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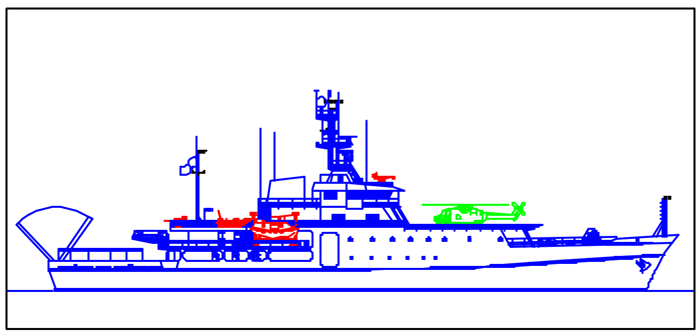
INTRODUCTION

Ships have used electrical motors for propulsion since the turn of the century. Inadequate investigation during the design stage may preclude consideration of electric propulsion due to its high initial cost, additional space and weight requirements. Electric propulsion can however often provide better space utilisation, more economical operations with lower engine maintenance and reduced environmental pollution.

Electric drives provide flexibility in plant layout, plant operations, redundancy and equipment availability.

Electric propulsion is best exploited when applied to specialist ships such as offshore survey vessels, drilling ships, semi-submersible drilling rigs, tugs, icebreakers, ferries, research vessels and passenger/cruise vessels. In all cases electric drive justification requires consideration of the global ship engineering system and operating requirements.



DCMT's staff has extensive experience with electrical propulsion. Studies have been completed for icebreakers, survey vessels and ferries. DCMT has supervised the design and construction of electric propulsion system for oceanographical survey vessels and drilling rigs, completed concept designs for ferries and research ships and undertaken vessel condition survey for Canadian Coast Guard ice breaking buoy and supply vessel.

This document provides guidelines for evaluating ship propulsion systems. The guidelines will assist the decision process when selecting an electrical propulsion system. The ideas outlined will enable the most appropriate propulsion system to be selected based on the ship's intended operations.

Section 1 describes an approach and methodology to determine suitable selection criteria against which a propulsion system may be judged. The guideline emphasizes system comparison on a "global" basis rather than system criticism based on one characteristic. Both mechanical and electrical propulsion systems are discussed with specific reference to icebreakers and research vessels. Specific attributes of electrical propulsion are highlighted.

Section 2 of the guideline describes the various different types of modern day electrical propulsion systems available. The inherent characteristics of a.c. and d.c. motors are described together with the different types of motor converters available. Harmonics is addressed and the harmonic conditions impressed by the different converters are discussed.

Section 3 of the guideline describes the application of electric motors and their converters into a ship's propulsion system and discusses the characteristics and attributes of each system's operation and control.

SECTION 1 – PROPULSION SYSTEM EVALUATION

1. AN EVALUATION METHODOLOGY

When selecting any propulsion system it is important to establish a fair and logical methodology for comparison. A set of selection criteria should be established based on the ship's defined design goals. Each propulsion system should then be evaluated against the design goals and their attributes and constraints ascertained.

1.1 Selection criteria

Propulsion system evaluation requires consideration of:

- The ship's operation and agreed purpose,
- The ship's mission profile , and
- The propulsion and auxiliary power requirements.

From this information a set of "selection criteria" may be formulated and used as the basis for evaluating different propulsion systems based on recognition of the ship's design goals. Primary and secondary design functions can be prioritised and the different propulsion system attributes compared based on their ability to satisfy the defined requirements.

The selection criteria should include:

- *Experience* - propulsion systems presently used, performance and reliability.
- *Technical attributes* - Propulsion characteristics, type of propeller, machinery arrangement and flexibility.
- *Ship design* - Compartment arrangement, weight, fuel and space requirements.
- *Cost* - machinery first cost, overall costs, annualized operating costs, life cycle costs.

1.2 Design goals

Typical primary design goals may be:

- To achieve the mission profile with minimum operating costs.
- To provide a vessel with minimum size and capital cost.
- To provide a high degree of thrust control for slow speed operation.

When quantifying the design goals it is important to also recognise any "multi-task" functions and secondary roles. A typical example would be for an ice-breaking research ship. An attempt must be made to quantify if it is more important for the ship to be a good ice breaker, or a good research vessel. Which function should carry the highest priority.

1.3 Propulsion System attributes and constraints

For each propulsion system under consideration, the system's specific attributes and constraints must be defined, compared and prioritised.

Typical system attributes/constraints would be;

- Performance
  - → Equality – Does each system perform equally for each operational condition of the ship? Do they perform equally under the same operating conditions e.g. in ice, in open water, when towing?
  - → How capable is each system to fulfil the ship's defined operational missions.
- Economics
  - → What is the cost for each system to complete the ship's mission?
  - → What are the annual maintenance costs?
  - → What is the system capital cost?
  - → What would be the total ship capital costs?
- Machinery
  - → For each system what would be the total installed power?
  - → For each system how many prime movers would be required and what would be their rating?
  - → For each system would there be a commonality of prime movers or would different types, or different size units be required?
  - → How complex is each system to operate, trouble shoot and maintain?
  - → What effect does each system have on the ability to control ship speed and engine rpm?
  - → For each system what are the redundancy requirements?

- Ship design
  - → Does each system satisfy the vessel manoeuvrability requirements?
  - → Are acoustics and vibration a concern? Does one system provide easier mitigation solutions than an other?
  - → How mush space does each system require? What are their comparable weights?
  - → In meeting the ship's defined operational requirements, what are the comparative fuel consumption and tankage requirements?

2. WHICH PROPULSION SYSTEM – MECHANICAL OR ELECTRICAL?

2.1 Introduction

The basic characteristic of a mechanical propulsion system is its simplicity. The basic characteristic of an electrical propulsion system is its flexibility. The two alternative systems must however be compared on a wider basis observing their distinct characteristics and capability to:

- Reduce costs,
- Improve vessel control and manoeuvrability.
- Maximise ship power plant usage.

Regardless of the system's *perceived* attributes, reality must be *proven and justified* by a full consideration of the ship's

- operating requirements,
- mission profile and
- global ship engineering systems.

2.2 Mechanical simplicity or electrical flexibility

Mechanical propulsion systems are often preferred because of their

- Simplicity.
- Lower cost.
- Minimum equipment requirements.

Electric propulsion systems are often precluded based on their

- High capital cost,
- Additional space and
- Extra weight requirements.

The above statements are generalities that must be considered individually and specific to the ship under consideration. The flexibility offered by an electrical propulsion system could enable the "power house" to be located more conveniently thereby freeing up space for additional cargo within the same hull size. The simplicity offered by a mechanical system may be eliminated by a need to have unreasonably long shafts in for example an offshore supply boat.

Mechanical systems have lower first costs. Modern control methods permit mechanical drive systems to provide equal operating characteristics to the electrical plant, particularly if controllable pitch propellers are used. Electric propulsion systems have high first costs. They require more space and add additional weight. The electric system may however provide better space utilisation, more economical operations, lower engine maintenance and reduced environmental pollution. To obtain the same propeller torque under bollard conditions generally requires additional power from the mechanical system. Although such power is inherent with the constant power characteristics of an electrical drive, it may be cheaper to provide by up-rating mechanical drive.

Both drives offer substantial merits but they must be evaluated based on what "the job **requires**" rather than providing a system which will just "do the job".

The main advantage offered by the electric drive is its flexibility. Flexibility in plant layout, plant operations, equipment redundancy and availability. Furthermore the electrical drive possesses distinct operating characteristics that can reduce vessel operating costs, improve vessel control, increase vessel manoeuvrability and maximise prime mover usage.

2.3 Icebreaker Propulsion Systems

2.3.1 Introduction

It is interesting to examine the various attributes offered by an electrical and a mechanical drive when applied to an icebreaker. Traditionally icebreakers have used electrical propulsion systems. In the late 70's mechanically driven icebreakers were introduced into the Canadian Arctic. Their continued operation with the Canadian Coast Guard provides ample evidence of the suitability of a mechanical system to perform in the arctic environment. But is the mechanical system necessarily the "best" system. This can only be determined after defining "best" for the specific vessel and having an insight into the inherent characteristics each system can offer the application.

2.3.2 Electrical System Characteristics

Application to Fixed Pitch Propellers

Electrical propulsion system characteristics driving a fixed pitch propeller are shown on figure 1. The propeller demands torque in proportion to RPM. As the ship moves from open water into ice, the motor torque must increase to drive the propeller and at any rpm the torque required changes from that shown on curve (a) to that of curve (b).

At any power level below full power, an increased torque can be provided without loss of rpm. Under open water conditions, full power can be obtained at 80% torque, 120 % rpm, Under ice breaking conditions for example, the same power would be obtained at 100 % torque 100 % rpm.

Operation in Ice

For continuous progress through ice, the motor operates around point "B" delivering 100 % prime mover power at 100 % torque at 100 % RPM. This operating point is slightly lower than the motor's continuous capabilities. (Point N). If ice conditions worsen, or transient ice torques occur, the motor operating point moves closer to point N moving transiently between points B - B'.

Under ice milling conditions, the ice torques are transient and random. Ice torques in excess of 200 % MCR can occur for several seconds. The electric drive delivers these ice torques automatically and by controlling motor excitation and armature current, the motor will provide its full power. Torques up to 200 % can be supplied for up to one minute. Excess torques are met with corresponding reductions in motor rpm, thereby ensuring that the rated prime mover power is never exceeded.

If the propeller stalls in the ice, the motor’s automatic controls limit the motor torque to its maximum. At this point the motor power must be reduced in order to prevent automatic protection functions limiting the available torque. Maximum torque is then available to alternately power the propeller in the ahead and astern direction to free the propeller.

When ramming, the ship must accelerate at its maximum rate. With the electric drive it is possible to achieve the maximum rate available using the chosen propeller and hull design. An electric motor can deliver up to 250% of its rated torque to accelerate the shaft. This torque however must generally be limited and controlled in order to match the loading capabilities of the diesel engines and to prevent excessive propeller cavitation.

Increased torques for ice milling, acceleration and freeing stalled propellers can be obtained automatically up to the maximum torque limit of the motor. The amount of torque available is limited only by the thermal design of the motor. Automatic protection features, matched to the motor's thermal design, ensure that these limits are not exceeded. Typical protection systems operate on an inverse time characteristic such that 250 % motor torque could be provided for up to a minute, 110 % torque for up to 2 hours and normal ice breaking torque conditions, continuously.

Reversals

The electric motor can provide up to approximately 250 % of its rated torque. This torque is available in both the forward and reverse motor directions and accordingly enables the shaft to be accelerated at its maximum rate. As noted above, the acceleration rate generally has to be limited in order to prevent propeller cavitation.

At the start of a reversal operation the ship is moving forwards through the water. The ship's forward passage drives the propeller. This will cause the motor to generate power into the electrical system. This "reverse" power may cause the prime movers to be "driven" rather than to drive and must be limited to within the capabilities of the prime mover, generally 15 %. With an electric drive system the power generators may also be used to provider ship's power and some of the reverse power can be absorbed into the ship's system. Alternatively, resistors or other power consumers may need to be introduced to ensure that the application of reverse torque is controlled to prevent prime mover overspeeds.

When operating in ice, the reverse power is much less than that in open water and limiting the motor reversal rate a small amount, or delaying one shaft reversal a fraction behind the next, is generally adequate.

System controls

The propulsion telegraph is a power controller. Telegraph position determines the maximum delivered motor power. Motor operation is fully automatic and torque requirements are achieved through motor armature and field control techniques.

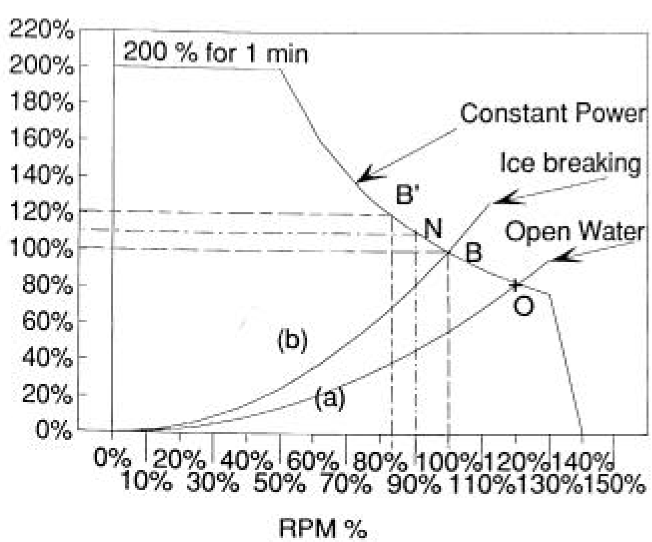


Fig 1 Electrical system characteristics

Protective limits operate automatically and reduce the maximum available motor torque to maintain motor temperature at an acceptable level. The maximum power control limits the capability of the ice breaker to break through a particular ridge, i.e. the electric system is self limiting and protects the machinery regardless of the ice conditions through which the navigating staff may wish to traverse.

The systems incorporate multiple closed loop speed, excitation and armature current regulators adjusted to ensure that the motor's operating values do not exceed their designed values and that the motor operates to provide constant power over a specific rpm range. The transient ice torque demands are met automatically using field strengthening and weakening controls to vary rpm around its nominal operating point. For open water operation, a more accurate rpm control (to within 0.5 %) can be incorporated for vessel position and speed control.

Full power can be obtained by progressively weakening the motor field allowing the propeller rpm to increase to its required value. (Point 'O' - Fig 1.)

2.3.3 Mechanical System characteristics

Drive characteristics

As explained above the electric drive operates on a constant power principle. This is achieved by meeting the increased propeller torque demands, by corresponding reductions in RPM. However the mechanical drive depends upon a fast propeller pitch response to reduce the torque due to ice loads from overloading and stalling the diesel engines.

The mechanical drive operating characteristics are shown on Fig 2 Mechanical Propulsion Characteristics. For comparison, point B, at 100 % torque, 100 % speed is the same for both the electrical (see figure 1) and mechanical drive. The mechanical system uses the propeller pitch controls to operate the system within the engine torque/speed operating range.

Automatic protection systems cause immediate and rapid pitch reductions should the operating conditions attempt to demand higher torques than the engine can deliver. The limits of this protection are indicated on Fig 2.

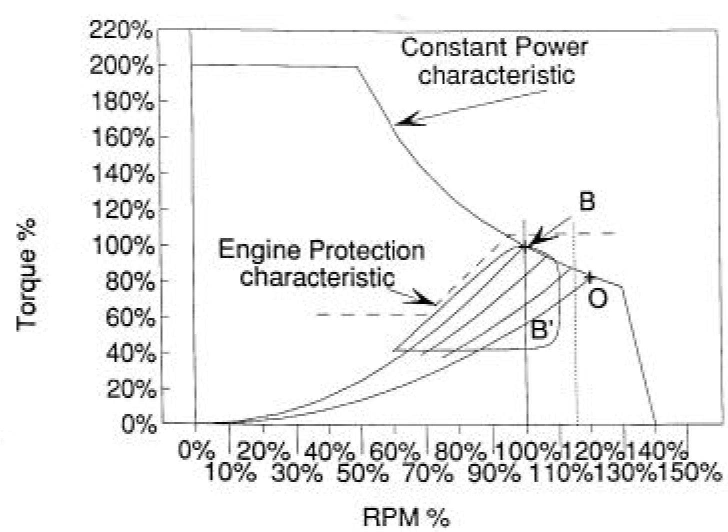


Fig 2. Mechanical Propulsion Characteristics

System controls

The control system senses engine fuel rack position and engine speed. Propulsion telegraph commands are used to increase propeller pitch for maximum thrust. Overloads are detected from the fuel rack and engine rpm signals and pitch and rpm regulators adjust propeller pitch and speed to maintain maximum thrust.

In the event of light over-torques, advantage is taken of the engine's limited over-torque capability. If the over-torque persists, the propeller pitch is reduced in stages to "shed" the load. If heavy overloads occur, the pitch is reduced immediately. The system operates within the area bounded by B - B' (fig 2).

If exceptionally high overloads occur such that propeller pitch reduction is unable to shed load, the clutch between the engine and propeller is allowed to slip. With the electrical propulsion system, such long duration overloads automatically reduce the available motor power. With the mechanical system, clutch slippage is monitored and if excessive, automatic controls open the clutch and disconnect the engine.

During ice milling, the rate of change of pitch can be limited by the presence of ice in the propellers and the rapid pitch changes required to prevent engine overloading may not be attainable. This condition is alleviated by the adding inertia to the propeller shaft. The inertia acts to absorb the ice torque transients and lessens the engine rpm reductions.

2.4 Electrical propulsion system applications

2.4.1 General comments

Electric propulsion is best exploited on multi-purpose and specialist ships. It is often the propulsion system of choice for research vessels, icebreakers, offshore survey vessels, drill ships and rigs, tugs, and large passenger/cruise ferries.

2.4.2 Advantages to exploit

With an electrical system driving a fixed pitch propeller, advantage can be taken of:

- Optimising the propeller pitch to suit specific operational requirements.
- Providing economic operations under prolonged slow speed running.
- The flexible propulsion machinery arrangement, which permit the auxiliary equipment to be more conveniently located for the vessel's operational requirements.
- Using a “Central Power Plant” configuration with multiple equally rated diesel engine generator units for economic operation and maintenance.

When compared to a controllable pitch propeller mechanical propulsion system, the fixed pitch alternative is more economic at low ship speeds. This can be seen from the propeller characteristics shown in figure 3. Even when a combinator is used, the fixed pitch propeller always provides a higher ship speed for the same shaft power.

The Central Power Plant configuration is most advantageous when the vessel's auxiliary electrical loads are high but are not all required during full power operation of the vessel. The number of engine generator sets on line can be controlled to maximise the running load on the minimum number of units.

Economies in installed diesel capacity and general fuel usage depend specifically on the ship's mission profile and must be analyzed taking into account the varying energy requirements throughout a mission.

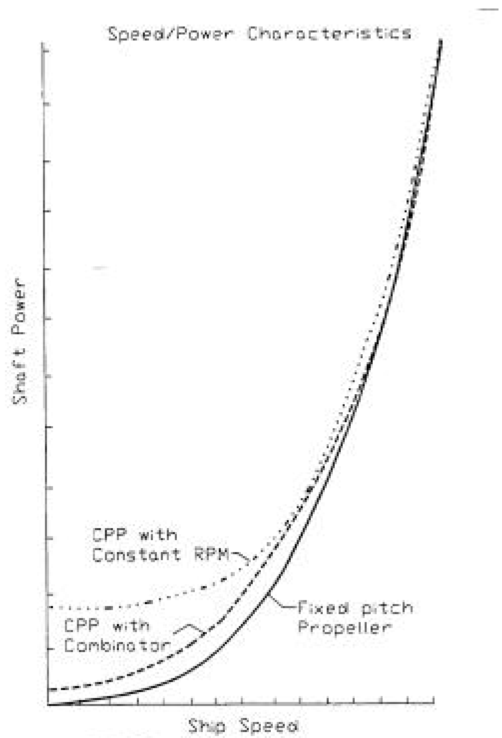


Fig 3. Propeller characteristics illustrating increased efficiency of fixed pitch v. controllable pitch propellers

2.4.3 Electric Drives for Ice Breakers

The specific attributes offered by electric propulsion on icebreakers include:

- A constant power capability.
- From 2 - 2.5 times rated shaft torque almost instantaneously.
- The ability to reduce the potential for prime mover stalling and other mal-effects due to high propeller ice torque demands.

- A highly responsive shaft rpm control.

These attributes assist the ice breaking process as follows:

- With constant power applied to the propeller the maximum ice breaking effect can be obtained regardless of the severity (within limits) of the ice conditions.
- With the high torque available from the propulsion motor;
  - → up to 2 - 2.5 times rated torque is available within 10 milliseconds to clear a stalled propeller blocked by ice;
  - → maximum torque is always available to meet the ice load demands during ice milling;
  - → maximum shaft acceleration can be achieved when ramming and reversing.
- High ice torque impacts on the propeller do not impact on the prime mover.
- The electric drive is highly responsive to shaft rpm change demands thereby enabling the ship's master to control the machinery in the most effective manner as required for navigation purposes.
- Motor speed and torque can be controlled automatically in order to ensure that power is applied within the limits of the prime mover and its turbo-charger.

2.4.4 Electric Drives for Research Ships, Buoy Tenders, Supply Boats and Survey Vessels

For research ships, buoy tenders, supply boats and survey vessels the ship’s operation often requires the crew to work and move large heavy equipment over and alongside the vessel. This can occur in high sea states, typically up to Sea State 4. The risk of an unscheduled propulsion system shutdown or loss of propulsion control cannot be accepted. Crew and equipment safety is paramount.

Propulsion system choice must be cognisant of the operational hazards and include proven features to ensure operational safety. Evaluation of the propulsion system characteristics must demonstrate that:

- Propulsion system reliability is foremost
- Precise vessel control can be achieved

For such ships an electric drive offers:

- Excellent propeller rpm control, which facilitates vessel positioning and control during deployment of instruments and equipment.

- Complete control of shaft rpm at all speeds down to zero, which provides excellent thrust control at low speeds
- Easy integration of propulsion machinery and navigation systems, which simplifies automatic vessel speed and positioning control.

Specifically for research ships, the relative ease of providing noise quietening techniques such as:

- Acoustic enclosures
- Elimination of gearboxes
- Synchronising propellers

These benefits can result in improved station keeping and low noise.

For an ice breaking research ship the change from a constant power control as required for ice breaking to a constant rpm control as may be required for station keeping is easy and simple to implement.

SECTION 2 - WHAT COMPONENTS SHOULD THE ELECTRICAL SYSTEM HAVE?

1. INTRODUCTION

In its simplest form as electrical propulsion system comprises an electric motor and a control device. There are many different types of electric motor, all of which have their distinct characteristics. There are different types of control device, also having their distinct characteristics. This section examines the components of an electrical propulsion system and highlights the characteristics that affect propulsion system choice.

Electric propulsion system choice depends upon:

- Power required
- Shaft RPM and
- The control characteristics required.

As with different prime movers (diesel engine, steam or gas turbine), particular electric motors are more suitable in certain applications than others. Knowing the power and shaft rpm, a choice can be made between:

- an AC Induction motor,
- an AC Synchronous motor or
- a DC motor.

Knowing the control characteristics required, a compatible converter can be selected.

2. TWO/FOUR QUADRANT CONTROL

Whichever propulsion system is used, it must be capable of controlling the ship. For some applications the control can be limited to providing power to turn the shaft and accelerate the ship up to its operational speed. To reverse the ship it may not be necessary to brake the shaft, i.e. the ship slows down due to its own resistance. However the propulsion system must be capable of driving the shaft in a reverse direction.

The marine electric propulsion drive has the capabilities of both a two-quadrant control (powering forward and reverse) and a four-quadrant control (powering forward, regenerative braking, powering reverse and again regenerative braking). Choice of control can determine which system components are required and how they are applied.

From Stop to Full Ahead, the drive applies both positive torque and positive speed to the shaft. From Full Ahead to Stop, the shaft must be braked and the regenerated energy resulting from the ship moving in the ahead direction, must be controlled and absorbed by the system. For astern running the opposites are true. Propeller characteristics are such that as the shaft slows down, the energy to be absorbed increases and consequently the propulsion system used must be capable of controlling this increased energy in addition to the rate at which it is dissipated.

The inherent characteristics of the electric propulsion system have a direct effect on the mechanical components to which it is connected. It is essential that the electric machine is under complete control at all times such that the energy flow from the electrical to the mechanical systems and vice versa is smooth and within the rating and capabilities of the shaft components. Both powering and braking must be matched to the mechanical components to ensure that overloading and component stressing does not occur.

3. PROPULSION SYSTEM MOTORS

Electrical propulsion systems may use either

- direct current (dc) motors or
- alternating current (ac) motors.

Present day technology using solid state converters and inverters, enables both the ac and the dc motor to be controlled with equal degrees of accuracy and accordingly motor choice is more dependent upon the power and speed requirements rather than the machine's controllability.

3.1 The DC Motor

DC motors are widely applied and extensively used for marine electric propulsion. Typical applications include research ships, cable layers and drill ships. The power requirements are generally from a few hundred kilowatts up to about 2 - 4 megawatts with speeds from 120 rpm and up.

The dc motor can be applied at both slow (120 - 200 rpm) speeds for direct drive application and at high speeds (600 - 1200 rpm) where a gearbox can be used.

The higher the speed, the cheaper the motor and in many cases, a high-speed motor and gearbox combination is cheaper than a direct drive motor. The commutator construction limits the power output of a DC motor and consequently for higher powered installations, it cannot be used.

Compared to ac motors, dc motors require more maintenance. However the marine propulsion dc motor is a totally enclosed machine with its own integral closed air circuit. In this environment, maintenance demands are not excessive and many machines have provided over 25 years of trouble free operation.

3.2 The AC Motor

The ac motor is the workhorse of the marine industry. The simple ac induction motor is used almost exclusively for marine auxiliary drives. For marine propulsion, synchronous and synchronous induction motors have been favoured however with recent advances in technology, ac induction motors are now being applied.

Use of ac motors with solid state converters is steadily increasing. Such drives can be economically applied above 2 MW.

3.2.1 Synchronous Motor Drives

Synchronous ac propulsion motors have been used extensively on marine electrical propulsion systems.

On the older ac propulsion systems, speed control was obtained by changing prime mover speed. Modern systems use solid state converters.

Synchronous motors have higher efficiencies and power factor characteristics than induction motors and are more economic in the high power, low speed range. The synchronous motor has a robust construction providing superior shock, vibration and survivability characteristics. It is more suited to direct drive high power, low rpm applications.

Synchronous motors can be economically designed to operate at speeds down to about 80 rpm. The motor field is accessible and accordingly can be easily controlled to provide good motor torque and speed control.

3.2.2 Induction Motor Drives

Induction motors are used extensively for marine auxiliary systems and its use, as a propulsion motor is very attractive. The motor has a simple configuration, a low maintenance requirement and a reasonable efficiency. The ease by which the drive can be applied on rotatable thrusters and under-water pod configurations will likely increase its popularity as an electric propulsion drive option.

The induction motor has a higher overtorque margin than the synchronous motor, but a smaller air-gap. Consequently alignment is critical particularly when the shaft is subjected to high torque impulse loads.

Induction motors are most economically applied in the 900 - 1800 rpm range, with powers up to about 8 MW.

4. WHICH CONVERTER?

4.1 Converter types

In its simplest form the converter is a frequency changer which converts the supply frequency to another frequency and sometimes to zero Hz or direct current. Motor control, both ac and dc, depends upon the type of converter used and its inherent attributes.

Most propulsion drives use solid state converters to convert the supply system constant voltage and constant frequency to:

- A fixed direct voltage (DC Rectifier - uncontrolled)
- A variable direct voltage (Converter - controlled)
- A variable voltage, variable frequency alternating supply (Rectifier/Inverter and Converter/Inverter).

Modern dc motor drives utilize a converter connected to the motor armature. The converter provides a variable voltage to the motor from, which is obtained variable speed. Earlier dc drives used rectifiers and motor field control to obtain variable speed.

Modern ac drives utilize an assortment of converters including:

- Synchro-converter
- Cyclo-converter
- PWM (Pulse width modulated converter)

The synchro-converter uses a controlled converter to obtain dc from an ac source. The dc is then changed back to a *variable voltage, variable frequency* ac power source for the motor.

The cyclo-converter uses controlled converters in a “back-to-back” configuration connected to each phase of the ac motor. It provides a direct conversion between the constant voltage, constant frequency source ac and a *variable voltage, variable frequency* motor ac supply.

The PWM or pulse width modulated converter uses an uncontrolled converter (rectifier) to obtain a fixed voltage dc, which is "chopped-up" to produce *a variable voltage, variable frequency* power source for the motor.

4.2 Solid State Converter Controls

AC motor speed control systems use solid state converters to control both synchronous and induction motors. The control methods employed depend on the type of converter used.

AC motor systems use

- Cyclo-converters,

- Current and voltage source converter/inverter systems, and
- Load commutated inverter/converter systems.

The common characteristic of all these systems is use of an electronic "mathematical model" that predicts motor behaviour, and a "flux-vector" control that determines motor speed and torque control.

4.2.1 Synchronous motor applications

Synchronous motor systems use synchroconverters or cycloconverters.

Synchro-converter operation requires the motor to operate at above 10 % speed. Below this, forcing techniques must be used to ensure successful converter operation. Motor induced shaft torque pulsations can occur and particular attention must be given to the shaft mechanical design.

The majority of ac propulsion systems use cyclo-converters. The cyclo-converter's inherent characteristic to operate at about 1/3 rd the power supply frequency, make it admirably suited to direct drive applications operating around 200 rpm. These systems are more appropriate for slow, direct drive applications and are economical above about 2 - 4 MW.

Cyclo-converters have complex harmonic characteristics. "Beating" occurs between the input and output sinusoidal waves producing side and sub-harmonics, which are difficult to predict. Experience with cyclo-converter systems is however extensive and their harmonic problems recognised. Systems can be designed to ensure such harmonics do not cause serious problems.

4.2.2 Induction motor systems

Induction motor systems use either pulse width modulation techniques (PWM), voltage source or current source inverters. Induction motor systems offer definite economic advantages for medium to low powered marine propulsion applications where low cost, high-speed motors can be used together with a gearbox.

The PWM ac induction motor drive offers definite advantages for marine propulsion applications up to about 8 MW and in particular to thruster applications. As main propulsion drive operational experience is gained, it is likely that this drive will replace the dc motor for low power applications.

PWM converters using non-controlled rectifiers enable the power supply system to retain a high power factor and a low harmonic content. By using a rectifier bridge, the regenerated energy of the propeller cannot be absorbed by either the prime mover or the electrical system and accordingly additional energy absorbing resistors must be connected between rectifier and inverter.

When braking a propeller the regenerated energy increases with reduction in shaft (motor) speed. The resistor's characteristics are such that the energy absorbed is directly related to the voltage applied, which decreases as shaft (motor) speed decreases, directly opposite to the application requirements. Precise shaft control on many ships is relatively unimportant where precise control of the machinery at all speeds is important, a lack of good shaft rpm control can be detrimental to system performance and operational safety.

4.2.3 Mechanical considerations

In designing shafts for modern electric propulsion systems (i.e. where SCR converters are used), careful consideration needs to be given to the torque pulsations present as a result of harmonic currents in the motor current waveform. Such pulsations need to be analyzed as part of the shaft torsional vibration analysis to ensure that shaft resonance do not occur within the normal system operating range.

In addition consideration must be given to the potential high shaft torque that can occur under propulsion motor fault conditions, and design actions taken to limit the maximum torque imposed on the shaft.

4.3 Harmonic conditions and noise

Static converters introduce harmonic conditions that must be addressed. The harmonics occur as a result of the chopped current waveforms produced with a solid state converter. Experience with harmonics is extensive and procedures for their control are available.

4.3.1 Acceptable harmonic distortion conditions

There are few national or international standards that specify acceptable harmonic distortion criteria for marine systems. For guidance reference can be made to IEEE 519 “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”, IEC 92 “Electrical installations of ships and mobile and fixed offshore units”, major classification societies and governmental bodies.

<u>IEEE 519 “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”</u>

IEEE 519 was written primarily for the industrial users and power supply utilities. This standard establishes acceptable voltage distortion levels for a consumer’s electrical distribution systems in order to protect the utilities power quality when delivered to other consumers on the system. The standard also outlines calculation and analysis in addition to providing recommendations for harmonic levels.

Although not specific to marine applications the IEEE 519 harmonic analysis methods and proposed harmonic indices may be applied to marine electrical systems. The acceptable levels of harmonic distortion should be used with care and marine systems have been operated successfully with higher levels of distortion than those specified in the standard. Table 10.2 of the standard recommends Total Harmonic Distortion (THD) for voltage between 3% for special applications and up to 10% for dedicated systems. (A dedicated system is one that is exclusively dedicated to the converter load.)

IEC 92 "Electrical installations of ships and mobile and fixed offshore units"

For marine systems, IEC 92- 101 Amendment #1 Clause 2.8 specifies that the THD should not exceed 5%. This level applies to the ship's general distribution system and not specifically to a propulsion bus supplying a heavy SCR type load. Note 2 to the clause recognizes that harmonic levels may be higher and only requires care to be taken when selecting consumers if this is the case. IEC 92-304 Amendment #1 requires that semiconductor converters shall not cause voltage distortions, which are beyond the capability of other consumers on the system.

Major classification societies and governmental bodies

Lloyd's Register of Shipping requires a THD of no more than 8% at any switchboard. ABS and DnV have no specific requirements.

46 CFR Sub-chapter J has no specific requirements. The IEE (UK) regulations recognize that harmonics can cause overheating and equipment malfunction and only requires that account be taken of such harmonics in the system design.

4.3.2 Recommended harmonic condition judgement criteria

Unless the regulatory bodies being applied to a specific project have specific harmonic distortion standards, acceptable level must be determined by the capabilities of the equipment connected to the harmonic "infested" system and engineering judgement.

IEEE 519 recommends the following harmonic indices as harmonic environment "judgement" criteria:

- Notch depth, notch area and bus voltage (RSS) distortion.
- Individual and total voltage distortion.
- Individual and total current distortion.

The *acceptable* harmonic distortion at a "dedicated" bus supplying only the harmonic producing equipment, depends solely on the capabilities of the connected SCR systems to operate satisfactorily in harmonic environment they produce. These levels must be defined and accepted by the SCR system vendor.

For a ship's service bus, the recommendations of IEEE 519, IEC 92 and Lloyd's Register of Shipping should be applied and the harmonic distortion limited to 5 – 10 % THD.

4.3.3 Harmonic effects

Harmonics in the electrical supply system may:

- Require cables, motors and generators to be oversized for the direct power requirements,
- Cause mal-operation of electronic measuring and other equipment,
- Cause flicker in lighting installations and pre-mature breakdown of fluorescent lighting ballasts,
- Cause oscillating torques in electrical machines,
- Cause unwanted electromagnetic and acoustic noise.

Harmonics can be addressed by

- The installation of suppression chokes or filters,
- System configuration to isolate the harmonic infested bus or to increase the "pulse" number of the system.

When used with SCR converters, the motor design must consider the harmonics and sub harmonics that can occur with such systems and design actions implemented to ensure that magnetic saturation does not occur either on the motor, transformers or system reactors. The harmonic conditions can be improved using reactors between the motor and its converter.

Harmonics reduction will reduce noise and vibration levels. Further improvements are possible by reducing the excitation and ventilation requirements during low noise operation. If exceptionally low noise and vibration levels are necessary (e.g. for use of sensitive underwater measurements, transmissions etc.) specific design features can be included in the motor design such as increased air gaps, high reactance machines, increased yoke thickness, resilient motor mounts etc.

SECTION 3 – ELECTRIC PROPULSION SYSTEMS

1. INTRODUCTION

Conventional ship electric propulsion systems have utilized direct current motors controlled from either dc generators or SCR converters. Advances in power electronic technology have enabled dc motor characteristics to be derived from an ac motor. This section describes modern electric propulsion systems including those using ac motors to take advantage of the reduced weight, size and cost.

2. AC/SCR/DC PROPULSION SYSTEMS

The AC/SCR/DC motor propulsion drive system has been applied to electrically propelled ships for more than 20 years. A typical example of the drive configured with an integrated power supply system is shown in figure 4.

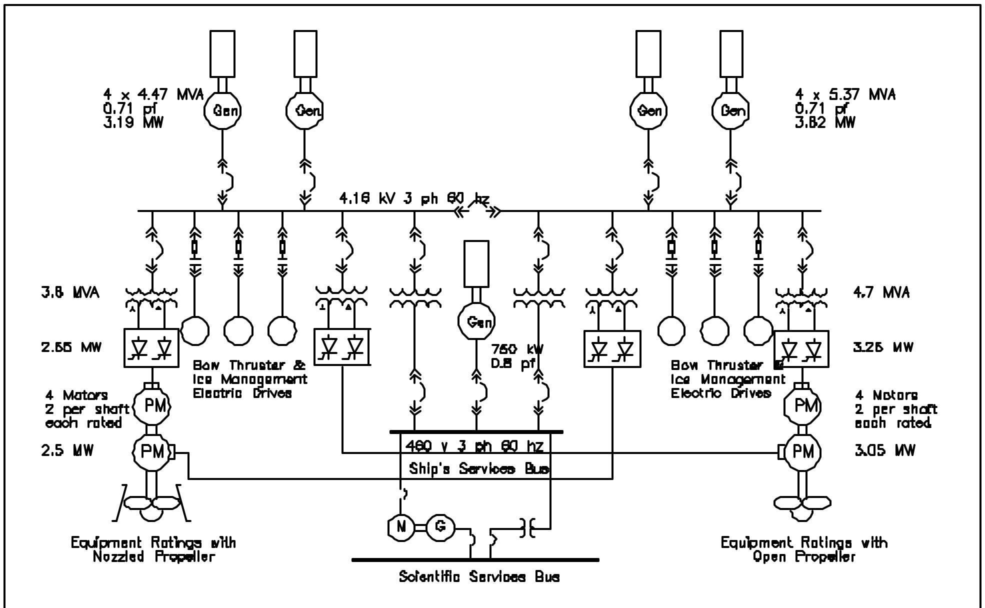


Figure 4 – AC/SCR/DC PROPULSION DRIVE

The technology is well developed and has been utilised for non-marine applications such as steel rolling mills since the late 1960s.

The modern marine ac/scr/dc propulsion system is developed from the AC/Rectified DC motor drive and works on a modified Ward-Leonard principle. The system is designed to drive a fixed pitch propeller either directly by a slow speed DC motor or through a gearbox. Ship speed variation is obtained by changing propeller RPM through armature voltage and field control of the

DC motor.

By using a DC motor, full advantage can be taken its constant power characteristics. Reference to Figure 1 indicates the range of operation available for this drive. Torques well in excess of 100% can be achieved for short times when operating at or near full speed, without exceeding full power.

The DC motor drive can develop high motor torques able to provide rapid acceleration for the propeller (Up to twice rated torque). No load to full load acceleration times of a few seconds can be achieved without causing any unacceptable overload on the system components. Although primarily a function of ship and propeller design, the rapid response times available with this type of drive result in speed demand changes being implemented more rapidly resulting in enhanced vessel control.

The use of AC generators for electric power generation, enables one set of diesel generator units to be utilised for both propulsion and ships auxiliary, hotel and navigation systems supply and advantage taken of the Central or Integrated Power Plant concept.

The inclusion of a large solid state converter load will cause harmonics and distortion of the electrical supply. This may result in additional heating of electrical machines, shaft resonance and additional noise. However such effects are well recognised and can be adequately dealt with using filters.

The solid state devices produce voltage notches, which can be reduced by using a "stiff" power system, i.e. by using a low "sub-transient reactance" generator. A low sub-transient reactance generator, however, results in a higher system short-circuit current and may require the use of more expensive switchgear.

The use of a solid state converter inherently introduces the potential problem of a propulsion motor being short-circuited by the converter devices during regeneration. This results in high torques being applied to the shafting system and care must be taken to ensure that such an occurrence does not cause

- Resonance in the normal operating range of the shaft
- Severe over-torques on the shaft and associated couplings.

Fortunately, such occurrences are limited as they can only occur

- when the motor is regenerating,
- when a failure occurs in the AC system control voltage resulting in an inability of the control system to "turn off" the SCR devices.

The effects of the above must be evaluated at the design stage and either overcome by shaft design, or by the use of high-speed fuses in the AC line.

Inherent in the use of an SCR drive system is that the supply system power factor will vary with the variation in propulsion motor speed and where prolonged low speed operation is contemplated, account must be taken of the possibility of prolonged operation at a low power factor. For a propeller load where the torque generally varies on a square law, although low speed operation results in a low power factor, the current drawn is also low and generally well within the rating of the generator. Care must be taken however to ensure that the generator voltage regulator is able to maintain the voltage within its required boundaries when operating under such conditions.

System control

Full "four quadrant" control (powering, braking and regenerating in both directions of rotation) is possible using a single armature SCR converter and a reversing field control unit. Speed can be controlled accurately with a fast dynamic response to system load changes.

Propulsion motor control is achieved using both armature and field control of the DC motors. In general the control system would set a specific voltage level for the armature dependent upon telegraph setting, and then use field control to "fine tune" the DC motor in a dynamic sense, as load conditions change its speed. In this manner, optimum dynamic control is possible thereby minimising response times to system changes and maximising vessel manoeuvrability.

The control systems provided for this type of drive are normally electronic, microprocessor based using digital techniques. The exact arrangements vary from one manufacturer to another however up to date systems suitable for the marine application would utilise a single module for the generator controls and of a single module for the SCR converter controls. The modules are generally self-diagnostic and are complete with individual "LED" type indicating lights or visual readouts indicating the source of a problem. Such modules are generally specific to an item of equipment and provided with external contacts for connecting to a remote central alarm and monitoring panel. Should a module fail, it would be removed and replaced with a new unit.

3. AC/CYCLO-CONVERTER/AC SYNCHRONOUS MOTOR DRIVE

3.1 System Description

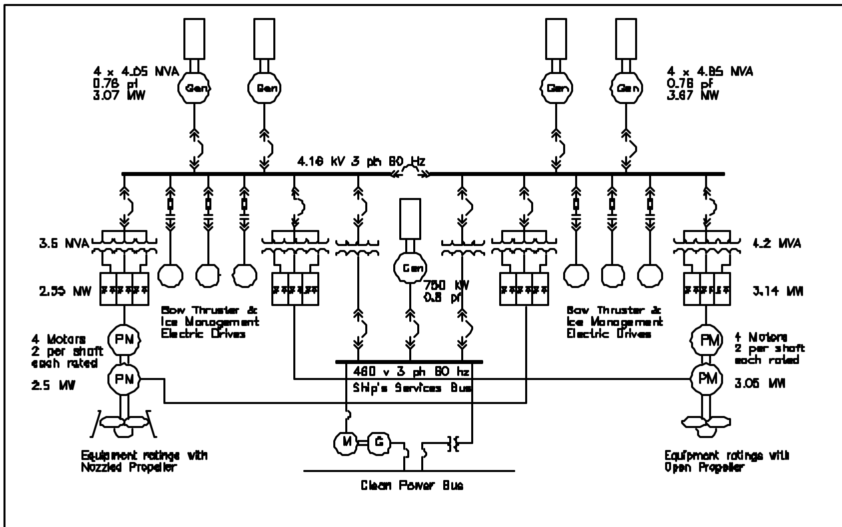


Fig 3. – AC CYCLO-CONVERTER DRIVE

The AC/Cyclo-converter/AC variable frequency synchronous motor drive (AC/CYCLO/FPP AC drive) uses a principle developed in the 1930's when mercury arc rectifiers were used as frequency converters for a railway transportation scheme. A typical system configuration for an integrated system is shown on figure 5.

Utilisation of the cyclo-converter for ship propulsion has increased rapidly over the last 10 years and systems have been used on some Russian icebreakers, the Carnival Cruise Lines cruise ships and some Canadian Coast Guard Icebreakers.

The cyclo-converter is generally applied to large power, low speed drive systems. The marine applications were developed as the demand for higher powered electrical propulsion systems increased. Above approximately 2 - 4 MW, and particularly in the 10 - 14 MW range, the cyclo-converter schemes are more economic than the DC motor schemes.

The system uses an AC motor to drive the ships propeller, speed variation being achieved by varying the frequency of the motor supply voltage. The "cyclo-converter" changes the constant voltage, constant frequency supply source to a variable voltage, variable frequency supply for the AC propulsion motor. Almost identical torque, speed and system response characteristics to a DC motor can be obtained from the AC motor. Although an induction motor can be used with the cyclo-converter, for marine applications a synchronous motor is preferred as its flux can be controlled, and it has superior shock, vibration and survivability characteristics resulting primarily from its larger air gap.

Double armature propulsion motors can be used to increase propulsion drive redundancy. Both brushless and slip ring synchronous motors can be applied to the drive. A slip ring motor provides better controllability, is more efficient and offers a more flexible mechanical arrangement for the shafting system design.

Two basic cyclo-converter arrangements can be applied, one using reactors to supply the cyclo-converter, and one using transformers.

The reactor is simpler than a transformer, requires less space, and is lighter and more efficient. Using reactors results in a higher voltage being applied to the motor windings resulting in a lower stator current and accordingly smaller supply cables.

Transformers are more complex, less efficient and heavier than a reactor however they can be connected in a manner to reduce the total harmonic content seen at the supply terminals.

Cyclo-converters produce complex harmonic currents and distort the AC input waveform. The harmonics can "beat" with the input waveform resulting in the production of sideband harmonics in the input waveform. The sideband harmonics vary in both magnitude and frequency with variation of output frequency and accordingly, for ships electric propulsion drive, harmonics covering the whole spectrum would be present.

Careful consideration must be given to any equipment connected to the main AC supply system to ensure it will work with a harmonic infested supply.

3.2 System Operation

The cyclo-converter is a single stage frequency converter comprising a set of fully controlled SCR "rectifier/inverter" bridges connected to each phase of the input supply and in which the output voltage waveform is composed of segments of the input voltage wave. Each set of bridges is used to chop up the 3-phase supply and produce a single-phase output that is connected to one phase of the AC motor. It is a more complex arrangement than the AC/SCR/DC motor system converter both in operating principle and in control equipment requirements.

The main advantage of this drive is its use of an AC motor particularly in the higher power range. The AC motor is more efficient than the DC motor, less complex and requires less maintenance. Used with the cyclo-converter, the AC motor has similar characteristics and an equivalent dynamic performance to the DC motor drive.

The equivalent characteristics and dynamic response for this system are obtained at the expense of complexity in the system controller. A field orientation technique is used to control motor flux in order to prevent the motor "pulling out of step" under high torque conditions. Motor torque and flux have to be controlled independently. The controller must accurately model the motor and perform extensive mathematical calculations. This is achieved using a high performance microprocessor interfacing the drive motor and system logic controls.

Together with other microprocessor based control equipment the modules incorporate the stator current regulators and synchronising controls, flux regulators, speed regulators, control logic and equipment protection circuits. The control modules generally include self-diagnostic features, fault finding information and message displays.

4. THE AC/PWM INVERTER /AC INDUCTION MOTOR DRIVE

4.1 System Description

The AC/PWM Inverter/AC Induction motor drive (AC/PWM/FPP AC drive) uses an ac induction motor coupled to a reduction gearbox to drive a fixed pitch propeller at variable shaft rpm. The induction motor speed is varied by controlling the output of a dc voltage fed, 3 phase AC, pulse width modulated (PWM) inverter connected to the motor. The PWM inverter is connected to the AC supply system using a diode rectifier bridge. Power regeneration can be achieved either by connecting resistors to the DC voltage bus, by replacing the diode rectifier unit with an SCR converter or by configuring the drives connected to the dc bus to absorb the regenerated power.

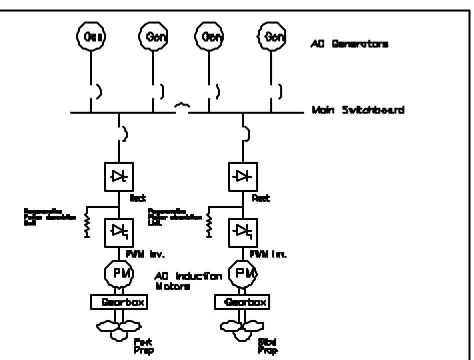


Fig 6 – BASIC AC-PWM INDUCTION MOTOR DRIVE

A basic single line arrangement of the drive is shown on Figure 6.

The PWM AC induction motor drive can offer definite advantages for marine propulsion applications up to about 8 MW and in particular to thruster applications. As main propulsion drive operational experience is gained, it is likely that this drive will replace the dc motor for low power applications. Of those systems in service, there are no reports of dissatisfaction amongst owners or problems with the system.

The technology of pulse width modulation has been available since the 1970's and is well proven in the lower power ranges. With increased solid state device ratings application of this technology into the higher power ranges would seem natural and without undue problems providing adequate precautions are taken with regards to equipment rating and cooling, and cognisance is made of the PWM waveform characteristics when designing the induction motor.

4.2 Control

AC induction motor speed is controlled by varying the motor input voltage and frequency using a "flux vector" controller similar to that of a cyclo-converter drive. Full four quadrant control (0 - 100% forward and reverse, with regeneration and motor braking) can be achieved, and almost identical "dc motor" torque speed characteristics can be attained.

As with all SCR systems, harmonics are generated by the inverter. Because the PWM inverter utilises a different technique for constructing the ac output waveform, a lower harmonic content than that obtained with "phase" controlled inverters is introduced into the ac motor. Furthermore by using a diode rectifier unit to connect the system to the ac line, reduced harmonics occur in the ac supply system. As harmonics are generated, harmonic analyses should be performed and the harmonics accounted for when designing the remaining system. The precautions taken would be similar to that taken for the AC/SCR/DC motor system, but the effects can be expected to be less.

4.2.1 Reverse Power Control

Facilities are required to absorb the regenerated reverse power during vessel manoeuvres. This can be done with resistance units connected to the dc circuit or by replacing the rectifier with a regenerative type converter to allow regeneration into the ship's electrical system. If a resistor is used the effects on the ac supply system will be minimised. By applying control techniques to "slow" the motor reversal time, the power regenerated can be reduced and the resistor size reduced to the minimum possible before ship reversal performance is affected.

When braking a propeller the regenerated energy increases with reduction in shaft (motor) speed. The resistor's characteristics are such that the energy absorbed is directly related to the voltage applied, which decreases as shaft (motor) speed decreases, directly opposite to the application requirements. Precise shaft control on many ships is relatively unimportant however for a research vessel, where precise control of the machinery at all speeds is important, a lack of good shaft rpm control can be detrimental to system performance and operational safety.

If the diode rectifier is replaced with a conventional SCR phase controlled converter, the system can regenerate into the main ac power system. In this case additional harmonics will be generated in the main ac supply lines.

4.2.2 Control complexity

The AC/PWM/AC Induction motor drive is less complex than the AC/Cyclo-converter/AC synchronous motor drive. It is comparable to the AC/SCR/DC motor drive in that it utilises a less complex motor but a more complex controller.

AC motor speed control is inherently more complex than dc motor control. Although the AC induction motor combined with a PWM inverter is able to produce almost identical operating characteristics as a dc motor drive, as with the cyclo-converter drive, obtaining these characteristics is at the expense of a complex controller. (Flux-vector or field orientation control). As a result of the application of the PWM AC motor drive in other industries, experience with this type of controller both in marine and industrial applications is increasing.

4.2.3 Drive advantages

PWM inverters have some definite advantages over phase commutated inverters.

- The method of switching the SCR's reduces the harmonic content in both the ac supply line and the motor during low speed operation.
- Voltage and frequency variation is obtained without requiring a variable voltage dc source and a simple rectifier converts the ac supply to dc. Using a rectifier improves the drive power factor.
- Full speed control is available down to zero speed without loss of control or system dynamic response. Motor "cogging" does not occur.

A major advantage of the voltage source PWM inverter is the reduction of harmonic content in both the motor and system supply circuits as a result of both the PWM technique and the use of a rectifier to connect the inverter to the ac supply system. Harmonics are however still present and considerations of the supply waveform distortion, harmonic heating, motor de-rating and the effects on the generators, switchgear, and protection systems should still be evaluated to ensure an adequate design.

Although an advantage from harmonic considerations, use of the diode rectifier is a disadvantage for dissipating regenerative power during ship Full Ahead/Full Astern and other manoeuvres.

4.2.4 System attributes

The AC/PWM/AC induction motor electrical propulsion system can provide the following system attributes:

- Flexibility of equipment arrangement
- Flexibility in operation
- Economic low power operation
- Superior dynamic performance providing better ship manoeuvrability and control
- High torque capabilities
- Constant power capabilities

The high torque capability, rapid response and constant power characteristics can provide equal performance characteristics to an SCR/DC system or the AC/cyclo-converter system. The superior dynamic characteristics available by using an ac motor will provide better system controllability and so be of advantage in vessel manoeuvrability.

System operation and performance should be equal if not better than that available with the AC/SCR/DC motor drive system with the advantages of increased efficiency and lower maintenance requirements associated with an AC induction motor.

The potential benefits available with a pulse width modulated inverter fed induction motor drive are comparable if not better than that of the AC/SCR/DC motor system and although present marine experience with this system is limited, the prospective costs savings without loss of performance can only be beneficial for marine electrical propulsion applications.