All practical measures should be taken to ensure that errors in the power available calculation are detected. The following features may be used to increase confidence in the calculation.

1. Provide error checking of circuit breaker status contacts by duplication and line monitoring.
2. Cross check power measurements using information from other transducers.
3. Cross check status measurements against circuit breaker current.
4. Line monitor all transducers.
5. Confirm the accuracy of transducers periodically.
6. Ensure there are unambiguous alarms and indications to warn the DPO that the power available calculation may be in error.

Maintaining adequate spinning reserve provides a means to reduce the effects of erroneous calculations.

11.12.17 In the case of vessels that have the ability to operate with the power plant configured as two or more independent power systems, separate power management calculation should be performed for each power system. In the case of a distributed control system all the hardware and software should also be separate.

11.12.18 The design of centralized control systems should exercise additional care to ensure calculations for independent power systems are truly independent.

11.13 REMOTE CONTROL

11.13.1 Automatic and remote manual control are functions normally provided by automation systems like PMS and VMS. The degree of automation is a matter for owner preference, as is the degree of remote manual control. Power management systems normally control all generator circuit breakers. Failure of the power management system should not cause spurious opening of generator circuit breakers leading to cascade failure and blackout or loss of position if load shedding intervenes.

11.13.2 Similarly, remote control facilities for thruster and service transformer circuit breaker should not cause spurious tripping. Such failures could cause multiple thrusters and/or generators to be lost.

11.13.3 Decentralizing the control interface to the power plant in such a way that matches the split in the redundancy concept provides a high degree of protection against the effects of hardware failures exceeding the worst case failure design intent. Consideration should be given to further distribution of the interface by providing one field station for each item of main machinery such as a generator or thrusters.

11.13.4 Failure of remote control systems should not inhibit local / manual control.

11.14 LOAD SHARING

11.14.1 **General:** Generators operating in parallel in a common power system must share load in proportion to their rating so that the full capacity of the power plant can be reached without any one generator overloading first. Failure to ensure balanced load sharing can result in one generator becoming overloaded leading to cascade failure and blackout or limiting the amount of power to less than the capacity of the power system.

All methods of load sharing have the potential to cause power plant instability if they fail but some methods introduce greater commonality and therefore greater risk than others. Design should strive to reduce commonality.

There are various methods of load sharing and the main ones are discussed in the sections that follow.

11.14.2 **Load sharing by compensated droop:** Mechanical governors used in early marine diesel electric plant were operated in uncorrected speed droop mode. These mechanical governors were less accurate than their modern digital counterparts and relatively large differences in the load carried by each generator could develop due to wear and other factors. Power management systems were used to trim out the difference to restore load sharing and correct the frequency across the entire load range. PMS control of the governors is effected by way of ‘raise’ and ‘lower’ contacts which drive the governor speed set point up and down to balance the load and maintained frequency. These contacts are a relic from the days when mechanical governors were controlled by ‘speeder motors’ as the remote control interface and are susceptible to failure modes.

Most modern governors still provide this interface facility. These contacts have been known to stick in either the raise or lower position causing the generator to shed load or take more load with the potential to destabilize the entire power plant if operated as a common power system.

This type of load sharing system also takes no account of the fact that a generator may have a problem which is temporarily reducing its capacity to deliver power. The PMS may continue to increase the governor set point to force the generator to carry more load. A typical example is a stuck intake valve or a fuel system blockage. If these faults subsequently clear, the capacity of the generator is driven to the PMS set point, which may be at maximum, leading to severe load sharing imbalance, excessive bus frequency and possible blackout.

Power management systems that trim governors are susceptible to the above faults and should have means to mitigate the consequences.

11.14.3 **Load sharing by isochronous load sharing systems:** The advent of electronic governors driving electro mechanical actuators for fuel control allowed the development of isochronous load sharing using analogue or digital load sharing lines. In this method of load sharing the governors operate in constant speed mode rather than speed droop. In constant speed mode the generators do not naturally share load and slight differences in speed set-point caused by measurement and control errors leads to one generator taking the entire system load.

In constant speed mode, information on the load being carried by each generator is passed to all other generators to make them share load equally. If the load sharing lines fail, a severe load sharing imbalance will develop and blackout may follow. Most manufacturers of these types of system offer redundant load sharing lines or functions which transfer control to uncorrected drop mode on detection of load sharing line failures. Although these methods address many of the deficiencies they are not sufficient in themselves to remove all failure modes that could result in blackout. Design should provide additional protective functions. Some vendors have developed protective functions that can be implemented on isochronous load sharing systems.

Note: A common error in the design of these systems is to omit contacts that follow the status of the main bus ties allowing each system to operate as an independent power system.

11.14.4 **Load sharing by fixed speed droop:** The advent of accurate digital governors has allowed a return to the use of uncorrected speed droop mode without the disadvantages inherent in the old mechanical and hydraulic governors. Accurate load sharing can now be obtained with minimal speed droop using these types of governor. This arrangement has the fewest number of failure modes and does not rely on the power management system for trimming nor does it depend on protective functions to transfer operating mode to speed droop. There are governor failure modes that can destabilize the power plant and protective functions are require to subdivide the common power systems or trip the faulty generators to prevent blackout. Vessels which are not at risk from this type of failure by virtue of operating their power plant as two or more independent power systems can still benefit from protective functions which reduce the risk of losing more than one generator on the same power system. Loss of multiple generators on one independent system is an undesirable failure effect even if the integrity of the other systems is maintained as it may impact the industrial mission. Some vendors have developed protective functions that can be implemented on power systems operating in uncorrected speed droop.

Note: Failure to full fuel is always an undesirable failure mode but it should only succeed in causing a blackout of a common power system if the system load is less than the rating of the faulty generator. The adoption of variable speed thruster drives makes this condition more likely and very large vessels can DP in benign conditions at very low load. Thruster bias can be used to increase the systems load as mitigation. It is difficult to reconcile burning large amounts of fuel as a protective function with an environmentally conscious policy.

Thruster bias, as a method of protection, may be defeated by load shedding systems that act on the overload of a single generator. It should be noted that the ratio of generator rating to system load increases with subdivision of the power system. The risk of partial blackout is increased by designs operating as multiple subdivided power systems. The risk of partial blackout may be acceptable in preference over the consequence of a full blackout. To mitigate against partial and full blackouts, protective functions associated with governors and AVRs are recommended for open and closed bus power system configurations.

It is reiterated that integrity and success of open bus power system operation is dependent upon the engines performing to their rated capacity. Maintenance objectives should be geared to achieving this.

11.15 BLACKOUT PREVENTION

11.15.1 **Power priority:** In diesel electric power plants there may be a need to prioritize power to the most important consumers. The thrusters and the auxiliary systems that service them are usually the most important consumers and if there is a need to shed load to prevent blackout these are the last to be affected.

Consumers associated with the industrial mission are normally the first to be shed unless integrity of power supply is to be maintained for safety reasons or to prevent potential escalation. Example power to drawworks designed for active heave compensation (additional information on active heave compensation is provided below). Designs should strive to ensure adequate power margins are available to supply station keeping and safety critical industrial consumers.

It may also be possible to identify a large amount of non essential load associated with heating, HVAC and ventilation that could be shed first if problems occur.

11.15.2 **Active heave compensation:** All systems and industrial processes should be designed to fail safe on loss of power as it must be accepted that supply breakers, transformers or generators can trip at any time. Design should explore opportunities to provide sufficient power to bring safety critical industrial consumers to a safe condition in the event of a shortage of power, by temporarily diverting power from the thrusters. This diversion should not result in a position excursion that exceeds defined limits. If the position excursion exceeds these limits, priority for power should be returned to the thrusters.

In very large DP vessels such as drillships it may be possible to make use of the large inertia of the vessel to buy time to bring industrial processes such as active heave compensation to a safe condition in a controlled manner.

The use of these power priority functions should be a last resort. Design should make every effort and provide protective functions to ensure the plant is unlikely to reach a condition where it becomes necessary to divert power from station keeping. Such functions should be designed to be fault tolerant, fault resistant and follow a systems engineering approach. There should be a high level of confidence that thruster power priority will not be permanently lost and power will revert to the thrusters on demand. Measures to establish this confidence should span all activities from the design phase through to testing.

11.15.3 **Blackout recovery:** Full automatic blackout recovery of the power plant to pre-blackout conditions (or better) is not a requirement of DP class notation. It should be considered as an essential risk reduction measure and fitted to DP vessels where warranted.

There are elements of SOLAS and main class rules that require a degree of automatic restart of electric power systems. It may be unwise rely solely on these requirements to ensure the vessel has a competent blackout recovery system. Design should provide for a blackout recovery system that is commensurate with its industrial mission.

11.15.4 **Blackout detection:** It is important that the methods used to detect blackout are reliable and that they do not operate spuriously particularly if the first action of the blackout recovery system is to open all the generator circuit breakers before proceeding to reconnect them.

Design should facilitate use of several methods to confirm there has been a blackout including blackout relays, voltage and frequency transducers. However, the diversity provided by this multiple detection scheme can be negated if all detection methods connect to one bus VT.

It is good practice to provide suitable delays to prevent a voltage dip initiating a blackout recovery sequence. Even in power systems with adequate voltage dip ride through it is acknowledged that voltage dips may result in the loss of some auxiliary systems. In such circumstances, it may be desirable for the power management system to restart them. This task should be assigned to a different function from the main blackout recovery function.

The preferred method to reduce the consequences of spurious blackout recovery is to limit the actions of the power management system to starting of consumers and rely on individual protection functions within generators and consumers to disconnect any transformers, faulty circuits and unwanted loads prior to restart.

There have been known and published vulnerabilities experienced in designs that ‘clear the board’ as a precursor to blackout recovery. Such designs need the highest level of blackout detection reliability.

11.15.5 **Automatic return of thrusters to DP:** Modern protective functions have advanced to the point where automatic restart and selection of thrusters into DP following a blackout is recommended. This aids in arresting vessel motion with minimum operator intervention. Some designs will halt automatic reselection of thrusters once vessel motion has been stopped.

11.15.6 **Independence from emergency switchboard:** Blackout recovery should not depend on the emergency switchboard or the emergency generator.

Blackout recovery should be possible with the emergency switchboard and emergency generator unavailable at least for a reasonable period of time. It is acknowledged that beyond a reasonable amount of time blackout recovery may need to depend on the emergency switchboard and generator to provide needed auxiliary systems.

11.15.7 **Testing blackout recovery:** When testing automatic blackout recovery systems it is important to trip the last generator not just shut it down or E-Stop it. This is a more realistic test as most diesel electric vessels blackout with the generators still running but not connected. The test protocol should be appropriately defined taking into consideration the characteristics of the power system. For example, it may be necessary to prevent the tripped generator immediately reconnecting depending on what type of simulated fault was used to trip it. It may be possible to push the lock-out button or simply hold down the CB open button.

Some blackout recovery systems have failed to operate when tested in under realistic failure scenarios even though they have worked perfectly in scenarios where the last engine was emergency stopped or manually shut down. Ideally, blackout recovery should be tested in the following scenarios.

1. Recover from all engines stopped.
2. Recovery from engines running but generator circuit breakers tripped.

Independence of the blackout recovery system from the emergency generator or switchboard should be established by testing and documented to prove the design (Starting of the emergency generator to be inhibited).

Tests should be conducted to validate full and partial blackout recovery on power plants operating in open and closed bus configurations.

11.16 DATA LOGGERS

11.16.1 Data loggers are an extremely useful tool for fault finding and for understanding events leading to DP incidents. Data loggers for DP control and PMS/VMS should be provided. Data logging functions in modern protection relays are also useful.

11.16.2 Means to ensure the alignment of time and date stamps applied by all data loggers on the vessel should be provided. Using a time signal from a DGNSS is one way to achieve this.

11.16.3 Design should ensure that all data logging functions are powered from a UPS or other battery sources so that they will continue to operate during a blackout.

11.16.4 Data loggers for PMS and VMS should be configurable such that the tags to be recorded can be selected efficiently. Design should consider the most appropriate tags to be recorded.

11.16.5 Guidance on desirable features for data loggers is given in Section 14.21.

11.17 REDUNDANCY AND CRITICALITY ANALYZERS

11.17.1 RCA is a useful tool whose primary objective is to limit the potential for configuration errors and defeating the redundancy concept. It can be integrated into the vessel's automation systems. If properly implemented they can supplement bridge and engine room checklists. A well specified and performed DP system FMEA should contain all the information necessary to develop an effective RCA. RCA is particularly helpful on vessels with complex multi-way splits with many options for cross connection.

11.17.2 These tools are available from a limited number of suppliers.

12 NETWORKS AND SERIAL LINES

12.1 DESIGN

12.1.1 Network design has evolved to Ethernet based solutions and use of communication switches rather than hubs. Configuration of network equipment is a key element of providing the necessary level of fault tolerance.

12.1.2 Networks, as discussed in this section are comprised of:

1. Human machine Interface.
2. Two independent full duplex data highways.
3. Remote Control Unit (RCU) / processor / Programmable Logic Controller (PLC).
4. Network switches.
5. Source of power.

12.1.3 A network topology with a proven track record and demonstrable history of reliability is recommended. The physical star, logical bus network is one such example.

12.1.4 Design of networks for DP should provide

1. Required speed and capacity.
2. Adequate bandwidth to accommodate and support the system design data load.
3. Predictable response across the full range of traffic conditions.
4. Reliability in a harsh environment.
5. Minimum downtime.
6. Ease of maintenance and repair.

12.1.5 Design should facilitate monitoring of the status of the network by the DPO. The alarm terminology used for network alarms should be designed to be readily interpreted and avoid misinterpretation.

12.1.6 Network design has evolved to Ethernet based designs and use of switches and is typically within the scope of supply of the DP control system vendor. In some projects the VMS network may be provided by an automation system vendor who is not the DP control system provider.

12.1.7 Design should facilitate monitoring of the status of the network by the DPO. The alarm terminology used for network alarms should be designed to be readily interpreted and avoid misinterpretation.

12.2 TESTING

12.2.1 Comprehensive tests for a network storm should be carried out during FAT and FMEA proving trials to ensure that such an event cannot fail both networks.

12.2.2 **Serial Links:** Serial interfaces should be tested to show they do not cause a common mode failure. Typical tests should prove that faulty serial interface cannot slow down a controller to a point where more critical controller functions are affected. Wire break tests are not sufficient to prove this and tests to prove immunity to jabber type faults, truncation of a message, frozen message, etc should be carried out. This will require specialized equipment.

12.3 MONITORING

12.3.1 Means of monitoring the performance and redundancy of the networks along with useful alarms should be available to the DP Operator. Monitoring of lost messages, collisions and loading should be available.

12.3.2 A mimic should be provided to show the health of network connections, power supplies and processors throughout the network. This should positively identify any faulty section or component.

12.4 DP ALERT SYSTEM

12.4.1 Networks should not be the sole source of communicating DP alerts.

12.5 TOPOGRAPHY

12.5.1 Generally a star topography has given a long history of satisfactory performance on DP vessels. Network switches should be included so that any faulty network node cannot ‘hang up’ both networks.

12.6 INDEPENDENT JOYSTICK AND MANUAL CONTROLS

12.6.1 These should not use the same networks as used by the DP system to transmit its thruster command to the thrusters etc.

12.7 CABLING

12.7.1 Networks should use fiber optics when they leave a compartment. Consideration should be given to running spare fibers.

12.7.2 Cable runs for redundant networks should be installed in separated cable routes to provide protection from fire and mechanical damage to both networks.

12.8 COMPATIBILITY

12.8.1 There may be compatibility issues between data serial communication systems used by different equipment suppliers. For example an engine supplier may use a different protocol or standard from the vessel automation system provider. Integration issues can be resolved if the engine manufacturer provides their communications interface for testing by the automation system provider. FAT may be a useful opportunity to do this but it needs to be specified in the contracts.

12.9 INDUSTRIAL NETWORKS

12.9.1 Offshore industrial network systems are subject to environmental factors and other design requirements not normally included in the design of an office network.

12.9.2 Design of networks for DP should provide:

1. Required speed and capacity and bandwidth.
2. Predictable response across the full range of traffic conditions.
3. Reliability in a harsh environment.
4. Minimum downtime.
5. Ease of maintenance and repair.

12.9.3 **Required speed and capacity:** The speed of the network and the number of field stations should be matched to the type and number of I/O channels used.

12.9.4 **Predictability:** The system must have some degree of determinism. As systems operate in a real time environment any failure or alarm must be reported and acted on quickly enough to prevent any knock-on effect further affecting the system. The network topology plays a part in this determinism. Token ring networks and star/bus networks operating in full duplex can be considered deterministic. Predictability also means that the performance of the network should be satisfactory across the full range of traffic conditions. Attempts to use data communications to implement protective functions requiring a rapid and predictable response may fail if high data rates delay the arrival of information on which the protective function must act.

12.9.5 **Reliability in a harsh environment:** Offshore environmental factors including, vibration, heat, salt-laden atmosphere, electrical noise, etc. must be taken into account when designing the network system.

12.9.6 **Minimum downtime:** If a network is unavailable, some systems or devices may stop communicating. At a minimum this will mean redundancy is compromised. The network system should have been in service long enough for any inherent design flaws to come to the fore or to have been stress tested to ensure mean time between failures is acceptable.

12.9.7 **Ease of maintenance/repair:** A well designed system should have built-in diagnostics that enable the electrical or instrument technicians to quickly pinpoint where system failures have occurred. Most vendors now provide some type of net status page or mimic on the HMI to assist fault finding. Where possible, modules should be designed to allow them to be swapped out either without switching off the rest of the network, or by isolating just the faulty section.

12.9.8 Other issues which may influence the choice of a particular network are compliance with relevant standards, scalability and ease of use.

13 UNINTERRUPTIBLE POWER SUPPLIES

13.1 PURPOSE

13.1.1 The purpose of a UPS in a DP system is to provide:-

1. Stable, clean power.
2. Continuity of power during main power system outage.
3. Power system transient ride through capabilities.

13.1.2 Design of UPS systems follow either a centralized topology or distributed topology. Centralized topology lends itself to a robust system but introduces commonality while a distributed system potentially could be less robust but minimizes commonality. Commonality potentially increases the amount of equipment lost as a consequence of failure.

13.1.3 The design of UPS systems, their power sources and distribution should:

1. Accomplish robustness.
2. Follow the WCFDI.
3. Not introduce additional vulnerabilities.

13.2 TOPOLOGY

13.2.1 Design of UPS systems follow either a centralized topology or distributed topology. Centralized topology lends itself to a robust system but introduces commonality while a distributed system potentially could be less robust but minimizes commonality. Commonality potentially increases the amount of equipment lost as a consequence of failure. Distribution of UPS power from centralized sources may be particularly challenging in DP Class 3 designs but some compromise between a large number of small UPSs and fewer larger UPSs (supporting the overall split in the redundancy concept) should be achievable.

13.2.2 The redundancy concept should not be dependent on battery endurance. UPSs should be provided in a manner which supports the WCFDI and matches the divisions in the redundancy concept. (Minimum two UPSs for DP Class 2 two-way split and minimum three UPSs for DP Class 3 two-way split plus backup DP control system).

13.2.3 The UPS battery endurance should only be considered as providing time to transfer control to other control equipment in an orderly manner. The DP system will typically not be fully fault tolerant once one of the UPSs has failed. It may be possible to recover operation by switching to the bypass depending on the nature of the UPS fault but fault tolerance may still be compromised.

13.2.4 Failure of a UPS output should not lead to failure effects exceeding the worst case failure design intent. Input power supplies for DP related UPS's should be split in line with the redundancy concept. Where a group of UPS's share a common input power supply, loss of that power supply (switchboard) should not lead to failure effects exceeding the worst case failure design intent when all UPS batteries in that group are exhausted. Classification society requirements for UPS battery endurance are typically 30 minutes. Consideration should be given to extending the endurance if required by the industrial mission. Where UPS's are provided with a normal and back up supply, the normal power supply should be from the appropriate part of the main power systems. The back up supply should be from the emergency switch board.

13.2.5 Design should acknowledge the reluctance to test UPS systems and incorporate means to establish conditions of the batteries. Testing of UPS systems should include testing under load conditions.

13.3 RECOVERY FROM ESD

13.3.1 Designers should be aware that some UPSs will not start from battery supply alone. This type of UPSs is unsuitable for DP vessels especially, those vessels with Emergency Shut Down (ESD) systems which disconnect the battery on ESD 0 (total shutdown). The UPS will not restart when the battery is reconnected and therefore there will be no control power available to restart the power plant. It may be possible to overcome this by arranging for backup supplies from the emergency generator but this approach makes recovery from ESD 0 dependent on the emergency generator starting. Dependence on the emergency generator for DP operations is to be avoided.

13.3.2 There is significant variation in the quality of batteries available for UPSs and the price difference is often related to the life expectancy of the batteries supplied with a unit. A cheaper UPS may appear attractive but the cost of ownership may be greater if the batteries have to be changed more frequently. Careful consideration should be given to the choice of control system UPSs in the vessel's specification. Further details can be found in IMCA M196 'Guidance on The Design, Selection, Installation and Use of Uninterruptible Power Supplies Onboard Vessels'.

13.3.3 There are several types of UPS.

1. The 'online' type, also known as the 'double conversion' type is the recommended UPS type for control systems onboard vessels.
2. Line interactive types may exhibit a small output voltage glitch as they transfer from line power to battery power. This glitch is usually too brief to affect the operation of controls systems with DC power supplies but may be detected by protective functions on variable speed drives as an indication that the control supply is failing. The drive may shut down in response leading to loss of thrust.

13.3.4 UPS designs having a function called Phase Tracking are not suitable for vessel applications. These UPSs attempt to track the mains power frequency waveform for synchronization purposes and are used in land based applications.

13.3.5 Some types of UPS are unable to charge their batteries from the poor quality power supplies found on some DP vessels due to high levels of harmonic content and poor voltage and frequency stability. Thus their batteries may be discharged when called upon to provide power in a blackout.