Propulsion System Considerations For Research Vessels

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Abstract- **Research vessels are unique among ship types because of the extremely varied nature of their operating profiles and requirements. While most commercial ships and many naval vessels tend to operate in a transit condition at fairly constant speeds, research vessels encounter very different operating conditions depending on the nature of the scientific research being conducted. These varied profiles can put significantly different demands on a propulsion system and make it difficult to design a system that adequately satisfies all the requirements and is cost effective to operate.**

I. Introduction

In selecting the propulsion system for a new research vessel design, it is the naval architect's aim to develop a system that adequately meets the varying operating conditions and most cost effectively supports the demands of scientific research. These operating conditions can include:

a) Long periods at cruising speed transiting to a research site or performing multibeam sonar surveys,
b) Multiple days on station with propulsion and thrusters under dynamic positioning system control
c) Trackline following at high and low speeds with propulsion and with and without bow or stern thrusters
d) Slow speed towing of large, high drag scientific equipment
e) Precise speed control
f) Quiet modes when low noise levels are required to support fisheries or special research

Among the major factors to be considered in the system selection are:

a) *Dynamic Positioning (DP) System Operations* – Research vessels typically require precise DP capabilities in very adverse environmental conditions. In many cases, the power demand for DP can exceed that for normal cruising. DP operations also impart significant cyclical loading to propulsion plant which can result in detrimental effects on machinery and other systems. Realistic definition of the required environmental conditions as well as selecting a propulsion system that can meet them is critical.
b) *Economy of Operation* – With ever increasing fuel prices and the competition for scarce research ship operating funds, economical operation is becoming more and more critical
c) *Acoustic Noise* – Many aspects of oceanographic research, including fisheries assessments and sonar survey, require acoustically "quiet" propulsion systems that comply with ICES 209 guidelines [1]
d) *Electrical System Power Quality* – With the trend toward fully integrated electric drive systems, minimizing electrical power distortion becomes an important concern to avoid detrimental impacts on sensitive ship and scientific equipment
e) *Maneuverability* – Support of overside handling operations, launch and retrieval of equipment, operation in shallow or confined areas, and docking in remote locations
f) Protection from Propeller Fouling with Overside Wires
g) Acquisition Cost
h) *Lifecycle Cost and Reliability* – Research vessels have a very demanding schedule with days at sea often exceeding 300 or more per year. This kind of rigorous operation requires systems and machinery that are very reliable and affordable to maintain
i) *Motion Stabilization* – Systems incorporating vertical axis propellers offer an intriguing potential for improved seakeeping by reducing roll motions. Improved seakeeping performance is perhaps the most important criteria for seagoing scientists.
j) Fuel Efficiency
k) Ice Class – operation in ice areas imposes requirements for heavier

This paper describes propulsor options for general purpose research vessels and focuses on procurement cost, economy of operation, maneuverability and dynamic positioning performance of each propulsor type. The propulsor options considered were:

-Fixed Pitch Propellers (FPP)
-Controllable Pitch Propellers (CPP)
-Z-Drives
-Podded Propulsors
- Vertical Axis Propellers
-AC and DC Drive Systems

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II. Design Requirements

For the purposes of this paper, a set of typical design requirements and operating profile was assumed based on several new general purpose research vessels programs under development. Most new mid to large size research vessels will require an integrated diesel electric propulsion system. For smaller size vessels, variations of geared diesel configurations may be considered, but generally for larger ones, electric propulsion is required to meet the slow speed and precise speed control requirements. The design requirements which have the most impact to the propulsor analysis are:

- Towing 25,000 lbs at 4 kts and 10,000 lbs at 6 kts
- Dynamic positioning in Sea State 4 or higher with a 2 kt beam current
- Sustained speed of at least 10 knots at 80% of the propulsion motor maximum continuous rating (MCR) in calm water.

A specific Dynamic Positioning System (DPS) notation from the classification society may be required for some research vessels depending on mission requirements. IMO Class DP 2 and higher require aspects of redundancy in the propulsion systems, thrusters, and control system. ANNEX 7 Draft MSC Circular Guidelines for Vessels with Dynamic Positioning Systems (DPS) IMO Resolution 645, June 6, 1994 defines the components required for dynamic positioning as well as the differences in the classifications.

A typical research vessel must usually follow a trackline over the bottom within ± 5 meters at best heading at any speed between 2 knots and full power with a constant towing load of up to 10,000 lbs in seas up to sea state 4 or beyond and a 2 knot current (perpendicular to trackline). Permissible maximum variation of the ship's heading from the track course (crab angle) is normally user-selectable up to a limit of ± 45 degrees.

III. Resistance Analysis

The methodology used for bare hull resistance speed-power computations of the various options was the Taylor Series using a worm curve derived from a model test of a large general purpose research vessel known as AGOR 23 [2].

A. Fixed Pitch Propellers

For FPP’s, hull-propulsion interaction factors were estimated to be the same as those measured in the model test. It should be noted the model test featured Z-drives and not fixed pitch propellers, though the hull-propulsion interaction factors should be similar. Appendage drag was developed based on formulas for twin screw, fixed pitch installations. For the FPPs, B-series charts for P/D of 1.3 were used to model the propellers which are mildly flat pitched to compromise between free route and towing efficiency.

B. Z-Drives

The Z drive is a geared, azimuthing propulsion option so named because the drive line resembles a letter “Z”. A right angle upper gearbox resides inside the hull and connects through a shaft to a lower right angle gearbox under the hull which can direct thrust in any direction, thereby eliminating the need for auxiliary thrusters. For Z-drives, the appendage drag number from the formulas was taken from the results of the fully appended parent model test since the tested ship had Z drives.

C. Podded Propulsors

Podded propulsors are essentially similar to Z drives except the drive motor is contained within the lower unit ahead of the propeller. This option offers a very compact arrangement by eliminating the need for drive motors inside the ship. They are very popular for cruise ships. Their use on research vessels is less established because of limited availability in smaller sizes and unproven underwater noise performance because the motor noise is directly coupled to the water.

D. Vertical Axis Propellers

Voith Schneider Propellers (VSPs) were considered for the analysis of the vertical axis propellers. Propeller efficiency data was received from the manufacturer of the VSPs. For VSPs, appendage drag was reduced to 5% of bare hull, approximately what is expected from bilge keels alone, and relative rotative efficiency was assumed to be 1.0. Other interaction factors remained the same. The manufacturer provided propulsor curves from model tests of their units for a similar size vessel.

VSPs offer a unique capability in reducing roll motion of the vessel. In this mode, they act to provide an alternating roll moment out of phase with the ship’s wave induced roll and thereby reduce the resultant response of the ship to seas. If seakeeping is a very important consideration for a new vessel, this capability should be weighed against the relatively higher acquisition cost for this type of propulsor.

E. Towing Conditions

The design condition of towing 25,000 lbs at 4 knots can result in over-torquing of the propulsion motors and drive train elements if they are sized to the free route top speed requirement since significant power is required from the propulsion system at a much lower RPM. Therefore, a computation of towing torque was performed, and the rated power was set by multiplying the towing torque by the towing RPM. The towing condition can often be the governing factor for installed power for many designs.

The VSPs are more complex than FPP and Z-Drives for towing. VSPs in tugs are provided with an end plate that dramatically improves their bollard pull behavior but produces drag at free route. Since VSPs can vary both RPM and pitch, somewhat analogous to a controllable pitch propeller, a high bollard pull was expected even without this end plate. This was not the case when the VSP was sized for the free route condition, even when the thrust was computed at low speeds from the VSP propulsor charts. Voith indicated that unless a tugboat setup was desired it would be necessary to use the next size VSP, resulting in increasing weight and cost. Further study would be required to trade off the cost and weight of a larger VSP against the powers required for cruise vs. free route and the required generator/motor ratings. For this study, a higher power in the towing condition was accepted.

F. Resistance Comparison Results

A comparison of the three propulsor options, Table 1, shows that there is little difference in powering performance, except when towing is considered. Figure 1 graphically depicts the propulsor comparison in DHP.

Table 1
Resistance Comparison for Different Propeller Options

Resistance Comparison (DHP)	**Propellers**	**Z-Drives**	**VSPs**
Required Sustained Speed Power	754	728	852
Minimum Installed Rating for Sustained Speed at 80% MCR	942	910	1065
Required Power for Towing at 4 kts	879	858	1458
Minimum Installed Rating for Towing at 90% MCR	980	953	1620

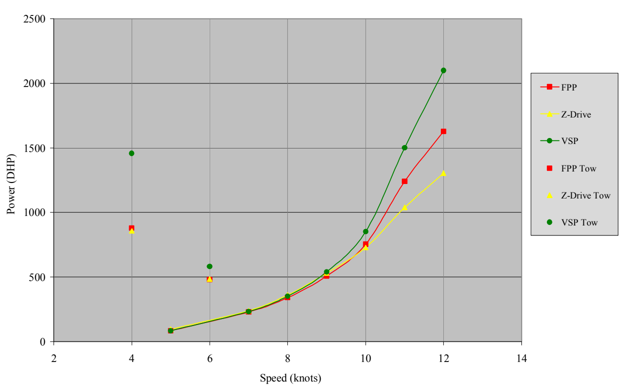

Figure 1. Speed power curves for propeller options

Table 2
Resistance Comparison for Different Propeller Options

Trackline Thruster Comparison **Required Power**	**Propellers**	**Z-Drives**	**VSPs**
Bow Thruster Rating (BHP)	400	413	415
Stern Thruster Rating (BHP)	64	N/A	N/A
Main Propulsion DHP Used	876	1057	1128

IV. ELECTRIC PROPULSION SYSTEMS

The major choice to be made for an electrical propulsion system is whether it will be alternating current (AC) or direct current (DC). Historically, DC systems have been the propulsion option of choice for fine speed control and high torque over the entire operating range. Within the last 20 years, AC systems have become increasingly popular as advances in technology have allowed them to provide the torque and speed control demanded by marine applications. The selection of an AC or a DC system has a major impact on the type of power conversion equipment required. DC technology requires only a single conversion from AC to DC. The DC motor speed is controlled by the DC output voltage of the power converter. AC technology uses a double conversion, AC to DC and DC back to AC. The initial AC to DC conversion provides the power converter with a fixed DC voltage bus. Power from this DC bus is then converted to variable frequency, variable voltage AC. The AC motor speed is a function of frequency and the converter output maintains a constant volts per hertz ratio. This means that at low speeds the output to the motor is low frequency and low voltage. As the motor speed increases, both the frequency and voltage increase. The ratio of volts to hertz remains constant.

Since AC converters require a double conversion, they are significantly larger, heavier, more expensive, more complex and require more cooling than an equal horsepower DC drive. Since AC converters are more complex than DC converters, the ship's crew may require more training (operational and maintenance) than if a DC converter is used. Even though the cost of the AC converter is higher, the cost of the AC motor is lower than a DC motor resulting in an approximately equal system (motor & converter) cost for both AC and DC.

A. HARMONICS

When power conversion units are used there is always a concern for harmonic distortion on the main power system. Harmonics are typically generated when AC to DC rectification occurs. A typical AC to DC converter is three phase and has a six thyrister bridge for a rectifier. This configuration results in significant harmonic distortion on the AC power system which can pose problems for sensitive electronics and science equipment and creates additional heat generation within the equipment. Harmonic current is introduced into the system by the rectifiers. This harmonic current flows through the different impedances (generators, cables, transformers, motors, etc.) in the system and causes harmonic voltage distortion on the AC bus. There are mitigation technologies available that can significantly reduce the amount of harmonic distortion on the AC system.

One method is to provide harmonic filters on the AC bus to absorb the harmonics in the system. This method however creates other power system stability and operational problems. The preferred method is to increase the number of pulses in the rectifier circuit. This can be done by adding phase shift transformer(s) on the feeder side of the rectifier and increasing the number of rectifier bridges. By doing this, lower order harmonics can be significantly reduced in the system; the higher the number of pulses in the rectifier, the greater reduction of the lower order harmonics. Table 3 shows how much the harmonic distortion can be reduced by adding the phase shift transformers and additional rectifier bridges.

Table 3
Harmonic Distortion for Different Rectifiers

Harmonic	6 Pulse Rectifier % Harmonic Current	12 Pulse Rectifier % Harmonic Current	24 Pulse Rectifier % Harmonic Current
5	20	2.6	2.6
7	14.3	1.4	1.4
11	9.1	9.1	0.9
13	7.7	7.7	0.8
17	5.9	0.6	0.6
19	5.3	0.5	0.5
23	4.4	4.4	4.4
25	4	4	4

A 6 pulse rectifier requires one rectifier bridge and no phase shift transformer. A 12 pulse system requires a phase shift transformer with two secondary windings and two six pulse rectifier bridges. A 24 pulse system requires a phase shift transformer with two primary and four secondary windings and four six pulse rectifier bridges. This method is far superior to using filters because it eliminates the harmonic current at the source. The negative side is that it requires phase shift transformers and additional rectifier bridges. The transformers are expensive, occupy additional volume, and can be heavy and generally are custom built to match the system. Although it takes more rectifier bridges each bridge can be smaller as they divide the load equally.

B. AC PWM Converters

In the size horsepower applications for mid and large size general purpose research vessels, the most applicable AC technology would be pulse width modulated (PMW) variable frequency converters. PWM converters use variable width pulses on the output to simulate an AC sine wave. By varying the width of the constant frequency pulse outputs variable frequency and voltage waveforms can be created. The output pulse frequency is generally in the 2 to 10 kHz range.

One of the issues with PWM technology is that the carrier frequency (2 to 10 kHz) creates torque pulsations and vibrations in the motor. The torque pulsations and vibrations can be mitigated through a torsional flexible coupling in the shaft line, but this adds weight and cost and requires periodic replacement of flexible elements. The PWM torque pulsations can also be mitigated using line filters and/or multi-winding motors, which would eliminate/minimize the pulsations. The latter is usually less expensive. The torque pulsations and vibrations can result in airborne, structure borne, and radiated noise problems. This can be an issue for research vessels that desire to meet radiated noise guidelines such as ICES 209. Vendors generally indicate that line filtering and some motor design changes can be used to minimize this problem and that the ICES radiated noise requirements can still be met with AC technology.

In PWM technology there are two options available for the AC to DC conversion. Standard diodes can be used or the converter can have what is called an active front end. A standard PWM converter will use a 6 pulse diode rectifier for the AC to DC conversion. This unfortunately introduces 6 pulse harmonic currents into the main power system. The harmonic distortion however can be minimized by going to a 12 pulse or 24 pulse configuration. This generally will result in no harmonic filters being required. It complicates the system as it will require phase shift transformers and multiple rectifier bridges. Additionally the diode front end does not allow regeneration of power back into the power system. Regeneration is used during crash stop maneuvers to brake the propulsion shaft before reverse torque can be applied to the motor to stop the vessel. Regeneration is typically always used to brake the shaft in a crash maneuver. With a diode front end the PWM converter must use a dynamic braking resistor and chopper circuit. The energy from the propulsion motor is dumped into the dynamic braking resistor to slow it down before reversing the torque on the motor. The rating of the dynamic braking resistor depends on the ahead reach permitted and the minimum anticipated hotel load underway. The chopper is used to control the amount of braking applied. These dynamic braking resistors generate a lot of heat and additional ventilation is generally required when they are used. They also take up quite a bit of space.

An alternative is to use an active front end. An active front end is effectively the same as the DC to AC inverter run in reverse. The active front end is more expensive than a traditional diode front end but has some significant advantages. The primary advantage is that it does not introduce harmonic currents into the power, thus eliminating the need for phase shift transformers and multiple rectifier bridges. The active front end only requires an isolation transformer or AC line reactor. Additionally with an active front end, regeneration can be used so no dynamic braking resistors are required.

In the past, there were issues with AC motors powered from adjustable frequency drives developing high torque at low speeds. Since the development of torque vector control logic in PWM converters, an AC motor is now able to develop high torques at very low speeds without creating excessive heating in the motor. Because AC PWM converters use a constant voltage DC bus, the front end rectifier operates at a very high power factor (0.95 to 0.98 lagging). This is true for both the diode front end and the active front end converters. This high constant operating power factor does not put any additional requirements on the selection of the generator ratings.

C. DC Converters

The DC converter is much simpler than the AC converter since it only requires one conversion. A standard DC converter will use a 6 pulse rectifier bridge. As described above this creates harmonic distortion issues. In order to eliminate distortion problems, 12 pulse or 24 pulse systems are required. With a 12 pulse system harmonic filtering is generally still required. The use of 24 pulse technology has in the past provided satisfactory shipboard power quality and not required the use of harmonic filtering. Another benefit of using 24 pulse technology is that the propulsion motor current has significantly less ripple. Ripple current causes torque pulsations and associated airborne and structure borne noise issues. DC converters also utilize regenerative braking during crash stop maneuvers. There are no dynamic braking resistors required. Full torque is available from zero through rated RPM with a DC converter system.

Since the DC output voltage of the rectifier is variable, the power factor of the converter is variable. The power factor is very low (as low as 0.3 lagging) at low motor speeds (low DC output voltage) and much higher (as high as 0.93 lagging) at full speed (maximum DC output voltage). If sustained operations are required at low shaft RPM, especially when towing is involved because it increases the motor current (torque requirement), then the generator selection can be affected. Typical generators are rated at 0.8 power factor. With the low speed propulsion power requirements the main generator selection will have to consider using lower power factor generators (0.6 or 0.7). This could result in generators that are larger and heavier.

D. Propulsion Motors

The selection of an AC or a DC system has a major impact on the propulsion and thruster motors. AC motors would mostly likely be induction motors or permanent magnet synchronous motors. AC motors in general are smaller, lighter, less costly and require significantly less maintenance than DC motors. Unlike a DC motor, AC motors do not have any brushes or commutators to maintain. DC motors typically require many brushes which can cause significant carbon dust build-up in the motor. This can lead to lower insulation resistance readings as the carbon dust creates tracks to ground.

Because of the low rated speed of the propulsion motors (92 RPM) both the AC and DC motors are going to be large for their horsepower and will have to be a special design. There are no off the shelf motors rated at this low a speed. The bow and stern thrusters should not be as big a problem as they generally have a higher rated RPM and may employ reduction gear boxes. Thruster RPMs are not known however at this time. Typically the thrusters are AC motors with variable frequency drives.

E. AC Induction Motors/Permanent Magnet Synchronous Motors

PWM converters can use either induction motors or permanent magnet synchronous motors in this horsepower range. The induction motor is the simplest. Permanent magnet synchronous motors are often used, however, because they run at a synchronous speed. This means that the speed is directly proportional to the applied frequency. In an induction motor there is slip in the rotor. The motor runs at a slightly less than synchronous speed (synchronous speed minus slip). The slip is proportional to the load applied. Synchronous motors typically also have a little better torque performance.

AC motors have been in use for many years and the technology is well proven. Adjustable frequency drive controls of AC motors have also been around for a number of years and the technology is improving continuously as computer controls are now being used. The risk with the AC motor technology is compliance with low noise requirements. This quiet technology is still relatively new for AC systems. There have been some developments in cruise ship applications and some of the vendors believe that the technology is available to meet the ICES radiated noise requirements. This could possibly require developments in the converter design and the motor design coupled with the use of line filters.

F. DC Motors

DC motors have been used in propulsion systems for many years. The technology is well established and significant improvements have been made through the years in developing ultra quiet motors. This was done through refinement of the winding configuration and the iron core of the machines. Unfortunately since the development of AC adjustable frequency drives and the fact that Europe has switched over almost completely to AC technology, the market for DC motors has decreased significantly. Because of this many manufactures no longer have DC motors or converters available. This has driven up the cost of the DC motors as there is little competition in the market.

As stated above the biggest problem with DC motors is the fact that they require carbon brushes. As these brushes wear they create carbon dust which can lead to grounding problems in the motor’s windings. They require scheduled maintenance which must be adhered to in order to prevent problems. The proper selection of the brushes is critical in reducing maintenance. Brush selection is based on the load profile of the motor. Unfortunately in marine propulsion applications the load profile is not consistent. During high speed transits there is heavy loading on the motors, however during slow speed or Dynamic Positioning System operations the motor load is generally significantly less. This results in a compromise brush selection that is not optimal for either operating condition. DC motors are also quite a bit heavier and larger than a comparable HP AC motor.

G. Selection of Reliable Equipment

The selection of reliable equipment is paramount to the reduction of premature repair and maintenance workload. Given the shipyard's motivation to reduce cost, many yards will procure equipment based strictly on cost. Although the equipment installed must meet ABS, and/or USCG approval or certification, this does not assure reliable equipment will be provided. It is extremely difficult to enforce the procurement of reliable equipment and components in the acquisition contract. Some of the equipment purchased may actually be land based industrial equipment modified for marine use with limited accumulated marine experience. Depending on the acquisition strategy, there are, however some general requirements that can be included in the System Specification that will invoke the procurement of better equipment. These requirements will be the same for either an AC or DC system or a combination of both, and cannot be addressed completely within the scope of this study. They include such requirements as:

- Equipment shall be designed for marine service and shall have a proven service history for similar designs
- Systems and their components shall be designed for a 30 year service
- All systems in contact with seawater shall be constructed of copper-nickel piping

As noted above, these requirements are often difficult to enforce, however, they do result in equipment selections that will be more reliable, less prone to failures, longer lasting and require less maintenance. Redundancy for single point failures in the propulsion systems should be considered and depending on the desired Dynamic Positioning notation significant redundancy may be required.

H. Maintenance Personnel

The use of AC technology will require better training and a more qualified ET or ship's electrician. The technology is more complex than the DC technology. With DC technology however there is significantly more routine maintenance required on the motors.

I. Ship Arrangement and Layout

As noted earlier, the space requirements for the AC and DC systems are quite different. This can affect the machinery arrangements significantly. Table 4 and Table 5 list the significant differences between the two choices. The tables assume that 24 pulse technology will be used to eliminate the need for a harmonic filter. The information presented is applicable to both the main propulsion and the thrusters.

Table 4: DC System Characteristics

PARAMETER	**DC TECHNOLOGY**	
	FACT	**IMPACT**
Converter Size	Smaller.	Less space and lower installation cost.
Converter Weight	Lighter.	Smaller foundations.
Phase Shift Transformer (24 Pulse System)	Two primary windings and four secondary windings required per motor/converter.	Additional space, weight and ventilation required.
Isolation Transformer (Active Front End)	Not applicable	
Dynamic Braking Resistor	Not applicable as regeneration is used.	
Converter Environment Requirements	Less sensitive to temperature.	Less environmental conditioning required.
Noise	Lower electric, airborne and structure borne noise.	Lower ambient noise and hull noise transmitted to the water.
Motor Size	Larger.	Requires more space.
Motor Weight	Heavier.	Requires larger foundation.
Generator Selection	DC converters operate at variable power factors, as low as 0.3 lagging.	Could cause generators to have a lower power factor (0.6 or 0.7) rating and be larger and heavier.

Table 5: AC System Characteristics

PARAMETER	AC TECHNOLOGY	
	FACT	IMPACT
Converter Size	Larger.	More space and higher installation cost.
Converter Weight	Heavier.	Larger foundations.
Phase Shift Transformer (24 Pulse System)	Two primary windings and four secondary windings required per motor/converter.	Additional space, weight and ventilation required.
Isolation Transformer (Active Front End)	One primary and one secondary winding. May also require an AC line reactor instead of a transformer.	Much smaller and lighter than a phase shift transformer. Also requires less cooling.
Dynamic Braking Resistor	If a diode front end is used this will be required. If an active front end is used no dynamic braking resistor is required as regeneration is used.	If required these resistors will require space and additional ventilation.
Converter Environment Requirements	The DC-AC conversion components are more sensitive to higher ambient temperatures. Often requires de-rating in marine environment. If an active front end is used then the same applies to the AC-DC conversion.	Over sized drives may have to be purchased, or additional environmental conditioning required to prevent de-rating.
Noise	High frequency AC noise induced into the motor and from the drive AC converter bridge, which can create airborne and structure borne noise issues.	Additional line filters, isolation mounting and noise insulation may be required in noise sensitive applications. Technologies being investigated could minimize this issue.
Motor Size	Motor generally smaller.	Requires less space.
Motor Weight	Motors generally lighter.	Requires smaller foundation.
Generator Selection	PWM converters operate at constant high power factors (0.95 to 0.98) so no special considerations have to be given in determining generator rated power factor.	Smaller and lighter generators are possible.

J. Bow and Stern Thrusters

In general the thrusters are not in use during quiet operations so they typically are AC systems. It should be required that these units use 24 pulse AC to DC conversion or an active front end to reduce or eliminate the need for harmonic filtering. An active front end is usually not required for thruster applications because regeneration is generally not required.
If possible the thruster units should be selected so that higher RPM motors can be used. The higher the motor RPM, the smaller and lighter the motor will be.

V. Conclusion & Recommendations

Based on previous installations and the proven technology available, thrusters should use AC technology. Even if the noise issue associated with present AC technology is not overcome, the thrusters are typically not in use during quiet operations.

For the main propulsion system, either AC or DC technology is acceptable from a functional stand point. Both systems have their advantages and disadvantages as described previously. There is some radiated noise risk associated with the AC technology as current ICES compliant propulsion systems remain DC. Vendor research and development efforts currently underway should reduce this risk.

Other conclusions of this paper are:

- FPP, Z-Drives, podded propulsors, and VSPs all have comparable installed HP requirements for cruising.
- For the normally modest speeds of a research vessel, the towing condition may become the governing condition in determining required power.
- FPP, podded propulsors, and Z-Drives have comparable powering ratings to meet the required towing conditions.
- All options require bow thrusters.
- FPPs require stern thrusters.
- Z-Drives, podded propulsors, and, especially, VSPs have faster response and more maneuvering capability than FPPs.
- FPPs have the least expensive acquisition costs.
- If seakeeping is very important, VSPs offer the possibility of roll reduction
- FPP offer the lowest radiated noise of any option

The following requirements are recommended for electric propulsion plants:

- If DC technology is used, all converters (propulsion and thrusters) should be a minimum of 24 pulse.
- If AC technology is used, all thruster converters should be a minimum of 24 pulse. On the main propulsion system, the converters should use active

front ends. No dynamic braking resistors should be used.

- Harmonic filters should not be used as the primary means to reduce harmonic distortion. Harmonic filters can create significant issues in the power generation system. If filters are used as a secondary measure of minimizing harmonic distortion, they should be actively controlled by the automation system to prevent power generation problems.

- All converters should be located in conditioned spaces that have the cooling capacity to maintain 75° F at full load on the converters.

- Freshwater cooling for the transformers, drives and motors is recommended to reduce air conditioning load.

- If a DC system is selected, an analysis should be performed to determine the optimal generator power factor.

- If DC motors are used, removal paths should be provided for rotor removal from the ship for maintenance.

- HVAC calculations should consider the heat rejection from transformers (phase shift or isolation). These are often large heat loads at full power.

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REFERENCES

[1] Mitson, R.B., "ICES Cooperative Research Report No. 209 - Underwater Noise of Research Vessels – Review and Recommendations", International Council for the Exploration of the Sea, May 1995

[2] Frank DeBord Jr., Mike Musatow, "Final Report Phase II Model Tests of the Oceanographic Ship AGOR 23", Arctec Offshore Corporation, October 1989