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A Comparison of Thruster Propellers and Variable Speed Drives for DP Vessels

By: Amrik Kallah

Cegelec. (Rugby, U.K.)

Session Planner

Dietmer Deter: Nautex *Houston*

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Abstract

Diesel electric power and propulsion technology is now well established and is being installed on most, if not all, Cruise Liners, Multi-purpose Shuttle Tankers, Floating Production Storage and Offloading Vessels, Cable Layers etc etc. Innovative dynamically positioned drill Ships are currently being designed and built around the world for oil exploration in ultra-deep waters (approx. 3000m). These vessels invariably have a large complement of thrusters in order to hold position under very adverse environmental conditions. The thrusters may be fitted with a controllable Pitch Propeller (CPP) or a Fixed Pitch Propeller (FPP).

This paper first compares the performance of a CPP thruster driven by a constant speed induction motor with that of a FPP thruster whose speed is varied by a SCR (Silicon Controlled Rectifier) controlled DC motor. Three most important AC-AC type variable speed drives are then described and the impact of each on the design of Power Plant and distribution systems highlighted.

Introduction

Dynamically positioned vessels often employ a variety of thruster types. The following are available:

a) Lateral thrust units or tunnel thrusters.

b) Azimuth (rotatable) thrust units with magnitude and direction thrust controls. The latest development in these is the podded type thrust units with electric motor in the pod rather than inside the hull.

c) Water jets e.g. Gill jet thrust units.

d) Cycloidal propellers e.g. Voith-Schneider thrust units.

The number, size, type and location of these thrusters requires careful consideration. The details are essentially determined by maximum environmental conditions under which the vessel is required to hold position in the event of a single fault. Having decided upon the required complement of thrusters for the vessel, the choice then is whether to use controllable pitch or fixed pitch propellers.

The fixed pitch propeller must be driven by a variable speed drive in order to adjust and if necessary reverse the thrust. The controllable pitch propeller is normally, but not always, driven by a constant speed motor, the pitch is adjustable and reversed to achieve thrust variations and reversal. In the past, the following were the two commonly used configurations:

- FPP and DC motor with SCR Convertor (a simple and easily understood variable speed drive system. It is also very similar to the Synchroconverter, AC drive systen introduced later.).
- CPP and AC induction motor (a robust fixed speed motor).

Both these arrangements enable the propeller thrust to be controlled from zero to maximum in either direction. Both arrangements would normally be supplied from a constant voltage AC switchboard arranged in the **"Central Power Plant"** configuration (see Fig. 1). The next section compares the loads imposed on the vessel's power plant and distribution system by the two systems.

Power Plant design Considerations for CPP's and FPP's

The two thruster and drive systems under consideration impose different kW, current (kVA) and kVAR demands on the power plant as discussed below when delivering zero to maximum thrust (Ref. 1).

The power drawn by a FPP is a function of the thrust delivered. By its nature, very little power (a few kilowatts) is drawn at zero thrust as at zero thrust the motor is stationary. The power drawn by a CPP at zero thrust, however, is approximately 20% of the rated power. This is the power required to rotate the propeller at full speed while the blades are feathered to give zero thrust.

As thrust increases both CPP and FPP powers rise; at rated thrust they will consume very nearly the same power as the overall system efficiencies are approximately the same. The CPP will be slightly less efficient due to it needing a larger hub, the DC motor on the other hand is less efficient that the equivalent AC motor at rated power. These effects can be assumed to be compensatory.

Fig. 2 shows the power consumption of the two configurations drawn to a base of thrust.

The current drawn from the supply (the kVA) is also a function of the thrust. The curve is not the same shape as the power curve since the power factor of both the induction motor and DC convertor varies with load. The FPP torque varies in proportion to propeller thrust. The AC current taken by the AC induction motor is more complex. The power factor at rated power will be very similar to that drawn by the DC convertor, about 0.87. However, induction motor at low loads has a poor power factor which when combined with the requirement of 20% power causes the induction motor to take considerable current while the thruster is at zero thrust. Figure 3 shows the variation of kVA or current drawn from the AC supply to a base of thrust.

Figures 4 and 5 show the variations of reactive power (kVAR) and Power Factor to a base of thrust. These curves show that at rated load the two arrangements draw nearly equal power (kW), equal currents (kVA) and equal reactive powers (kVAR) at similar power factors. However, at reduced load, the FPP and DC motor arrangements use less power and less current. At zero thrust the CPP needs 20% power and 35% current whereas the FPP needs less than 2% of each.

The thrusters of a Dynamically positioned vessel are sized to withstand bad weather and usually have a margin to cover failures. The rated output of the thrusters is only needed for brief periods. For most of their operating life, the thrusters will run at less than half thrust, the average is likely to be 25% to 35% thrust. **At these low levels of thrust the FPP and DC motor configuration uses considerably less power (kW) and current (kVA) than its rival.**

Pro’s and Con’s of Fixed Pitch and controllable Pitch Propellers

a) **Propeller Erosion**
A CPP running continuously at constant maximum speed will suffer from erosion of the blades, this effect is much reduced on the FPP since it spends most of its life running at 25% thrust (50% speed) or less.

b) **Propeller Noise**
The FPP running at reduced speed will create less noise and aeration than a CPP at full speed. Noise and aeration can interfere with subsea acoustics.

c) **Complexity and Maintenance**
The FPP requires a relatively complex high power DC convertor but is mechanically very simple.

The CPP has more complex mechanical parts but no high power electronics. Both have an electronic servo system. The DC motor has brush-gear and commutator which needs regular maintenance. The FPP has less underwater parts which might require maintenance, but it has more complex equipment in the thruster compartment.

d) **Size**
The DC motor will be marginally bigger than its AC equivalent. The DC motor needs a convertor cubicle which needs to be housed in a clean dry compartment. The CPP needs a hydraulic power pack and oil reservoir. The power pack needs to be in a clean dry compartment. The two systems are not dissimilar in size. The DC motor needs more space to ensure access to the brushgear.

e) **Response Time**

The CPP can usually change pitch more quickly than the FPP speed can be adjusted. It is debatable whether this faster response produces faster change of achieved thrust. The response times achieved by DC motor are more than adequate for the DP system and faster responses would not improve vessel's position keeping performance.

f) **Thrust Setting Accuracy**

The thrust setting accuracy of the FPP and DC motor arrangement will be more precise than that achieved by the CPP system. The setting accuracy of most CPP systems is limited by the need for a "dead band". This dead band is usually 1 or 2 % but is acceptable to DP systems.

g) **Fatigue Life**

DP systems continuously modify the thruster settings. The thrust demands are adjusted at least 15 times per minute and perhaps 60 times per minute. These frequent adjustments are of no consequence to the continuously variable control system used by a DC motor. Most CPPs use relays and solenoid valves, these devices do suffer adversely from frequent operation. The DC motor drive is less vulnerable to frequent variations.

It can therefore be concluded from the above discussion that fixed pitch propellers driven by variable speed motors have considerable electrical and mechanical as well as operational advantages over the controllable pitch propellers driven by constant speed AC motors. It is perhaps for theses reasons that most of the new built vessels have azimuthing type thrusters with FPPs driven by variable speed AC motors - synchronous or induction. The DC motor based system used as an example in the above discussion has virtually become extinct because with the advent of more sophisticated power electronics, devices and control techniques, high dynamic performance equal to or better than the DC drives is now readily achievable without the power/speed limitations and maintenance problems of the brushgear/commutator.

The next section of the paper discusses the **three** (3) most commonly used variable speed thruster drive systems:

- PWM (Pulse Width Modulation) Inverter
- Cycloconvertor
- LCI (Load Commutated Inverter) - Synchroconvertor

PWM Drive and AC Squirrel Cage Induction Motor Thruster System

The first AC alternative to have been considered is the well known PWM system, based on gate turn-off (GTO) thyristor technology employing two stage power conversion AC/DC (constant voltage source) /AC. Since a diode bridge is used to produce DC voltage before chopping it to produce AC output, the PWM drive draws almost unity power factor current from the supply, as a result of which the generators may have power factors approaching 0.9 as against 0.8 - 0.85 for LCI and 0.70 - 0.75 for Cyclos. PWM drives are best suited to high speed motor drive applications in order to give an economic design of induction motor, thus invariably requiring a stepdown gearbox to drive the propeller. Two level PWM drives (see Figure 6) are normally used for low voltage, low power applications. For high power PWM drives a much more complex three level pulse width modulation (see Figure 7) becomes a necessity requiring a high number of components; the increased complexity leading to lower reliability.

Major factors which must be considered when specifying PWM drive technology are as follows:

- Equipment Cost
- Reliability
- Regeneration
- Efficiency

Cycloconvertor Drive and AC Synchronous Motor Thruster System

The cycloconvertor is an SCR Convertor System which converts a fixed frequency, fixed voltage input into a variable frequency, variable voltage output in a single stage without the need for a DC link and may be used to power either synchronous or asynchronous motor. A typical cycloconvertor bridge configuration shown in Figure 8 has one reversing AC convertor (two 6 arm Graetz bridges connected in anti-parallel) supplying each phase of a three phase machine. The cycloconvertor "constructs" the output voltage wave-form from sampled portions of the supply wave-form (see Fig 9), in effect the process is one of modulated phase control in which the supply side current harmonics depend upon the supply to load frequency ratio. Therefore the choice of maximum output frequency must be set in the light of motor design constraints, acceptable output distortion and tolerable levels of supply current harmonics. Typically, the maximum useable output frequency may be somewhere between 1/3 and 1/2 of the input frequency. Furthermore because of the phase control modulation, the cycloconvertor will always draw lagging reactive current, even if the motor operates at unity power factor. Hence for a cycloconvertor, the maximum theoretical input power factor is 0.843.

Cycloconvertor drives are generally associated with low speed, high power applications that may also have a high dynamic performance requirement. In marine applications, only synchronous machines have been used with cycloconvertors (Ref. 2). Synchronous machines are preferred to cage induction motors (asynchronous machines) due to their large air gap giving them a higher degree of robustness.

The cycloconvertor solution is particularly well suited to main drive propeller or azimuthing (including podded) thrusters fitted to ice breakers which require high torque at low speed; it is therefore possible to free a propeller frozen in ice or to cut a block of ice without stalling the motor.

The installed kW capacity required for a cycloconvertor would be the same as for an AC/DC thyristor controlled scheme. However, the installed kVA capacity would be approximately 30% more than that required for AC/DC alternative. Other bridge configurations are available, each differing slightly in convertor utilisation, input power factor and transformer kVA requirements.

LCI (Synchroconvertor) Drive and AC Synchronous Motor Thruster System

The LCI or Synchroconvertor drives were first used some 20 years ago in power generation plants and in industry for:

- pumps
- fans and
- compressors

They were required to operate over a limited speed range i.e. 60% to 100% of speed and the applications did not have any dynamic performance requirements. It is perhaps for these reasons there is a misconception that LCI drives:

- cannot operate at low speeds
- have low dynamic performance
- are non-regenerative
- cannot provide overtorque at low speeds.

Modern applications of Synchrodrives are much more demanding and many high performance LCI drives have been designed, built and commissioned by the author's company and by other suppliers. Typical examples of such drives are given below:

- 1.7 MW Descaling Pump Drive:
  30% → 100% speed in 1.7 seconds
- 10MW Boiler Feed Pump:
  0 → 100% speed in 12 seconds (performance restricted by pump cavitation)
- 2MW Banbury Rubber Mix Drive:
  170% full load torque at zero speed

For marine applications including main propulsion and thruster drives, the above extremely high dynamic performances are neither necessary nor desirable due to power plant and propeller cavitation limitations.

The LCI or Synchrodrive system converts a fixed voltage, fixed frequency input into a variable voltage, variable frequency output. An LCI drive consists of two conventional, fully controlled thyristor bridges, connected by a decoupling DC link choke. Figure 10 shows a simplified 6 pulse arrangement. These bridges are generally referred to as the supply convertor and the machine convertor; the supply convertor is connected to a constant voltage and frequency AC system.

The supply convertor provides a controllable DC link current which the machine convertor controls so as to produce a rotary MMF in the stator of the machine. A simplified representation of the process is shown in Figure 11, where it can be seen that the thyristors of the machine convertor are switched in sequence and at each switching operation the MMF axis of the stator field advances by 60^0. The instance at which switching takes place is determined by shaft encoders or (machine) back EMF detectors, but the control is arranged so that the stator and rotor MMF axes maintain a close angular relationship, i.e. the motor cannot fall out of step but behaves as a DC motor.

Under normal motoring conditions (above approximately 10% speed) the supply convertor rectifies power into the DC link whilst the machine convertor synchronously inverts this power into the synchronous machine. The power factor and frequency at which power is drawn from the supply is independent of the operating power factor and frequency of the machine convertor, in fact the kW and kVA taken by the drive are the same as that required by a thyristor fed DC motor, so also are the harmonic currents and resulting waveform distortion. The higher efficiency of the synchronous motor offsets the losses of the extra bridge.

Reversal is achieved by phasing the machine convertor into rectification. The motor then acts as a generator and supplies DC current and power to the link via the machine convertor and then to the supply via the supply convertor which operates as an inverter. The drive slows down and when standstill is reached the operation is returned to the normal motoring state, but with reversed switching sequence on the machine convertor so that the drive accelerates in the reverse direction.

While link current may fluctuate during a reversal it can never change direction.

The analogy between a synchroconvertor drive and its DC motor equivalent is direct and simple. The supply convertor functions as does the conventional AC/DC convertor in providing a source of controllable voltage, whilst the machine convertor and synchronous machine functions as a DC motor with a six segment commutator.

The switching procedure described for the machine convertor can only take place above approximately 10% speed since a minimum level of machine voltage is required to ensure correct switching, or commutation of the thyristors. At lower speeds the supply convertor forces the link current to zero momentarily so that the machine convertor thyristors can be switched over “off load”; link current is then re-established.

LCI Characteristics Summary and Comparison with other Drive Types (Ref. 3)

a) **Torque Speed**
The LCI synchronous motor drive is capable of developing 100% full load torque over the entire speed range but can develop considerably higher torques during the start mode when inverter commutation is by pulsing the DC link current and not by natural commutation.

b) **Torque Pulsations**
All quasi-square wave frequency inverter drives develop torque pulsations at low speed. The LCI drive is no exception to this, and so although continuous operation at speed less than 10% is possible, it may not be necessary. This limitation is of no consequence in marine applications because the propeller does not produce significant thrust for speeds up to about 30% to 40%.

c) **Speed and Power Considerations**
The LCI synchronous motor drive system is particularly suited to high speed/high power applications as, even with salient pole construction, drive motors can readily be offered with an output shaft power of 10MW at 1200 rev/min. This would be enerally far more difficult to achieve with a DC motor.

d) **Harmonics**
The harmonic currents produced by the LCI drive system in the main supply network are very similar to those produced by a conventional convertor-fed DC drive. the techniques for predicting the harmonic orders and amplitudes are well established. Passive, damped filters may be installed, if required, to keep within, sometimes very stringent, THD (Total Harmonic Distortion) Class Society/Owner requirements.

e) **Power Factor**
The synchronous motor itself operates at high leading power factor (0.9 approximately) but as far as the main supply is concerned the performance is similar to that of a converter-fed DC drive. Again this is similar to the situation with quasi-square and current-source force commutated inverters.

f) **Regeneration**
The drive power circuit is inherently regenerative to the main supply system thus enabling the vessel or the thruster to be stopped and reversed quickly. Voltage source (PWM) inverters require an auxiliary line-commutated bridge if regeneration into themain supply is required or alternatively a thyristor and dynamic braking resistors may be required to execute dynamic braking.

g) **Drive Efficiency**
Owing to the naturally commutated inverter design, possible with the synchronous motor drive system higher inverter efficiencies are achievable.

Conclusions

A comparison of CPP thrusters driven by AC induction motors and FPP thrusters driven by variable speed SCR fed DC motors has shown that although the two arrangements draw nearly equal active power (kW), current (kVA) and reactive power (kVAR) at rated thrust, at zero thrust the FPP needs only 2% power and current compared with 20% power and 35% current needed by the CPP. It can be shown that increased initial costs of variable speed drive systems for the FPP thrusters can be paid back quickly over a short period from savings in operating (fuel) and maintenance costs.

It is also concluded that although the synchroconvertor drive system - supplied by author's company as well as many other reputable manufacturers/suppliers has become well established as the main propulsion drive system for Cruise Liners, it is equally suitable for thrusters drive systems in dynamically positioned vessel's. Its performance is very much similar to that of SCR fed DC drive system but without the power limitation of and problems associated with commutator. Therefore for all potential applications, PWM Synchroconvertor and Cycloconvertor drive systems should be selected after a thorough review of application requirements, cost, complexity, reliability and maintainability.

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