Propulsion Motor Subsystem

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1. Introduction

A propulsion motor subsystem includes equipment that converts electric power from the power distribution system (for ships with an integrated power system) or from a propulsion generator (for ships with a standalone electric drive system) to rotating mechanical power on a shaft that connects directly, or via a reduction gear, to a propulsion propeller or waterjet. If present, propulsion motors can be the sole source of mechanical power for a propeller or waterjet, or can augment other prime movers, such as propulsion diesel engines or propulsion gas turbines as part of a hybrid system. In some cases, such as azimuthing propulsors (also known as podded propulsion), the propulsion motor will also include a propeller and steering functionality. Propulsion motor subsystems can fit within many propulsion and electrical architectures.

For a more in depth discussion, see Doerry (2020) or Patel (2012).

2. Propulsion motor subsystem components

A propulsion motor subsystem is more than just the motor itself. As shown in Figure 1, it also can include a motor drive, propulsion transformers, electrical filters, dynamic braking resistors, shaft bearings, thrust bearings, cooling systems, monitoring and control systems, shaft grounding systems, and cables.

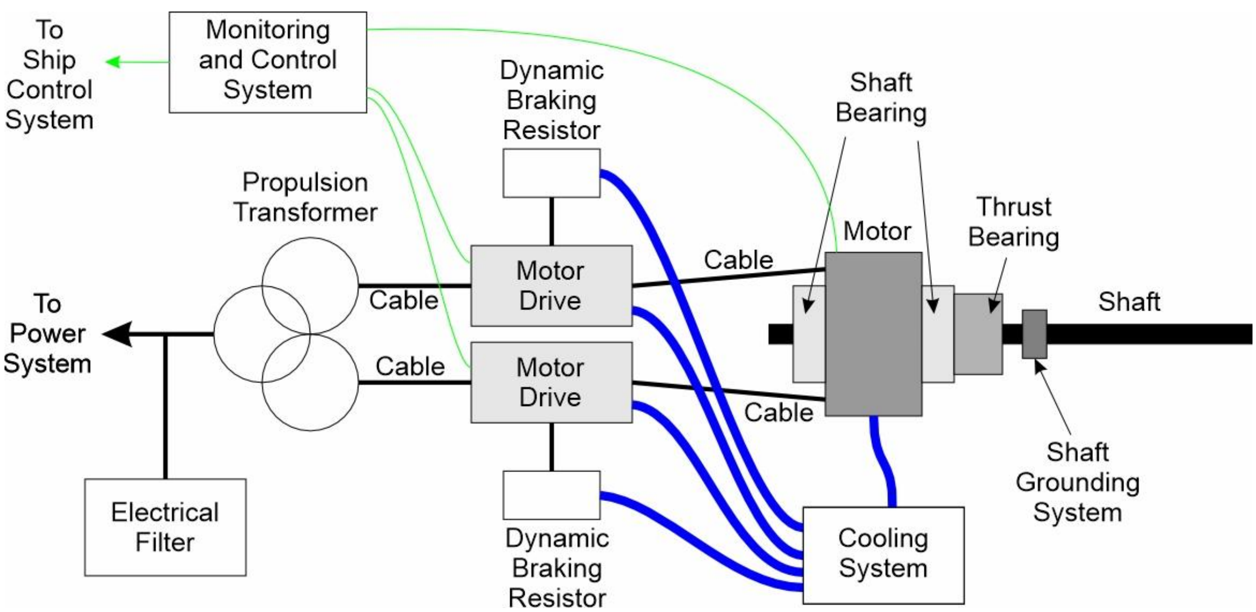

Figure 1: Propulsion motor subsystem

2.1. Motor

As one would expect, a motor is the primary component of the propulsion motor subsystem. Most of the other components of the propulsion motor subsystem exist to support the motor or to ensure the electrical power from the electrical distribution system meets the appropriate interface standards.

There are many types of motors that could be used onboard ship. Each has its own set of advantages and disadvantages. In the end, the motor type that meets the ship's requirements at lowest cost is usually selected. The following subsections briefly describe six of the many types of motors that one may encounter in ship design. See Kirtley, Banerjee, and Englebretson (2015) and Yanamoto et al. (2015) for details on each of the motor types.

2.1.1. Synchronous Motors

Synchronous motors are the most common type of motor used for ship propulsion. In a synchronous motor, a dc current is supplied to a field winding on the rotor. AC is supplied to the stator windings to create a rotating magnetic field. The magnetic field from the rotor is aligned to the rotating magnetic field on the stator resulting in the rotor having a speed proportional to the electrical frequency on the stator. The motor drive supplies the ac power to the stator (armature) winding with the requisite frequency and voltage magnitude to provide the shaft power and shaft speed required by the propeller. The field current magnitude, provided by a field excitation circuit, determines the power factor on the stator windings. The power factor can be adjusted to unity to minimize the losses within the motor.

2.1.2. Permanent Magnet Motors

A permanent magnet motor is a synchronous motor where the field winding has been replaced with high strength permanent magnets. Without the field coil, a field excitation circuit is not needed. Permanent Magnet motors are usually more power dense and more efficient than synchronous motors and induction motors, but are also usually more expensive.

2.1.3. Induction Motors

An induction motor does not provide excitation to the field winding; instead the current in the field winding is induced from the rotating magnetic field from the stator (armature) winding. To produce this induced current, the speed of an induction motor shaft is a little less than the speed of the rotating magnetic field from the stator winding. As with the synchronous motor, the motor drive supplies the ac power to the stator winding with the requisite frequency and voltage magnitude to provide the shaft power and shaft speed required by the propeller. Induction motors can be very robust and cheaper than synchronous motors and permanent magnet motors; however, they usually are less efficient and not as power dense.

2.1.4. Direct Current Motors

Brushed dc motors were at one time very common on ships with modest propulsion power requirements. In a dc motor, the armature windings on the rotor are supplied power via a commuter; the commutator mechanically switches the direction of current flow in various segments of the armature winding in order to produce a magnetic field that interacts with the magnetic field produced by the field winding on the stator. Brushed commutators however, are limited to 1 kV due to the need to extinguish the arc as the brush disconnects from a commutator bar. Due to the high maintenance costs associated with brush wear on the commutator, brushed dc motors are seldom used in new designs. Instead ships with dc systems employ motor drives and ac motors.

2.1.5. Superconducting Motors

Superconducting motors are usually synchronous motors with either or both the stator (armature) winding and the rotor (field) winding employing superconducting wires. Superconducting motors can be very power dense and more efficient than synchronous motors, permanent magnet motors, induction motors, and brushed dc motors. Superconducting motors have not been employed in ship designs (except for an occasional test demonstration) largely due to their high cost.

2.1.6. Homopolar Motors

Homopolar motors are dc machines that do not employ a commutator. These motors however, require high dc currents at relatively low voltage. They also employ high current brushes to transfer power to the rotor. The motor drives are not typical because of the need to deliver large amounts of dc current at low voltage. Homopolar motors can be very quiet because of the lack of torque pulsations from ac operation on ac machines, or commutator operation on brushed dc machines. The field winding on the homopolar motors may employ superconducting windings. Homopolar motors can be very power dense but have not been employed in ship designs (except for an occasional test demonstration) largely due to their high cost.

2.2. Motor Drive

Motor drives convert power from the distribution system to the voltage and frequency required by the motor. Motor drives are often unidirectional in that power can only flow into the drive from the distribution system, and not back into the distribution system. To quickly slow / stop a shaft when stopping or reversing a ship, regenerated power from the propeller may be directed by the motor drive to the dynamic braking resistors. Many, but not all, motor drives employ a dc link internally; a rectifier stage, often called a “front end” is used to create the dc link voltage which is then used by an inverter stage to produce the voltage and frequency needed by the motor.

The front end may employ one of a variety of circuits. Common front ends include passive diode rectifiers, silicon-controlled rectifier (SCR) controlled rectifiers, and power electronic single level or multi-level converters (often referred to as “active front ends”). Similarly, the inverter stage may employ one of a variety of circuits; typically, a single level or multi-level converter.

The design of the front end determines the level of harmonic currents produced by the drive. If these harmonics are greater than specified by the interface requirements for the distribution system, then propulsion transformers and/or electrical filters are used to achieve compliance with the interface requirements.

Cycloconverters have also been used as motor drives. A cycloconverter converts ac power of one frequency to ac power of a lower frequency without a dc link. Cycloconverters can provide high quality output voltages to the motor, but have harmonic rich currents on their input. Consequently, propulsion transformers and electrical filters are usually employed to achieve the required power quality at the interface with the power distribution system.

2.3. Propulsion Transformer

Propulsion transformers are used to convert the voltage of the power distribution system to the voltage needed by the motor drive. Propulsion transformers also are used to reduce the harmonic content of the current at the interface with the power distribution system.

2.4. Electrical Filters

To minimize cost, the input stage of a motor drive (front end) typically employs a circuit topology that results in considerable differential mode harmonic currents as well as common-mode currents. Electrical filters may be used to reduce these non-fundamental frequency current components at the interface with the power system to a low enough level so as to achieve specified interface requirements. Electrical filters can be active or passive. An active filter is essentially a power electronic converter that injects non-fundamental frequency currents 180° out of phase and of the same magnitude as the non-fundamental frequency currents from the motor drive. Passive filters use networks of inductors, resistors, and capacitors to provide a low impedance for the non-fundamental frequency current components and a high impedance to the fundamental frequency component.

2.5. Dynamic Braking Resistor

Dynamic braking resistors are used during maneuvering evolutions when it is needed to reverse the direction of the shaft quickly. The motor drive is configured to have the motor act as a generator to quickly slow the shaft. The regenerated energy from the motor is usually dissipated in a bank of resistors called dynamic braking resistors. Once the shaft is at near zero speed, the motor drive is configured to power the motor in the reverse direction to eventually stop, and then possibly reverse the direction of the ship. Note that the dynamic braking resistor is intended to stop the shaft, and not the entire ship.

2.6. Shaft bearings

Shaft bearings support the shaft and ensure the shaft is properly aligned in the motor. Often, shaft bearings are integrated into the motor housing. In some cases, shaft bearings may be mounted independent of the motor housing as pedestal bearings.

2.7. Thrust bearing

A thrust bearing transfers the longitudinal thrust on the propeller shaft to the ship's hull. The thrust bearing may be located on either end of the motor.

2.8. Cooling System

The motor, motor drive, dynamic braking resistor, and the electrical filter may all require cooling of some type to remove their waste heat. To cool these types of equipment, fans may be employed to circulate cooling air; the air in turn may be cooled with an air to fluid heat exchanger. Common cooling fluids include sea water, fresh water, and glycol – water mixtures. In some cases, heat producing components are directly mounted to cold plates that are in turn cooled by one of the cooling fluids. High power density components may incorporate cooling coils directly in the component design.

2.9. Monitoring and Control System

In addition to the embedded controller within the motor drives, an overall propulsion motor system controller monitors signals from the various subsystem components, interacts with the overall ship-wide machinery control system, and establishes set-points for the motor drive controllers. This controller may be integrated with the motor drive controller, or may be stand-alone.

2.10. Shaft grounding system

Because the rotor is typically made of steel, currents can be induced onto the shaft. These currents, if allowed to flow through the reduction gear or along the shaft to the exterior of the ship, can result in galvanic corrosion. To prevent these currents from causing corrosion, the motor shaft is often grounded using a metallic brush connected to the hull of the ship. For additional protection, some ships also use an insulating material as part of the motor shaft coupling to the rest of the shaft.

2.11. Cables

The cables used to interconnect the propulsion transformer, motor drives, and the propulsion motor are generally specially designed to mitigate the impact of common-mode currents. These cables feature a number of grounded drain wires and shields to control the electric and magnetic fields within the cable.

3. Propulsion motor control modes

Three control modes are typically employed for propulsion motors: Constant power, constant speed, and constant torque. Each of the modes is appropriate for different operational situations.

3.1. Constant Power

Regulating the power provided by the propulsion motor is typically employed under normal operating conditions when precise speed control is not required. By drawing a constant electrical load from the power system, the prime mover speed governors are not reacting to variations in propulsion load; fuel economy is improved and wear and tear on the prime movers is reduced. The constant power mode is particularly useful in heavy seas when the propeller load on the shaft has significant fluctuations.

3.2. Contant Speed

Regulating the shaft speed is appropriate when precise speed control is required. For naval ships, constant speed mode is typically used during underway replenishment when two ships must operate side by side at a fixed speed and separation distance. Constant speed mode may also be appropriate when towing objects behind the ship for special scientific experiments. Regulating shaft speed should generally not be done at high ship speeds; the cubic nature of the speed power curve results in large power fluctuations on the prime movers. Similarly, regulating shaft speed should ideally not be done in heavy sea states.

3.3. Constant Torque

Regulating the shaft torque is appropriate when precise speed control is not required. Constant torque operation in high sea states, debris laden waters, or ice results in less stress placed on the propeller and shafting as compared to constant power or constant speed regulation. Constant torque operation is a compromise between stressing the propeller shaft and placing power fluctuations on the prime movers.

4. Source of losses

In the early stages of ship design, understanding the sources of energy losses within the propulsion system is important for ensuring that sufficient power generation is available and that fuel tanks are of sufficient size to meet endurance requirements. Within a propulsion subsystem, the losses are a nonlinear function of the shaft speed. This section will provide insights as to the sources of loss for the various propulsion subsystem components. See Doerry and Parsons (2023) and Doerry (2020) for additional details.

4.1. Motor

The losses in a propulsion motor are typically dominated by two terms: a no-load loss and a loss that is proportional to the current squared. At low ship speeds, the no-load losses can dominate; for this reason, using a constant efficiency across the entire speed range is not appropriate. See Doerry and Parsons (2023) for guidance in interpolating and extrapolating efficiency data points to determine the losses at any ship speed.

Multiple motors may be connected to the shaft to improve reliability and to reduce losses at low speeds. By using only one motor at low speeds, the no-load losses for the other motors are not incurred. Some motor designs even allow for not powering portions of the motor to further reduce the no-load losses.

4.2. Motor Drive

As with propulsion motors, the losses in a motor drive are typically dominated by two terms: a no-load loss and a loss that is proportional to the current squared. At low ship speeds, the no-load losses can dominate. See Doerry and Parsons (2023) for guidance in interpolating and extrapolating efficiency data points to determine the losses at any power level.

To reduce the no-load losses, multiple motor drives may be used for a single motor; only the number of drives required for the power level may be energized.

4.3. Propulsion Transformer

As with propulsion motors and motor drives, the losses in a propulsion transformer are typically dominated by two terms: a no-load loss and a loss that is proportional to the current squared. See Doerry and Parsons (2023) for guidance in interpolating and extrapolating efficiency data points to determine the losses at any power level.

4.4. Electrical Filters

Both active and passive electrical filters have both no-load losses and losses proportional to the square of the non-fundamental frequency components. The losses are therefore a function both of the electrical filter design and of the motor drive design. Considerable analysis is typically performed in the design of the motor drive and electrical filter to ensure the electrical filter has the capability of dissipating the heat it generates.

4.5. Shaft Bearings and thrust bearings

The losses in shaft bearings and thrust bearings are usually very low compared to the rated power of the shaft. Often these losses are assumed to be within the tolerances of the propeller speed-power curve and therefore neglected.

These losses may be important at very low speeds; the manufacturer of the shaft bearings and thrust bearings should be consulted for estimating the low speed – low power losses.

4.6. Cooling Systems

The power consumed by the cooling system is usually considered a loss since it does not directly contribute to the propulsive power on the shaft. The amount of power consumed depends greatly on the design of the cooling system. In general, the power consumed is not a smooth function of the shaft speed or power; instead, the power consumed tends to rise step-wise as a function of propulsion power as additional fans, cooling pumps, etc. are brought online. The cooling system can be a significant portion of the power consumed when a propulsion motor subsystem is on, but not turning the shaft, or operating at very low speeds. At high speeds, the cooling system losses are proportionally much less.

5. Impact of operational profiles on propulsion motor design

An operational profile generally includes a ship speed vs percentage of time for each operational condition. One objective of design is typically to minimize losses at ship speeds that the ship operates for long periods of time.

If a ship operates most of the time at high speeds, then part-load efficiency is not of concern; minimizing the number of motors and drives often is the most economical. Choosing a motor with high full-power efficiency is beneficial.

If a ship operates much of the time at low speeds, then part-load efficiency is of great concern. Using multiple motors per shaft and perhaps multiple drives per motor such that motors and drives can be turned off when their power capacity is not required can be of great value. It may also be beneficial to choose motors that have better part load efficiencies. Permanent magnet motors typically have better part load efficiencies that synchronous motors which in turn have better part load efficiencies than induction motors.

In gas turbine mechanical drive applications, experience has shown that operating in trail shaft (where only one of two shafts is powered) with one gas turbine online can be more economical at low speeds as compared to powering two shafts, each with a gas turbine online. This is largely due to the large “no-load” losses associated with the gas turbine engines. The no-load losses associated with a propulsion motor subsystem are typically lower; operating in trail shaft is typically not more economical.

6. References

Doerry, Dr. Norbert H., *Integrated Electric Propulsion*, The Marine Engineering Series Edited by Michael G. Parson, SNAME, Alexandria VA, 2020 ISBN 978-1-7923-1226-7

Doerry, Norbert, and Mark A. Parsons, "Modeling Shipboard Power Systems for Endurance and Annual Fuel Calculations," SNAME J Ship Prod Des (2023)

Kirtley, James L., Arijit Banerjee, and Steven Englebretson, "Motors for Ship Propulsion," in Proceedings of the IEEE, vol. 103, no. 12, Dec. 2015.

Patel, Mukund, *Shipboard Propulsion, Power Electronics, and Ocean Energy*, CRC Press, Roca Raton 2012, ISBN 978-1-4398-8850-6

Yanamoto, T., M. Izumi, M. Yokoyama and K. Umemoto, "Electric Propulsion Motor Development for Commercial Ships in Japan," in Proceedings of the IEEE, vol. 103, no. 12, pp. 2333-2343, Dec. 2015.