POWER ELECTRONIC CONVERTERS FOR SHIP PROPULSION ELECTRIC MOTORS

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1. Introduction

The predominant type of prime movers for DP propulsion plants is the electric drive. Practically every DP propulsion device installed in newly constructed vessels as well as in most of the conversions is driven by an electric motor.

In the beginning of DP technology (which coincided with the advent of the DC/SCR technology), either AC motors were utilized driving CP propellers at constant RPM or SCR controlled DC motors were utilized driving fixed-pitch propellers at variable RPM.

In recent years, variable speed AC drives have become available and have been used in some applications for DP propulsion.

The most commonly used motor drives are:

- DC converters, or SCR (Silicon Controlled Rectifier) for DC motors
- Cycloconverters (Cyclo) for AC motors, normally for synchronous motors
- Current source inverter type (CSI) converters for AC motors (synchronous motors)
- Voltage source inverter (VSI) type converters for AC motors, i.e. asynchronous, synchronous and permanent magnet synchronous motors.

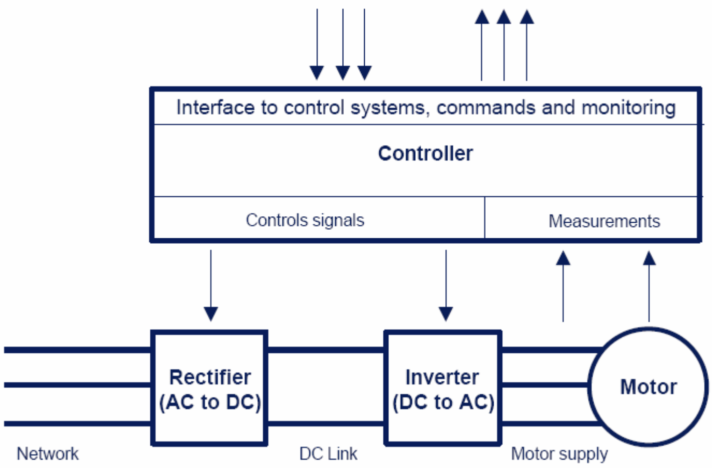


Fig. 1. Variable speed drive, showing a frequency converter with DC Link, typically for VSI and CSI type converters (Cyclos do not have DC link) [1]

2. AC Systems with Controllable Pitch Propeller

- Several generators which feed **AC of constant frequency and voltage** (4160 - 6000 VAC) into a common bus.
- **Constant-speed motor drive motors** drive the propeller
- Usually **cage-type induction motors** and may be designed with pole-changing switches to allow for two operating speeds

- **Electrical simplicity**
- **Highest efficiency at design point** (maximum load) of the electric drive systems
- CP propeller is less efficient than a fixed pitch propeller in partial load conditions - power drawn by a CPP at zero thrust is approx. 20% of the rated power
- **Electrical part of an AC-CP system is a simple** and reliable arrangement,
- But **CP propeller is considerably more complex than a fixedpitch propeller (FPP)** – also unaccessible for routine maintenance and requires drydocking of the vessel to gain access to or removal of the thruster

Fig. 2. Controllable Pitch Propeller

- CP propeller is considerably more complex than a fixedpitch propeller (FPP) – also unaccessible for routine maintenance and requires drydocking of the vessel to gain access to or removal of the thruster

When started direct-on-line (DOL), **the induction motor has a large starting current transient, typically 5-7 times the nominal current**, with significant shaft torque transients and voltage drops in the network ➔ minimum running generator capacity often must be defined to be able to start a large motor.

Stardelta switching is often used to provide higher starting torque with reduced transients, but is not the best solution. **Soft-starting devices such as auto-transformers have been shown to give better results**. Solid-state soft starters are not commonly used for high power levels.

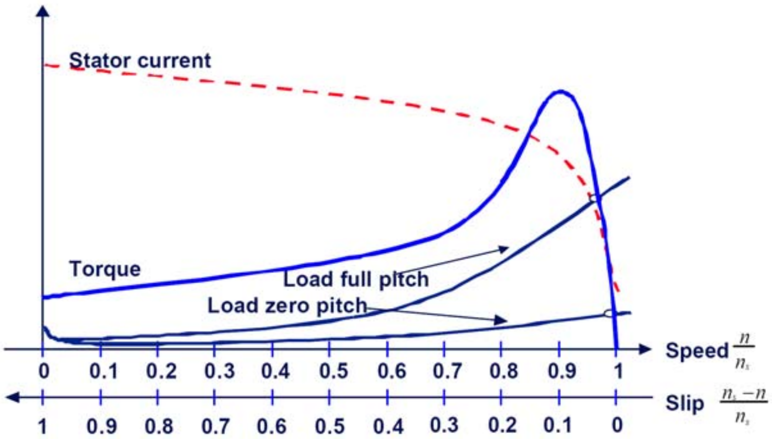


Fig. 3. Load characteristics for a direct on line asynchronous motor with load curves for a CPP propeller [1]

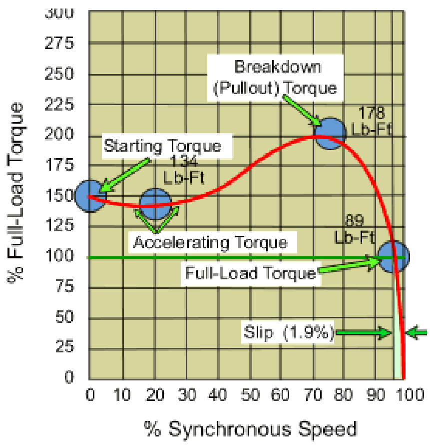


Fig. 4. Load characteristics for a direct on line asynchronous motor ***Siemens downloads***

3. SCR Controlled DC Drive and Fixed Pitch Propeller

- AC current produced by Diesel generators at constant voltage (600 VDC max.) and frequency.
- A fixed pitch propeller is driven by the DC propulsion motors. Varying the propeller RPM and reversing the rotation direction of the propeller shaft allow the thrust to be controlled in magnitude and direction.
- AC/DC propulsion combines the **highly efficient and reliable generation of AC current** with the DC motor capability of producing **high torque at low speed**, the feasibility of varying the characteristic by **adjusting the excitation**, and **easy reversing** of the direction of rotation.
- Full-bridge ***thyristor rectifier*** (*Silicon Controlled Rectifier = SCR*) feeds the DC motor with a controlled armature (rotor winding) current. The field winding (stator) is excited with a regulated field current.

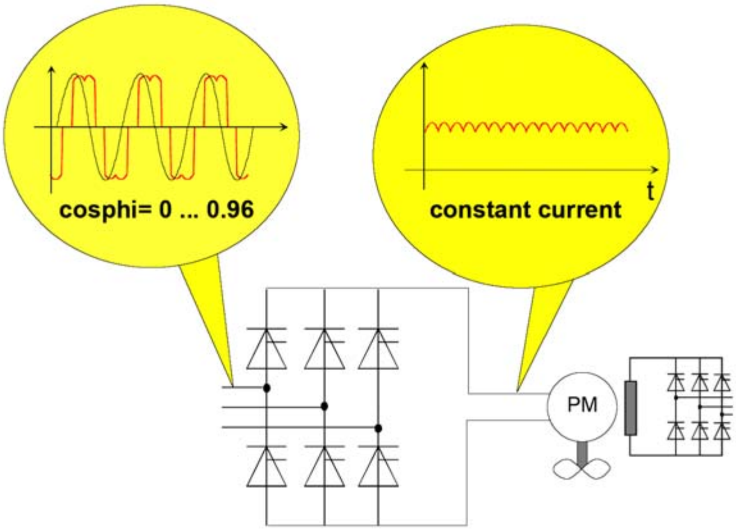


Fig. 5. Full bridge thyristor DC drive (SCR) [1], [2]

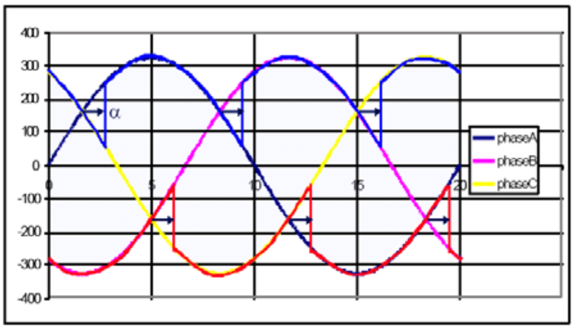


Fig. 6. The (average) DC voltage to motor is controlled by delaying conduction of the thyristors with the gate firing angle α (here, α =30 degrees), [1]

- **Speed of the DC motor is proportional to the DC armature voltage**.
- The **DC voltage on the motor armature windings (rotor)** is controlled by phase shifting the thyristors' conduction interval by the gate firing angle α. The gate firing angle α can be controlled from 0 to 180 degrees, and the voltage on the armature windings can hence be regulated from +1.35 to –1.35 V_s (line voltage).

- The torque is controlled accurately and with low ripple (if the armature inductance is high, *L*), but this, on the other hand, reduces the dynamic performance since the time constant of the armature increases.
- In practice, α **> 15 degrees**, in order to ensure controllability of the motor drive also with voltage drops in the network, and α **< 150 degrees** to have a commutation margin.
- **Power factor**
  Since the armature current is controlled by use of the firing angle of the thyristor devices, the AC currents will be phase-shifted with respect to fundamental voltage (v_s). In a DC motor drive, where the speed is varying from 0 to 100%, the power factor (PF) will also vary from 0 to 0.96. Theoreticaly, power factor can be calculated by folowing equation [2]:

$$PF = (3 / \pi) \cdot \cos \alpha \approx 0.955 \cdot \cos \alpha.$$

From equation follows that highest value of power factor is obtained for zero speed ($\alpha = 180^0$ or full speed $\alpha = 0^0$). Taking into consideration that α **> 15 degrees** we can not even theoreticaly obtain PF higher than 0.92, i.e. PF < 0.92.

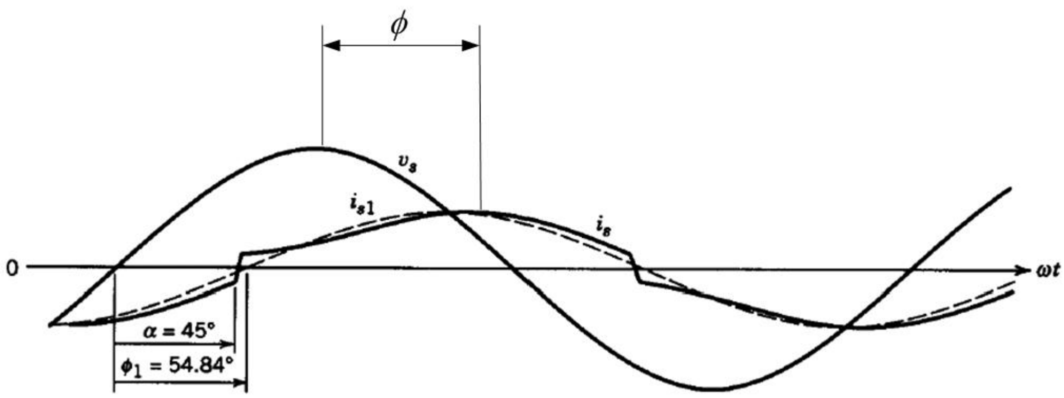
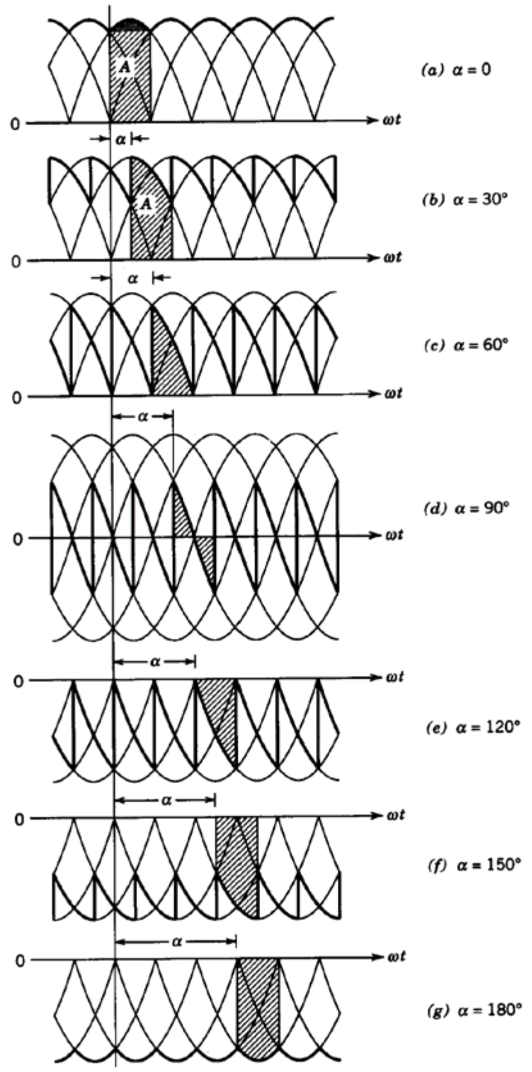


Fig. 7. Representation of power factor (*PF* = cos ϕ) [3]



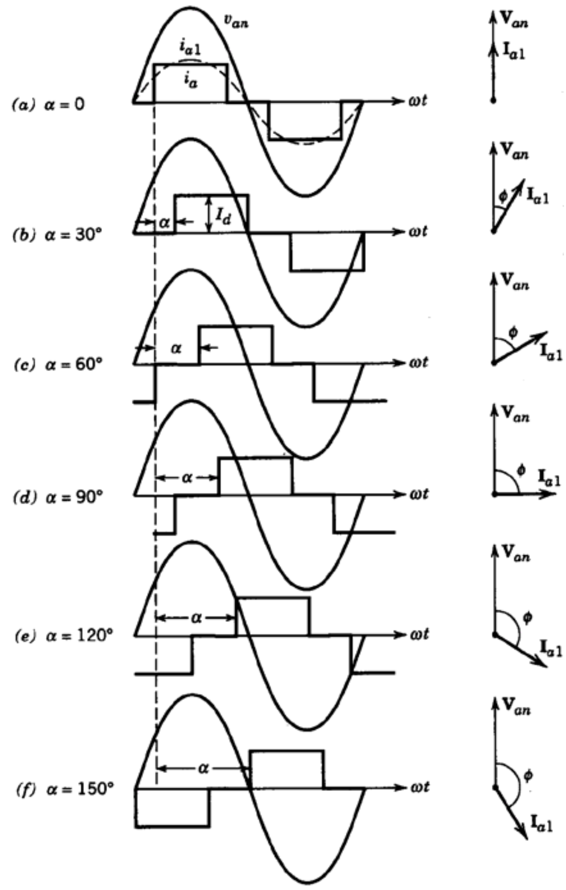


Fig. 9. Input line-current waveforms assuming zero AC side inductance (L_s=0) [3]

- PF=cos ϕ is the function of the gate firing angle α

Fig. 8. DC side voltage waveforms assuming zero AC side inductance (L_s=0) [3]

Disadvantages:

- **The limitation of voltage** (maximum voltages are 600 VAC/750 VDC) ➔ leads to heavy, expensive motors and cable runs
- **Commutator wear** ➔ higher maintenance requirements of the DC motors
- **Practical limit for DC motor drives is 2-3 MW**
- **The power factor will vary from 0 to 0.92** (α=15degrees) – corespondant to 0 to 100% propeller RPM.
- Power electronic equipment requiring a clean and cool environment (important for smaller vessels)
- The presence of electromagnetic interference (EMI)
- Undesirable response in electronic equipment (such as engine and generator controls, instrumentation, navigation equipment, engine room automation, computers, etc.)

Applications:

- Introduction of the high current SCR in the late 1960s, the AC/DC electric propulsion drive has become quite popular.
- Vessels with this type of propulsion system include **fishing trawlers and factory vessels**, **research vessels**, **icebreakers, offshore supply vessels**, conventionally moored and dynamically positioned drill vessels, and semisubmersibles.

Efficiency:
AC generators 97% x SCRs 98% x Propulsion DC motors 94%
(x reduction gear 98%)

Total system efficiency 89% (87%)

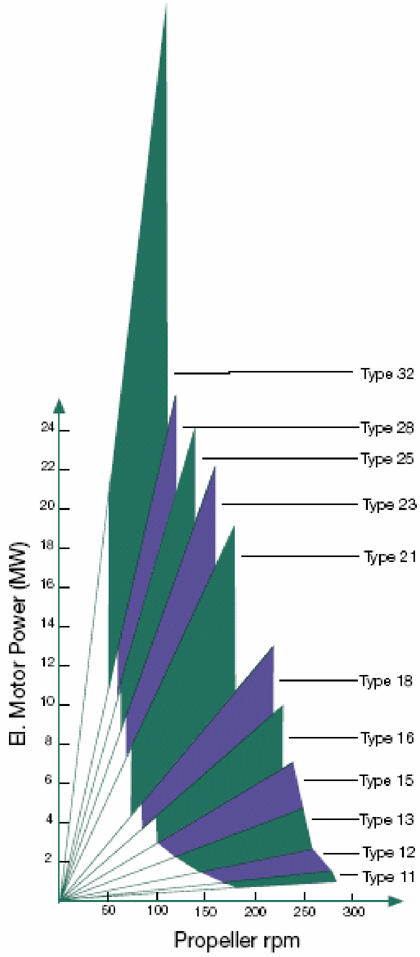
4. Ship electrical propulsion

PODDED PROPULSION

- Freely rotateable (azimuthing through 360°) and may produce thrust in any direction.
- Incorporates an electrical AC motor mounted directly on the short propeller shaft, inside a sealed pod unit that is submerged under the vessel hull.
- The motor drives a fixed-pitch propeller (FPP).
- Controlled by a frequency converter that converts a three-phase AC voltage of constant frequency into a variable three-phase AC voltage with variable frequency.
- Torque is available in either direction over the entire speed range (tipicaly from 0 to 300 RPM).

System description:

- Variable speed drives has been in industrial use since in many decades, but first at the end of the 1960's by use of power semiconductors. At the beginning, DC motors where the most feasible alternative for propulsion control.
- During the 1980's, AC motor drives became industrially available, and commercially competitive.
- Since then, almost all new deliveries of electric propulsion are based on one of the AC drive topologies.
- AC system generates medium voltage AC (3.3 kVAC, 6.6 or 11 kVAC) at constant frequency and voltage.
- Controls the RPM of the drive motor (induction or synchronous motors) by varying the frequency of the system.

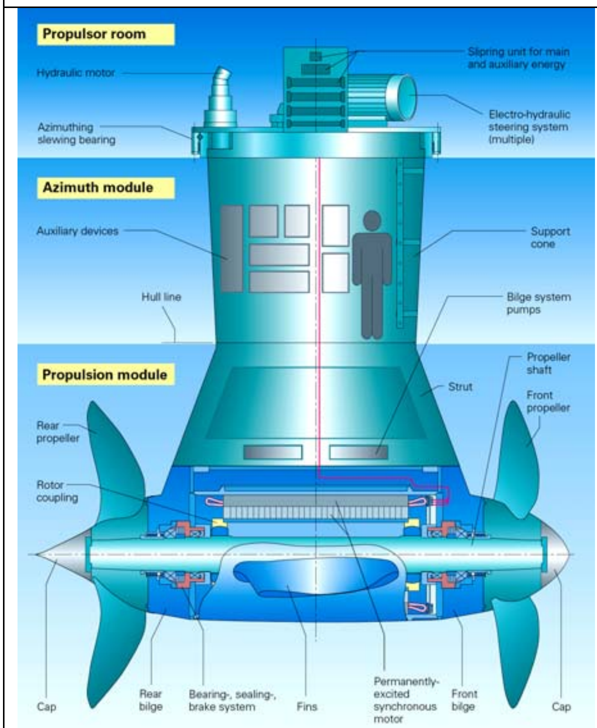


a)

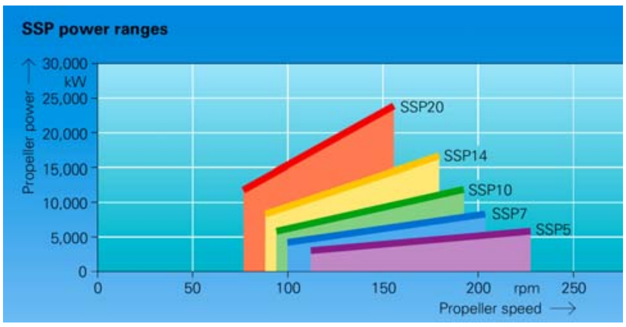
b) *Radiance of the Seas*, 2 x 19,5 MW Azipod® propulsion – ***ABB Marine***

c) Application of podded propulsion (higly improved manouverability) ***ABB Marine***

Fig. 10. Azipod power range and application



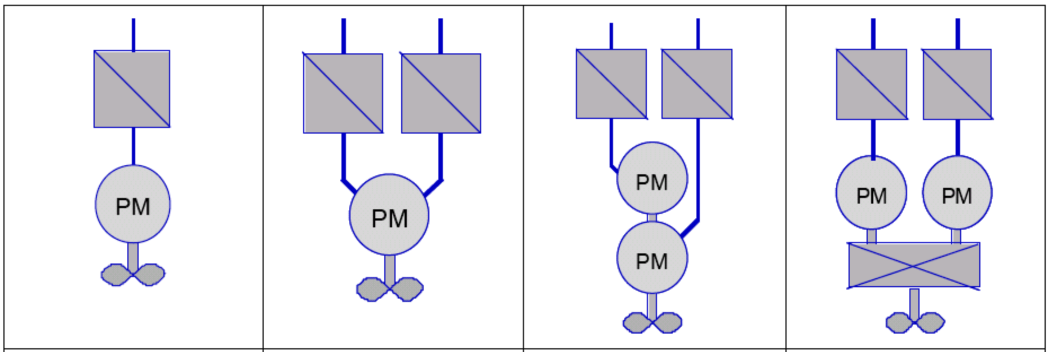
a)



b)

Fig. 11. *SIEMENS/SCHOTTEL PODED PROPULSOR*

Siemens Marine



Single motor drive	Two-winding motor with redundant converters	Tandem motor with redundant converters	Geared, dual shaft propulsion

Fig. 12. Shaft line drive configurations (in respect to redundancy) [4]

AZIMUTH THRUSTERS

- Azimuthing thruster, is powered from an in-board, typically a horizontal electro motor, and the mechanical power is transferred to the propeller via a **Z-shaped gear**. The underwater shape is optimized for low hydrodynamic resistance at higher ship velocity, for higher propulsion efficiency.
  - **Z-type gear transmission** ➔ vessels with limitation of in-board height of the thruster room, the electric motor will normally be horizontal.
  - **L-type gear transmition** – will normally be selected when the height in the thruster room allows for it simpler construction with less power transmission losses, vertically mounted motors.
- Thrusters that can be rotated in order to produce thrust in any direction.
- The thrust is controlled either by **constant speed and CPP design**, variable **speed FPP design**, or in rare cases with a **combination** of speed and pitch control. Variable -speed FPP designs has a significantly simpler mechanical underwater construction with reduced low-thrust losses compared to constant speed, CPP propellers.
- Conventional azimuth thrusters are at present (2002) in use with power ratings up to 6-7 MW.

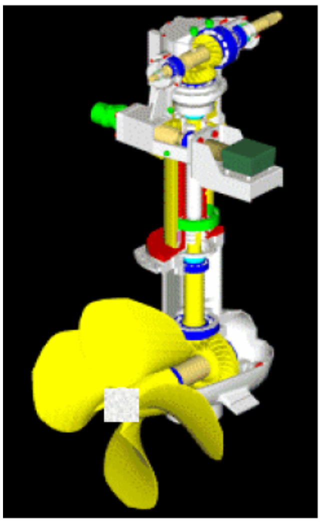
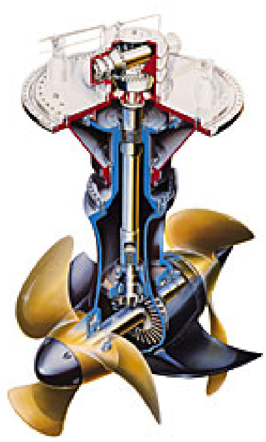


ABB Marine [1], [4]

Contra rotating propellers
Aquamaster CRP Rolls-Royce



Twin-propellers
(rotating at the same side)
Schottel propulsors

Fig. 13. AZIMUTH THRUSTERS

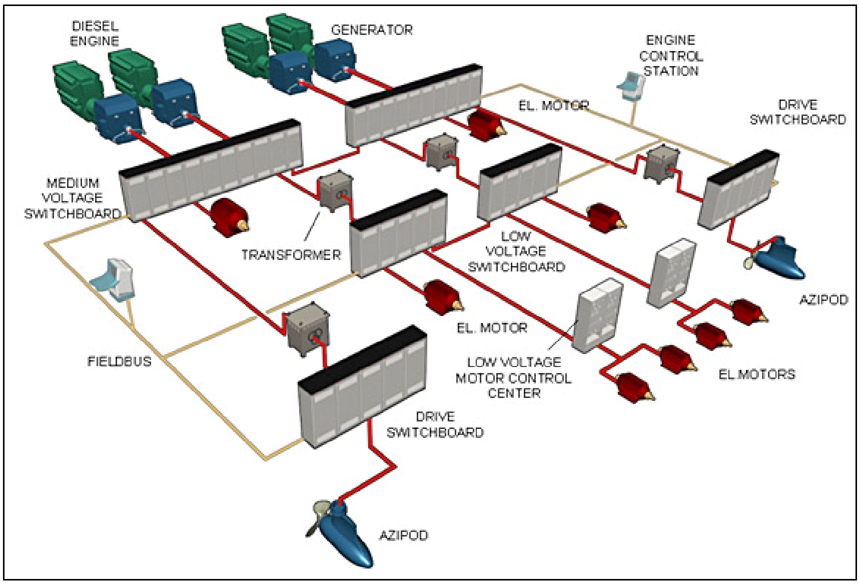


Fig. 14. Power distribution and control networks onboard ship, *ABB Marine*

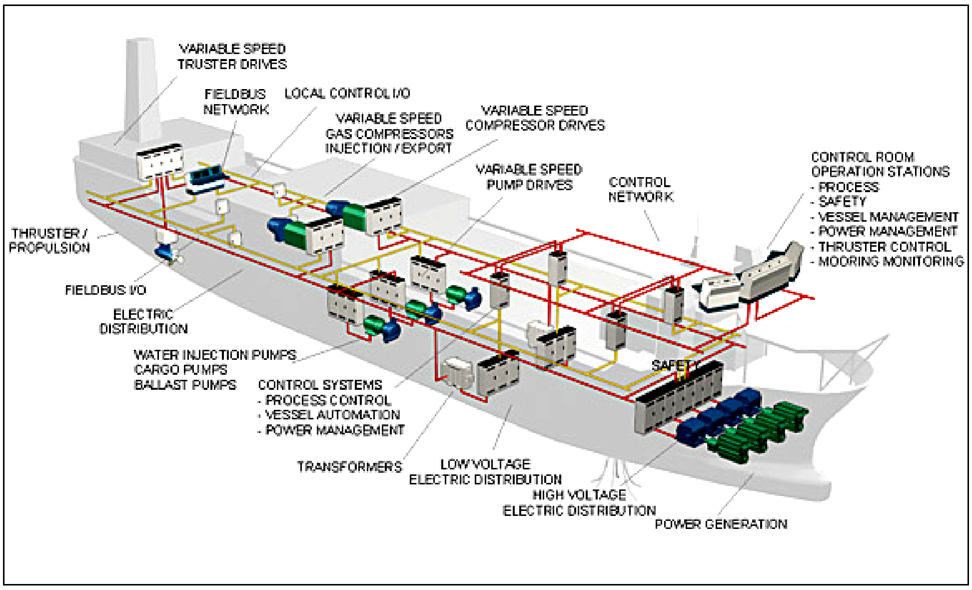


Fig. 15. Power distribution and control networks onboard FPSO vessel, *ABB Marine*

5. FREQUENCY CONVERTERS

Three basic system configurations are available for the variable frequency control:

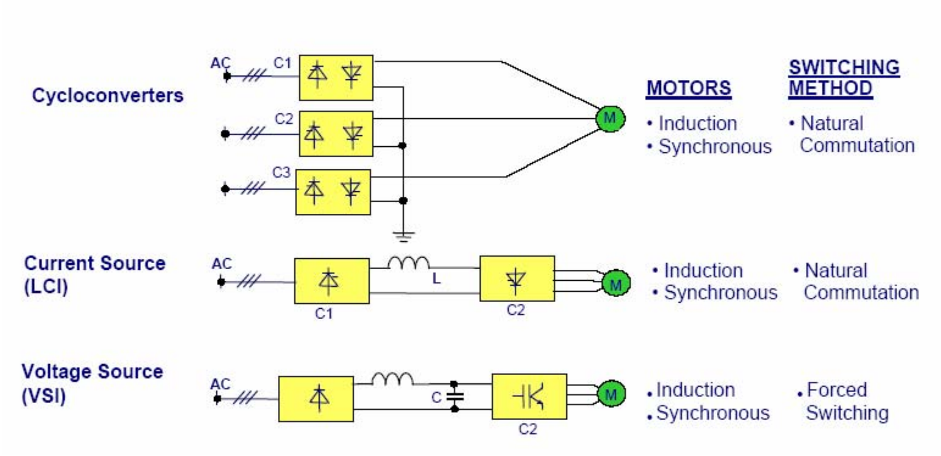


Fig. 16. AC motor drives used in marine applications, [5], *ALSTOM Power Conversion Ltd*

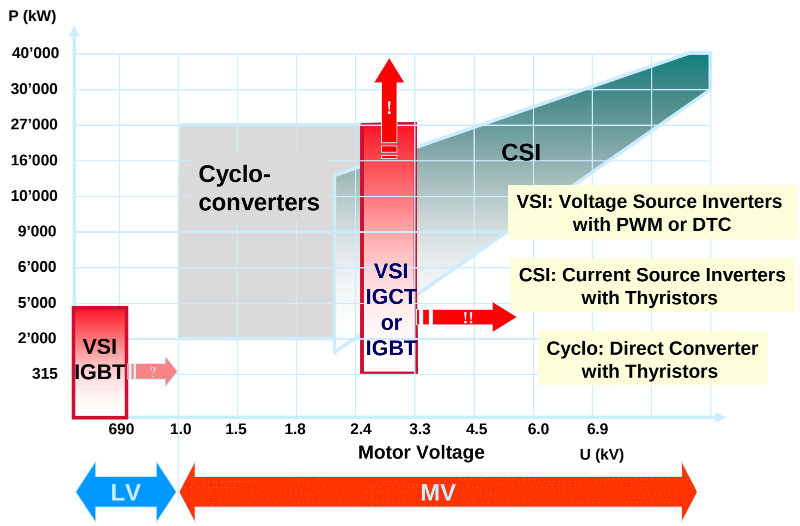


Fig. 17. AC motor drive technology review, [4], *ABB Marine*

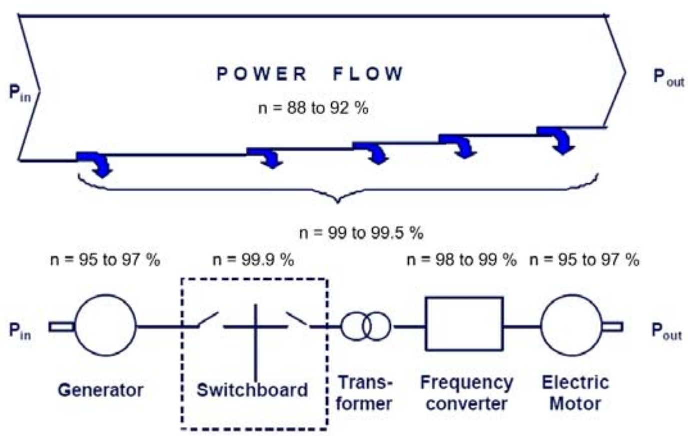


Fig. 18. Power flow and efficiency of electric installation, [1], [4]

5.1. CYCLOCONVERTER VARIABLE SPEED DRIVES

- The cycloconverter is an SCR Converter 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.

- In marine applications, only synchronous motors (AC motor with DC excitation) have been used with cycloconvertors. **Synchronous machines are preferred** to cage induction motors (asynchronous machines) due to their large air gap giving them a higher degree of robustness.

- Motor nominal voltage 1500V or 1800V

- The Cycloconverter and Current Source drives (Synchro, CSI, LSI) are direct descendants of DC drive technology and use the same **basic naturally commutated thyristor** converters (same 6 arm Graetz bridges)

- Its major advantage is **high torque at low speeds** with low torque pulsations and excellent dynamic response performance:

  ➔ applied as direct propeller drives on modern **icebreakers** (possible to free a propeller frozen in ice or to cut a block of ice without stalling the motor)

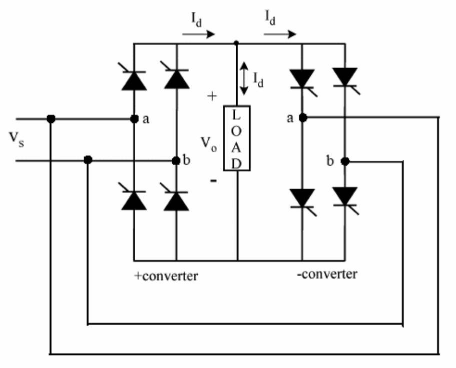
  ➔ in dynamic possitioning and passenger vessel applications (not necessary) where low speed / maneuvering performance is essential

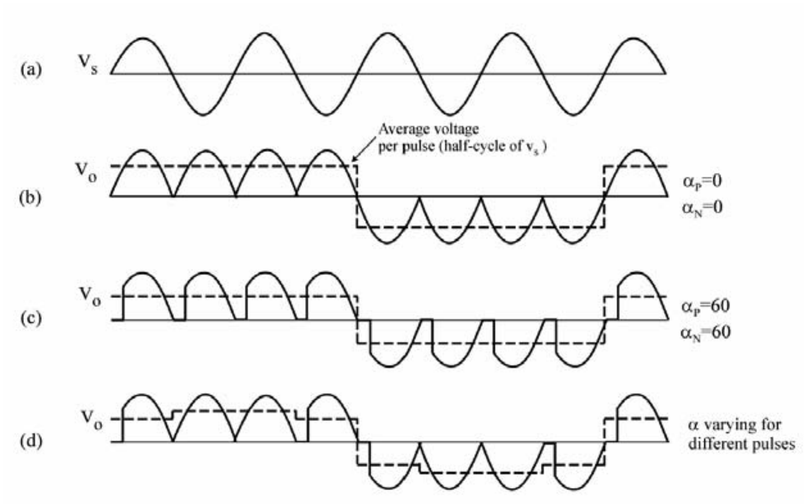
- Can inherently **reverse and regenerate**

- Can easily provide **large overloads** (e.g. 250% and field weakening)

- Multiple bridges give **high power ratings**

- Ratings typically up to 30MW pre drive motor, 500 RPM





[Cycloconver tutorial]

Limitations:

- **Output frequency is limited to 30 to 40% of AC supply frequency** (aprox. 20 Hz)
- Complex AC supply effects
- Because of the phase control modulation, the **cycloconverter will always draw lagging reactive current**, even if the motor operates at unity power factor.
- **The supply power factor (PF) is motor voltage-dependent and is about 0.76**
  ➔ The installed kVA capacity would be approximately 25 to 30% more than that required for AC/DC alternative.

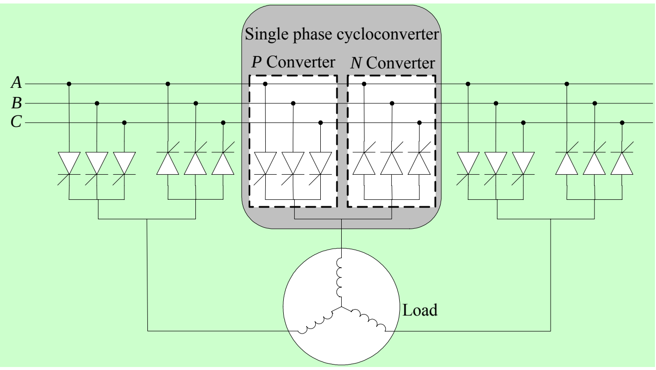


Fig. 21. 3-pulse half-wave cycloconverter (not used in marine applications)

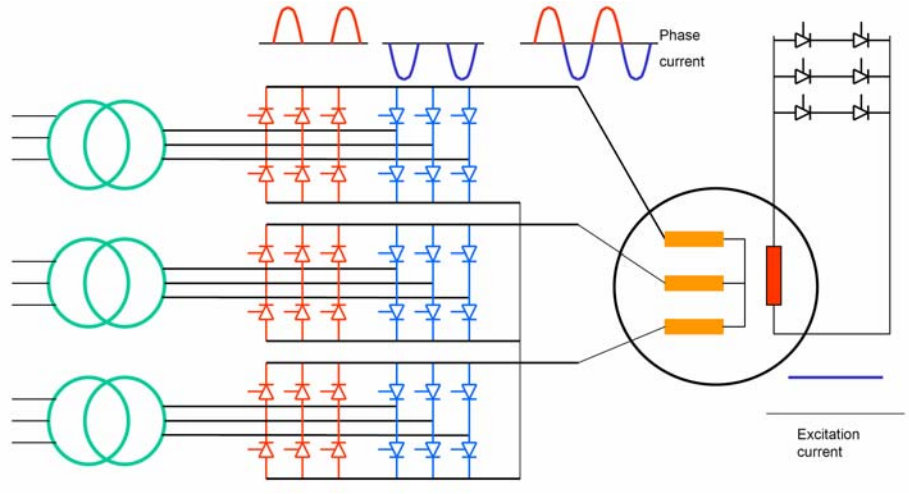
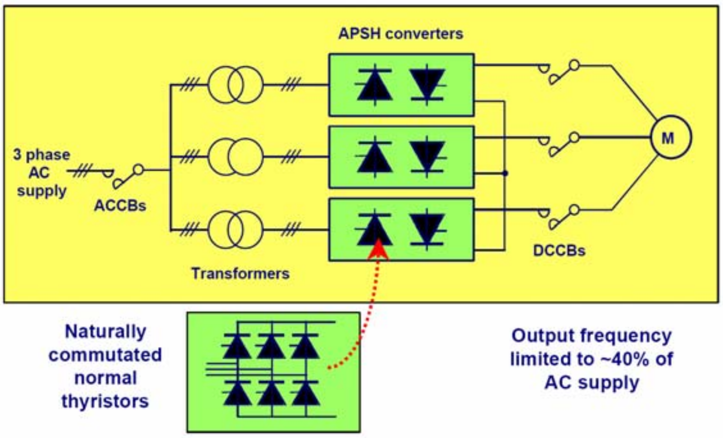


Fig. 22. 6-pulse cycloconverter - ACS6000c – ABB

- Direct AC to AC converter
- SCR Thyristor
- Synchronous motor (AC motor with DC excitation)
- High power at low speed



← **Fig. 19. Cycloconverter with 6-pulse configuration**:

- 6 pulse circuit uses three **anti-parallel thyristor bridges** (green rectangle).
- **Each bridge** is the same as used for a DC drive and uses **6 forward** (detail on the bottom of the figure) and **6 reverse thyristors**.

ALSTOM Power Conversion Ltd

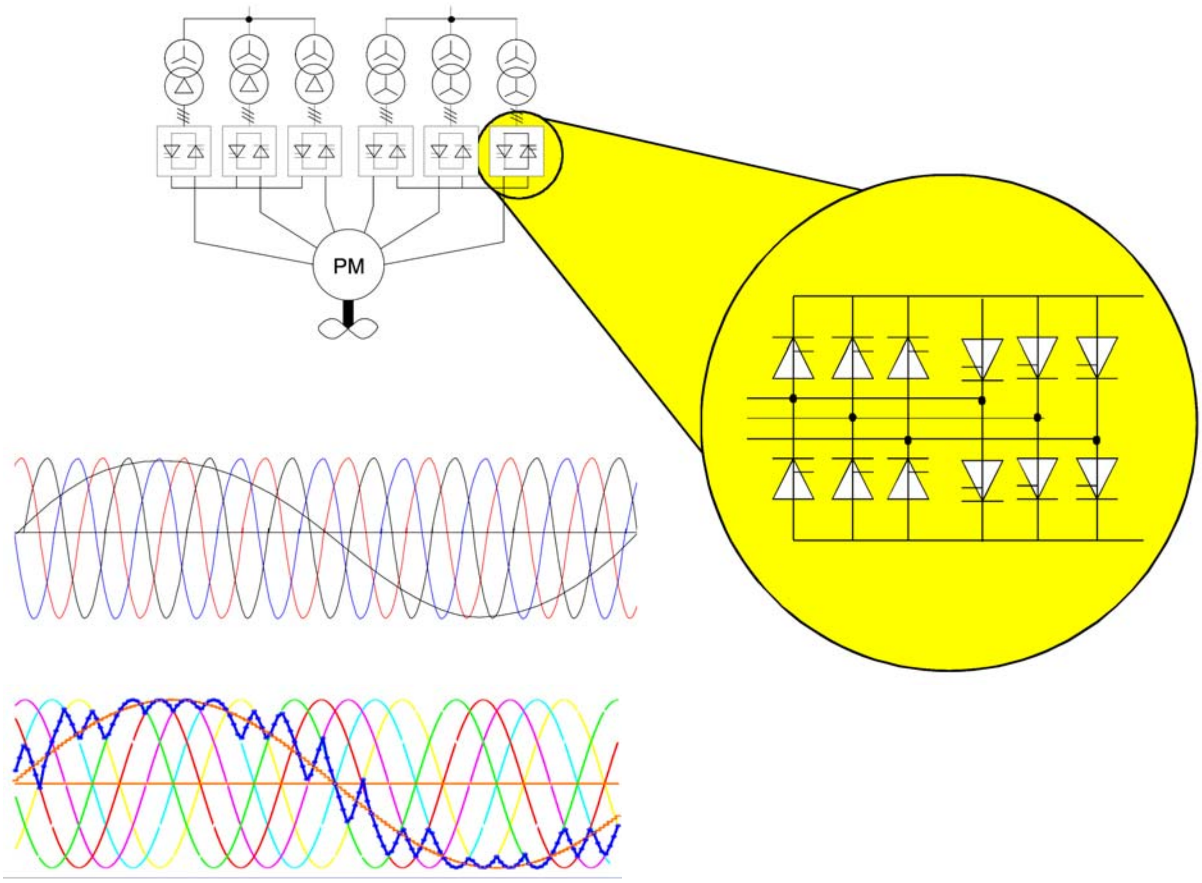


Fig. 20. Cycloconverter with 6-pulse configuration, [1], [2], [4], *ABB Marine*

- Cycloconverter bridge configuration is constructed of two 6 arm Graetz bridges connected in anti-parallel and supplying each phase of a three phase machine
- The cycloconvertor "constructs" the **output voltage wave-form** from sampled portions of the supply wave-form, in effect the process is one of **modulated phase control** in which the supply side current harmonics (I_{sh}) depend upon the supply to load frequency ratio (f_s / f_d).

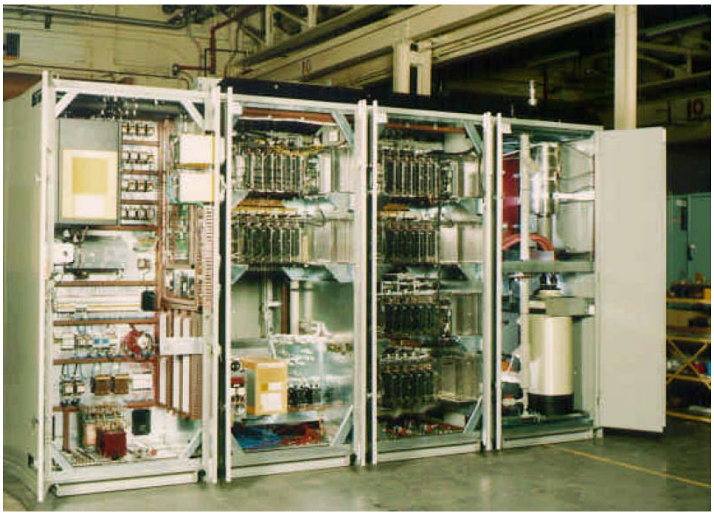


Fig. 23. 5.6 MW Water Cooled Cycloconverter Construction, [5]

Cycloconverter drive technology was ideally suited to the extreme requirements (large powers at low speeds and high dynamic performance) of the Icebreaker

Icebreaker example:

- twin shafts each rated at 11.2 MW,
- each shaft being powered by two 5.6 MW Cycloconverters capable of providing 175% full load torque (FLT) for 30 seconds at zero speed.

Fig. 24. Cycloconverter drive applied on icebreaker, [5]

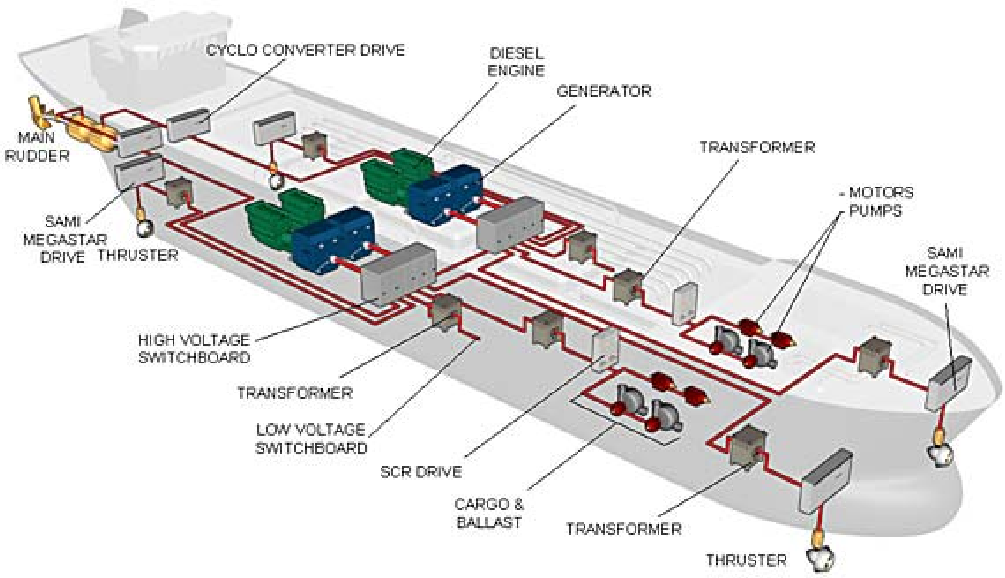


Fig. 24. Shuttle tanker equiped with

- **cyclo converter propeller drives** and
- silicon controlled rectifier **(SCR) drives for DC motor cargo & ballast pumps**

ABB Marine

Special power electronics animation-educational links [8]:

- Basic Thyristor Converter
- Single-Phase Full-Bridge
- Three-Phase Full-Bridge

5.2. SYNCHRO CONVERTER - CURRENT SOURCE VARIABLE SPEED DRIVES (Load Commutated Inverter – LCI, Current Source Inverter - CSI)

- The ***line side converter*** (naturally commutated AC/DC thyristor input converter) takes power from a constant frequency (60 Hz) bus and produces a controlled DC voltage on so called DC link, on the same way as SCR - DC drive converter.
- Current flow in the line side converter is controlled by adjusting the firing angle of the input bridge thyristors (line side converter) and by natural commutation of the AC supply line.
- The DC link inductor L is used to smoothe the DC current I_d, see figure bellow. It effectively turns the line side converter into a current source converter (with $I_d \approx$ const., constant output current of line-side converter), as seen by the machine side converter. As a result of the action of the link inductor L, such an inverter is frequently termed a *naturally commutated current source inverter (CSI).*
- The ***machine side converter*** (output side converter) normally operates in the inversion mode. Inverter thyristors are commutated by the synchronous motor induced voltage (emf).
- Pulse width modulation is not possible to apply in this type of converter (because thyristors are only on-controllable), so the inverter output current is composed by **quasi square wave**, generating a large amount of low frequency current harmonics into the motor (5th and 7th), increasing the losses and the heating inside the machine [8].
- The motor speed is controlled by changing the inverter output current frequency, f_o, while the motor flux and torque are adjusted by controlling the amplitude of the DC link current I_{dc}
- At low motor speed a minimum level of machine emf is required to ensure correct commutation of the thyristors. Hence, for operating speed lower than 10 % of the rated value, the method of "***dc link pulsing***" is used to commutate inverter thyristors. This method consists of reducing the dc link current to zero by temporarily operating the rectifier in the inversion mode. During this zero-current interval, the previously conducting thyristors regain their blocking capability and the motor current can be transfered from one inverter leg to the other.
- In order to assure the appropriate induced voltage at the motor terminals, which is necessary to turn off the inverter thyristors, the **synchronous motor must operate in the capacitive mode**, that is with leading power factor.
- **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. A dynamic braking resistors may be required to execute dynamic braking and they will convert the regenerated energy into the heat. The dynamic braking resistors are water cooled.

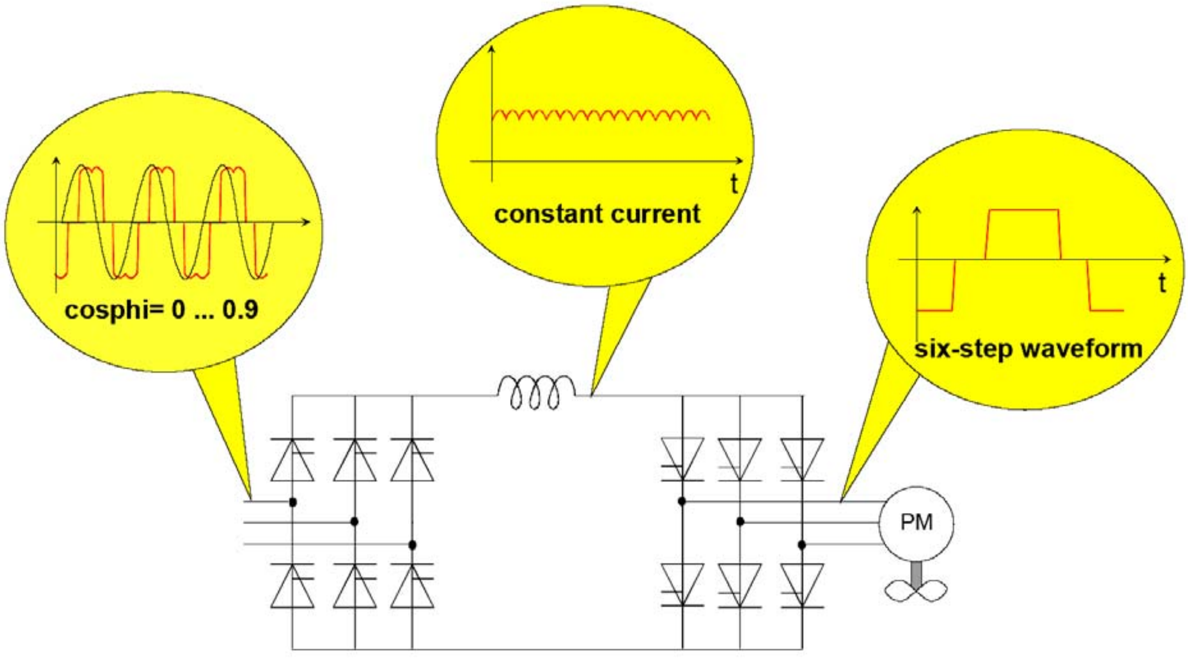


Fig. 25. 6 Pulse Synchronous LCI [1], [2]

- The thyristors of the **input bridge (*line converter*)** are **fired using natural commutation** and are controlled to keep the current at the required level in the DC link reactor.
- The thyristors of the **output bridge (*load converter*)** are **fired in step with the rotation of the motor** and act as an electronic commutator. This works by **using the back emf of the motor to also give natural load commutation of these thyristors**.
- CSIs, also called current-fed inverters, behave **like a constant current generator**, producing an almost square-wave of current. This gives 6 steps of stator current per motor cycle, see figure for six-step waveform.

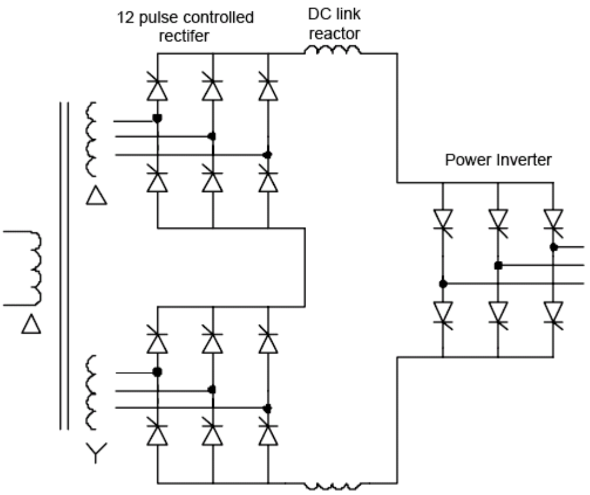


Fig. 26. 12 Pulse controlled rectifier with 6 pulse LCI) [9]

In marine applications LCI drives with 12 pulse on both converters has been used ➔ to get DC current as smooth as possible (rectifier) and to get 12-step waveform instead of 6-step on the output of the machine inverter ➔ lower torque pulsations on all speeds

Limitations

- **High torque pulsations**
  There is high torque pulsations on lower speed (quasi-square wave frequency inverter). However, since the propeller produce significant thrust only for speeds higher then about 30% to 40% of rated speed that limitation has no important consequence in marine applications.
- The LCI synchronous motor drive now is capable of developing **100% full load torque over the entire speed range** and can develop **considerably higher torques during the start mode** when inverter commutation is by *pulsing the DC link* current and not by natural commutation.

- **Power Factor and harmonics**
  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 **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 (synchronous motor operates at high leading power factor - about 0.9), in fact the **kW and kVA taken by the drive are the same as that required by a thyristor fed DC motor** (from 0 to 0.96 = $3/\pi \cdot \cos \alpha$ and depend on speed i.e. fiering angle α is proportional to *PF*), so also are the harmonic currents and resulting waveform distortion. Sometimes very stringent, *THD* (*Total Harmonic Distortion*) Class Society/Owner requirements would require installing of passive, damped filters.

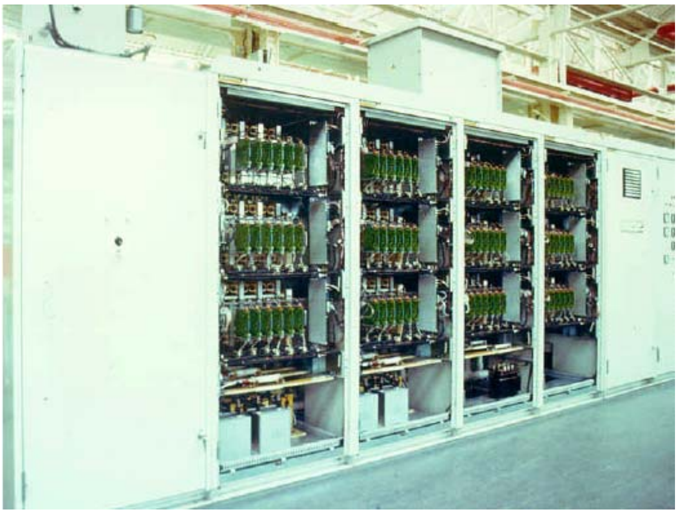


Fig. 27. Current Source Inverter – CSI [5]

Application

- Historicaly, LCI drives (onshore industry) were used over a limited speed range i.e. 60% to 100% of nominal speed and required to operate at very high torque at zero speed (170% of nominal torque) and to be able to accelarate from 30% to 100% in 1 to 2 seconds.

- For marine application these requirements are not desirable for two main reasons:
  - Propeller acceleration is **limitied by cavitation of propeller**. Basically, cavitation is water evaporation on propeller suction side which produces noise, vibration, stress and errosion on propeller blades and on surounding hull surfaces. Hence, propeller should accelerate slowly.
  - Due to **power plant limitations** – There is no available power on network in such short time. Power management system (PMS) ussualy takes up to 5 to 10 seconds to

allocate necessary power. Diesel engine driven generators need about 10 to 20 seconds to take the full load from 0 to 100%. Moreover, if PMS should start new generator, due to low available power on network, it will take more than 20 seconds until next generator start to share the load and more 10 to 20 seconds until be fully loaded.

- The **greater simplicity of the control system** is its main advantage.

- **Simple and reliable**

- **Output frequency can exceed AC supply Frequency, eg 80Hz**

- **Ratings typically up to 100 MW** (in marine applications < 30 MW per unit), 5000 rpm, 10000 VAC

- Suited to normal high power ship propulsion applications such as the cruise liner market.

- Provide **quiet propulsion** for passenger vessels

- Sometimes the required range of control of thrust can be accomplished by controlling the pitch of a controllable pitch propeller (CPP) in conjunction with the (limited) speed control of the synchronous propulsion motors (Queen Elizabeth II repowering).

Fig. 28. RCI Cruise Liner "INFINITY" [5]

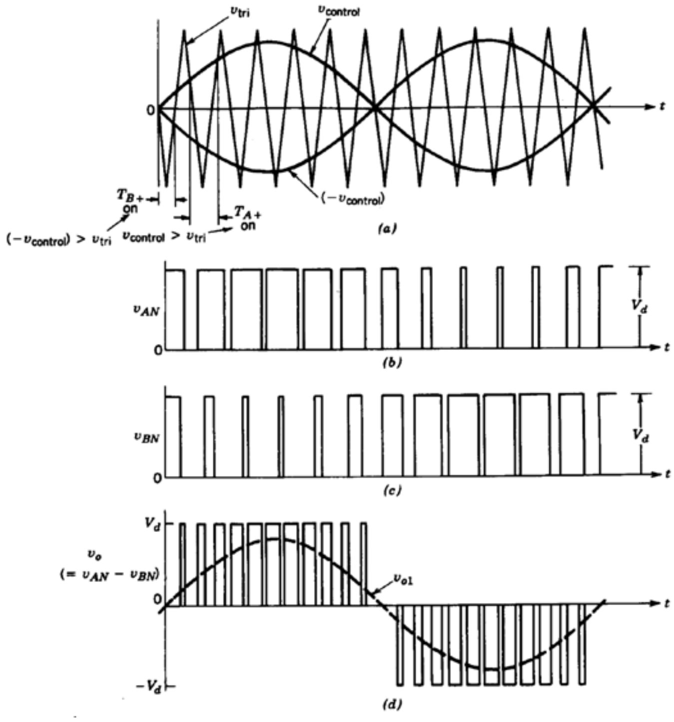
- Two 19 MW Mermaid **PODDED Propulsors - ALSTOM / ROLLS ROYCE**
- Each PODDED propulsor houses a synchronous motor which in turn is fed by dual channel load commutated inverters (LCI's)

5.3. VOLTAGE SOURCE DRIVES (VOLTAGE SOURCE INVERTERS – VSI)

The Voltage Source drives use **forced commutated power switches**. A wide range of forced commutated power switches are used with 3 types being the most popular:

1. Insulated Gate Bipolar Transistors - IGBTs
2. Gate Turn Off Thyristors - GTOs
3. Integrated Gate Commutated Thyristors - IGCTs

- The ***PWM (Pulse Width Modulated)*** drive, often also referred to as ***VSI (Voltage Source Inverter)*** is characterized by its DC voltage link which is fed from the power system by a diode rectifier. A capacitor bank *C* is used to smooth the DC link voltage and to minimize the effect of harmonic distortion from the output (inverter) stage on the supply.
- **Power factor**
  Since a diode bridge is used to produce DC voltage, the PWM drive draws almost unity power factor current from the supply ($PF = 3/\pi = 0.955$), **and is maintained at a constant level at all motor speeds**
- Hence, the generators may have constant power factors approaching 0.9 as **against speed dependent *PF* = 0 to 0.85 for LCI and *PF* = 0 to 0.75 for Cyclos.**



🡐 Fig. 29. Single phase PWM unipolar voltage switching [3]

- Sinusoidal control signal $v_{control}$ at the desired frequency (dependend on machine speed) is compared with a triangular waveform v_{tri}

Special power electronics animation-educational links [8]:

[Single-Phase PWM Converter]

Low voltage source inverter drives

- These converters use a simple input rectifier to give a fixed voltage DC link via an LC filter. This fixed DC voltage (VDC) is switched on/off very rapidly in the output inverter.

- The output line voltage has 3 possible states (+VDC, 0, -VDC) and the timing is varied by Pulse Width Modulation (PWM) to give **sinusoidal motor currents, with very low levels of motor torque pulsations**

Features

- Output frequencies to more than 300Hz
- Constant performance at all speeds/loads with low torque
- Very dynamic responses possible
- Reduced impact on AC supply (i.e. dips and harmonics)
- Ratings typically up to 3.5 MW, 2000 RPM, 6900 VAC

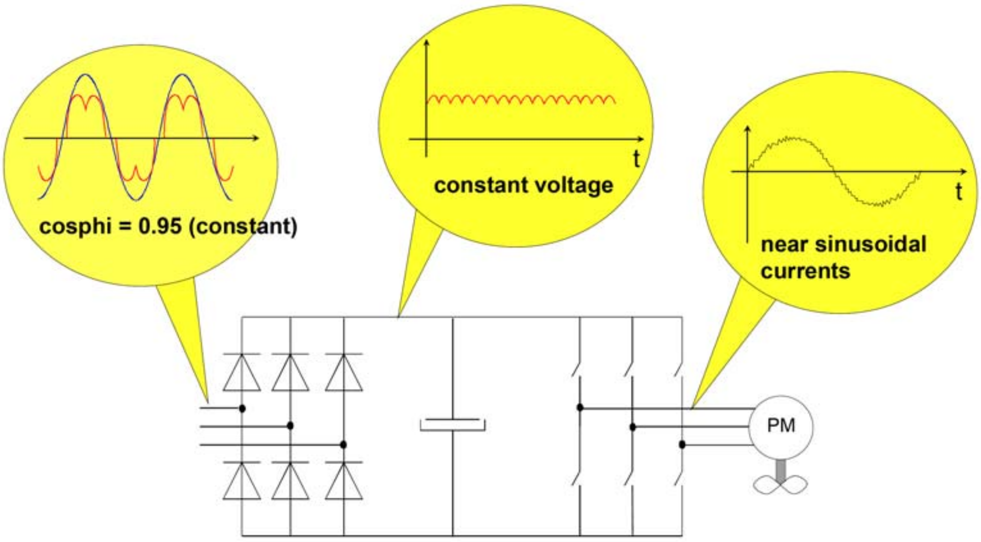


Fig. 30. 6 pulse PWM inverter drive, [1], [2]
(On this figure anti-parallel diodes are not shown)

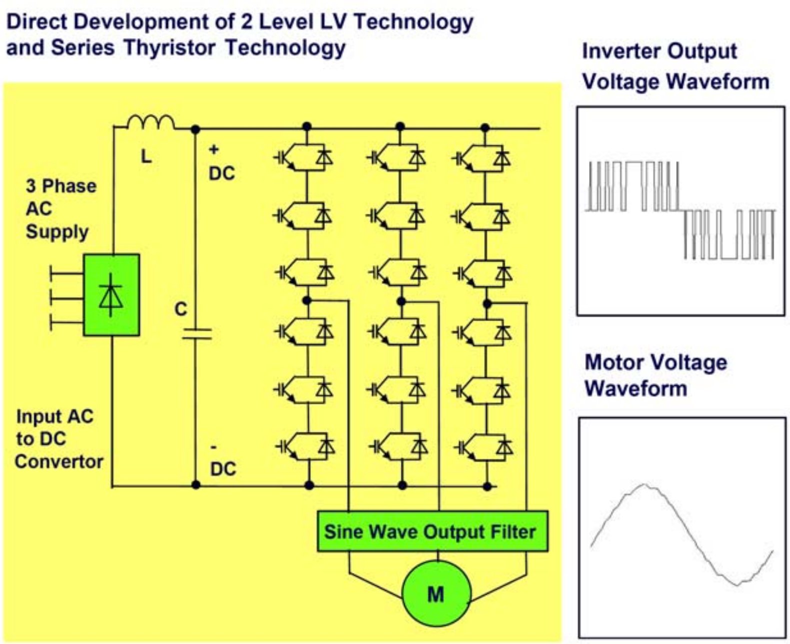


Fig. 31. 2 level circuit using water-cooled IGBTs [5]
- PWM inverter with unipolar voltage switching
- Figure is also showing anti-parallel diodes

Medium voltage source inverter drives

- The low voltage, Voltage Source Inverter PWM drives have proved so successful that a challenge has existed to apply this technology at medium voltages up to 6.6 kV. This increase is desirable to further increase power ratings and reduce cable sizes and costs.

- Multi-level PWM circuits are also available to further improve motor waveforms. For high power PWM drives a much more complex *three level pulse width modulation* increases complexity that might lower reliability.

Limitations

- Extra equipment required for regeneration (regenerative breaking is not necessary for applications where crash manouvre is not performed is i.e. for dynamic possitioning)
- Output filtering required for some standard induction motors

Applications

- Output frequencies to more than 300 Hz, hence PWM drives **are best suited to high speed motor drive** (900-1200 rpm) applications, requiring a stepdown gearbox to drive the propeller (azimuth thrusters with Z-type gear transmition) thus offering the cost- and weight-effective solutions.
- Constant performance at all speeds/loads with low torque pulsations
- PWM drive has excellent dynamic performance. The torque is smoothly controlled at all speeds, including zero speed, with speed feedback in a vector-controlled scheme.
- Harmonic distortion will often be below the limits defined by rules and guidelines without additional filtering.
- Ratings typically up to 20 MW (Commercially up to 8 MW), 2000 RPM, 6600 VAC

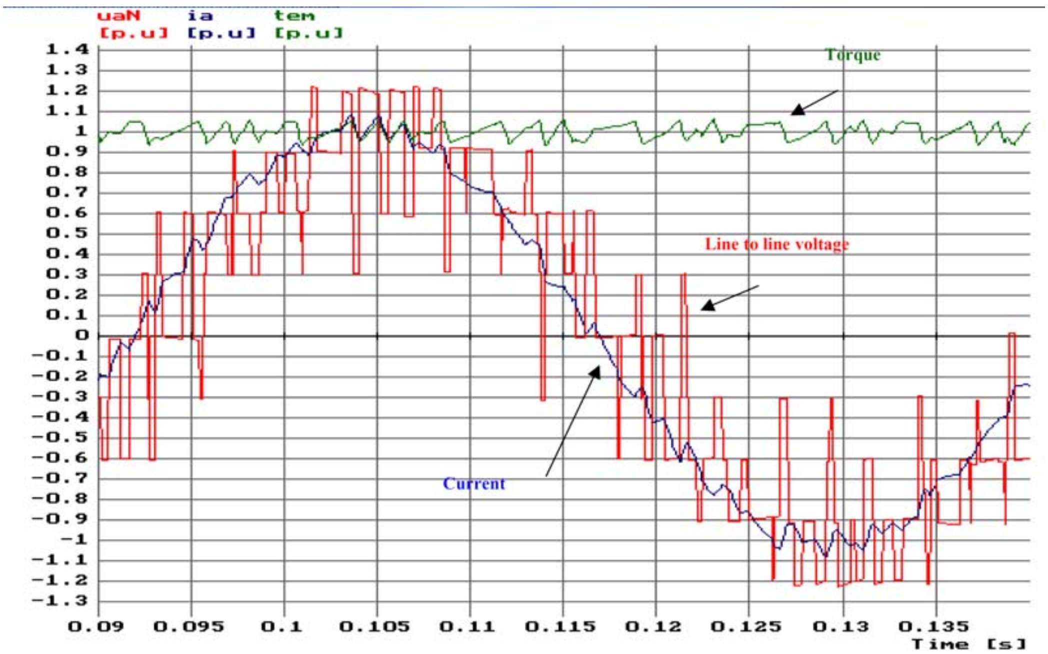


Fig. 32. Current, voltage and torque curves at output of PWM VSI [4]

6. Comparsion of all drives

All converters will impose some harmonic distortion on to the supply network which, if left untreated, could affect the operation and life of any other equipment connected to that supply.

The best way to lower harmonics in terms of cost and space is to design the power system such that the Total Harmonic Distortion (THD) does not exceed pre-defined levels without the need for additional filters.

Using PWM drive and 12-pulse configurations, the resulting harmonic distortion will often be below the limits defined by rules and guidelines without additional filtering.

The dominant harmonic currents are of the 5th, 7th, 11th, and 13th harmonic order. Using 12-pulse configuration will cancel the 5th and 7th harmonics.

Furthermore, using 24 pulse systems offer the lowest harmonic distortion levels.

Harmonic number	6 Pulse	12 Pulse	18 Pulse	24 Pulse
5	20.0%	-	-	-
7	14.3%	-	-	-
11	9.1%	9.1%	-	-
13	7.5%	7.5%	-	-
17	5.8%	-	5.8%	-
19	5.2%	-	5.2%	-
23	4.3%	4.3%	-	4.3%
25	4.0%	4.0%	-	4.0%
Total RMS value	**29.0%**	**13.2%**	**11.0%**	**5.9%**

Table 1. Summary of all available motor drives, [1], [2], [4]

	SCR DC motor drive	Cyclo-converter [1]	CSI (LCI) [2]	VSI PWM [3]
Amps at low speed	F(torque)	F(torque)	F(torque)	≈ 0
Cosϕ	0 .. 0.9 (≅ prop. speed)	0 .. 0.76 (≅ prop. speed)	0 .. 0.9 (≅ prop. speed)	> 0.95 (≅ constant)
Dynamic response (power, torque)	< 100 ms	< 100 ms	Slower	< 50 ms
Torque ripple	Smooth	Smooth	Pulsating	Smooth
Zero-speed crossing	Discontinuous	Smooth	Pulsating	Smooth
Efficiency at full load	Lower	High	High	High
Harmonic distortion: - at low speed - at full speed	 F(torque) F(torque)	 F(torque) F(torque)	 F(torque) F(torque)	 ≈ 0 F(torque)
Short circuit contribution	No	No	No	No
Motor matching required	Some	Some	Yes	No
Commutator	Yes	No (slipring)	No (slipring)	No

[1] With brushed synchronous motor
[2] With brushed synchronous motor
[3] With cage induction motor

8. Acknowledgement

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