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A Review on Power Electronics and Drives in Electric Propulsion System

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Abstract. This era is the part of the fast-growing world and it is thriving more in the field of advancement of technology. Power electronics and drives are one of the major fields that is getting updated every day. Due to increased power generation capacity, improved power qualities, increased automation, and improved capabilities, the electric propulsion has replaced mechanical propulsion. Similarly, the variable speed motors have replaced transverse motor starters to save energy and reduce load instability. With the detailed structure and working of the marine electric propulsion system, this paper focus on reviewing about the various power electronic devices and converter configurations that are used in marine applications, specifically in the propulsion system. Moreover, the detailed assessment of different motor and drive schemes employed in propulsion system is carried out. Further, the review will shift its centre towards controlling drives, which includes various control strategies and control techniques.

1. Introduction

In earlier times the mechanism that was in operation for propulsion of marine ships was mechanical. Although due to advancement of sophisticated circuits it has been replaced by electrical ships which has electrical propulsion system [2]. Power electronics has played a great role on the efficiency and uses of almost every electrical device. There are three major phases in an electric ship: (i) power source (ii) distribution centre and (iii) load centre [3]. Power electronics switches and devices are used to connect power source and load centers through bus which eventually distributes the power to every part of ship (which includes propulsion system). Due to increased power generation capacity, improved power qualities, increased automation, and improved capabilities, marine electric propulsion has replaced the mechanical propulsion ships and similarly the variable speed motors have replaced transverse motor starters to save energy and reduce load instability [6].

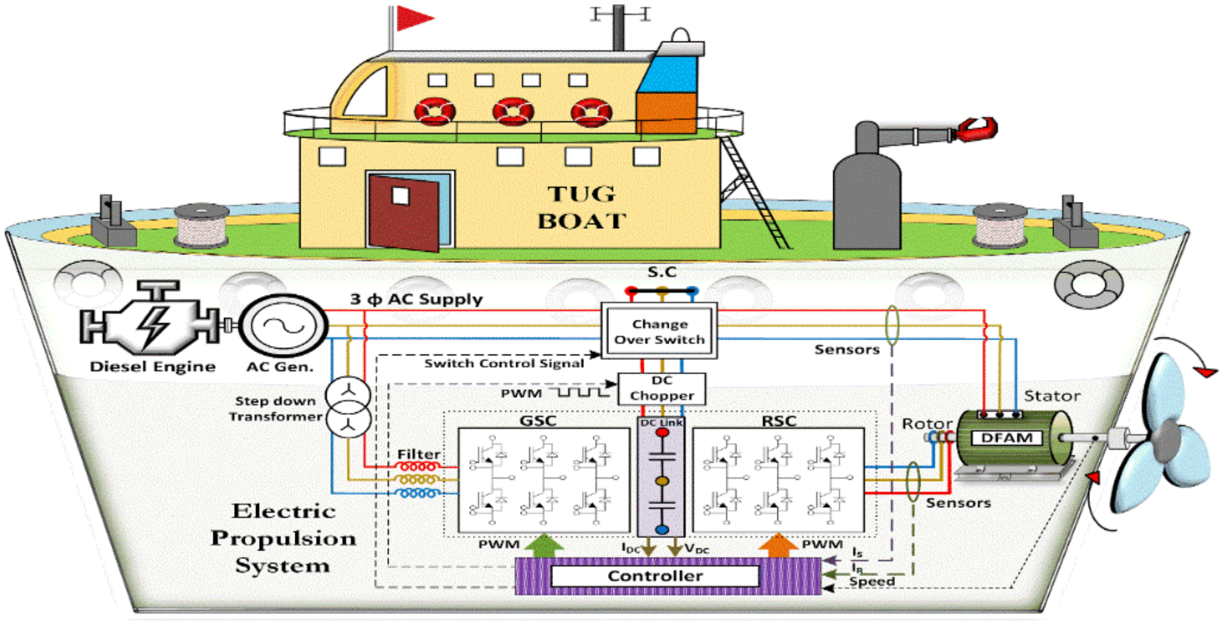


Figure 1. Overall schematic of electrical propulsion system [28].

The above diagram (figure 1) represents the schematic representation of electrical propulsion system. Here the diesel engine which acts as a prime mover rotates the generator. This rotating generator produces electricity and supply it to the transformer (step down transformer) and the load (stator of the motor). The transformer then supplies power to the motor through a series of power converters. These power converters are connected in series with the help of a dc link. The control strategy applied for the power converters is pulse width modulation. Controllers are also used in the circuit for controlling the speed of the propellers and the current fed into the rotor and stator.

The below diagram (figure 2) basically gives us the overview of the electric propulsion system. In the generation part, AC generator generates power and gives it to the bus bar. In the distribution part, power is distributed to the motor from the bus bar. In the propulsion part, electric motor rotates the propellers which produces propulsion. Here the motor is not directly connected to the propellers but is connected to the propelling shaft and the gearbox. The gearbox and propelling shaft are then connected to the propellers.

Traditional marine mechanical propulsion system uses main engines for propelling the shaft and each shaft is powered by its own dedicated main engine with particular provisions. Except when difficult combination of gearboxes cannot be used for shafts interconnect.

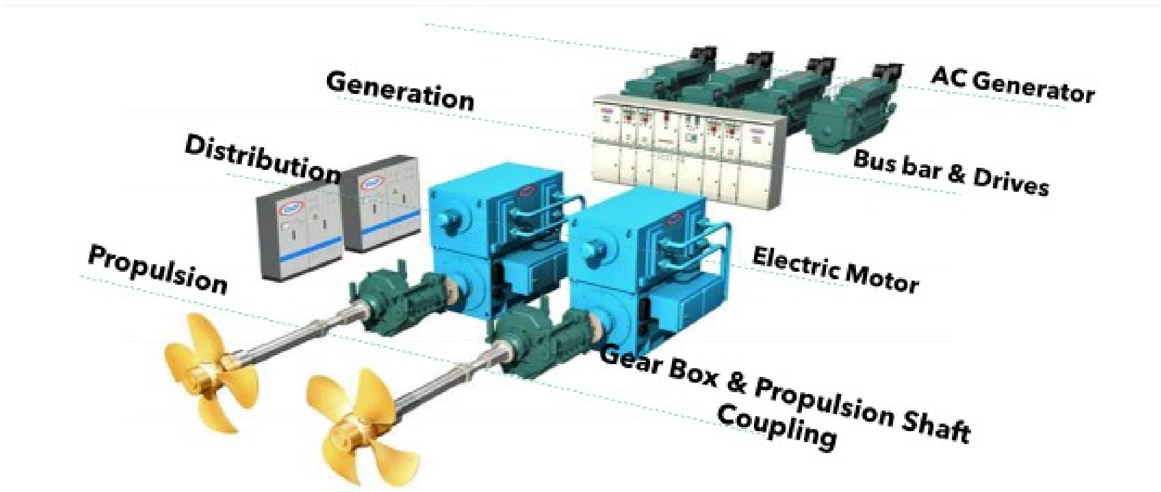
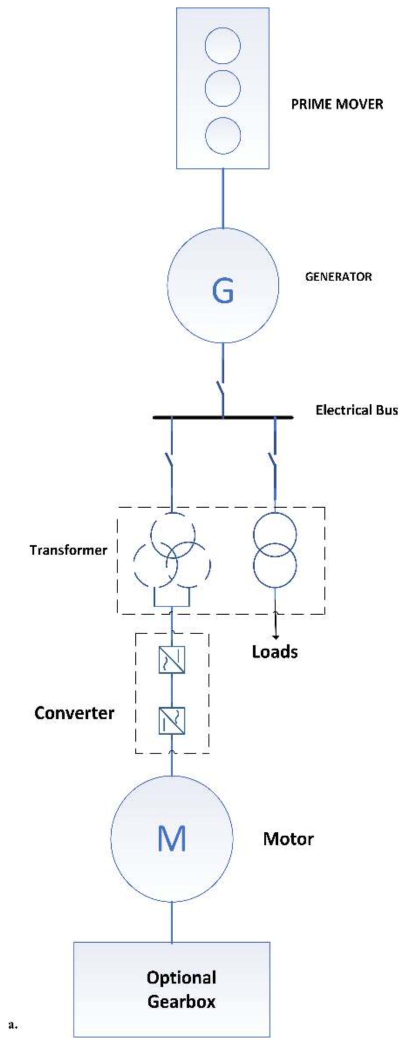


Figure 2. Schematic representation of Electrical propulsion system [28].



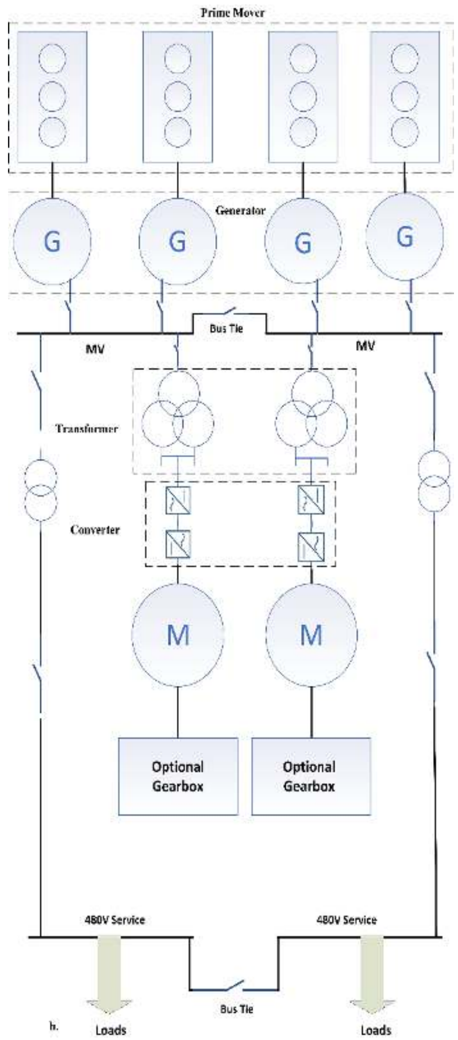


Figure 3. (a) Single sourced propulsion system. **(b).** Multi-sourced propulsion system with redundancy.

In fig (a), the prime mover produces the useful work and rotates the generator which in turn produces electricity for the marine electric propulsion. This prime mover can be a diesel engine which uses diesel and produces useful work or it can be a gas turbine too. Now this running generator provides electricity to the electric bus as shown in the fig (a).This electric bus provides electricity to the loads as well as the transformer which gets connected to the motor through a series of two converters as shown in fig (a).The motor is then connected to the gearbox which helps in the propulsion of the electric propulsion system. Fig (b) shows the multi sourced marine electric propulsion system with redundancy. In this single line diagram four prime movers are used which are then connected to four generators. Each prime mover rotates one generator. All the rotating generators produce electricity and supply it to the electric bus. Two electric busses are used for four generators (each bus for two generators combined) as shown in the fig (b). Each bus powers the load and the transformers. The transformers are connected to the motors through converters. These motors are connected to the gearbox which helps in the propulsion. This circuit is more redundant than that of fig (a) because here the electric supply to the loads and the transformer is not dependent only on a single bus. Even if one bus fails or has some faults in it the other bus can compensate for it by establishing a connection through the bus tie line. But in case of fig (a) the supply to the transformer and loads has no alternative. Therefore, circuit in fig (b) has redundancy.

Electric propulsion (EP) is a class of space propulsion that uses electrical energy to accelerate a propeller by various possible electrical and / or magnetic means [8]. The use of electrical energy improves the propulsion performance of EP propellants compared to conventional chemical propellants [10]. The major reasons to adapt to electric ship (electric propulsion system) is that astern operation and ship manoeuvring is possible without recourse to controllable pitch propellers or complicated reversing gearboxes [18]. Addition to electrical propulsion the electrical generators need not be limited to supplying propulsion power alone – they can also be arranged to provide the electrical power required for the ship's domestic and other use[24].For the electric boat related applications cost, weight, loss and size (whichever is has the priority) for different applications in the equipment is a major limitation on the acceptance of power electronics on boats[26].

2. Power electronic switches used in marine electric propulsion system

For the marine electric propulsion system to work smoothly and hassle free, power electronics switches plays a major role. All the major on-off circuits and control circuits are dependent on power electronic switches. Major types of power electronic switches are discussed ahead:

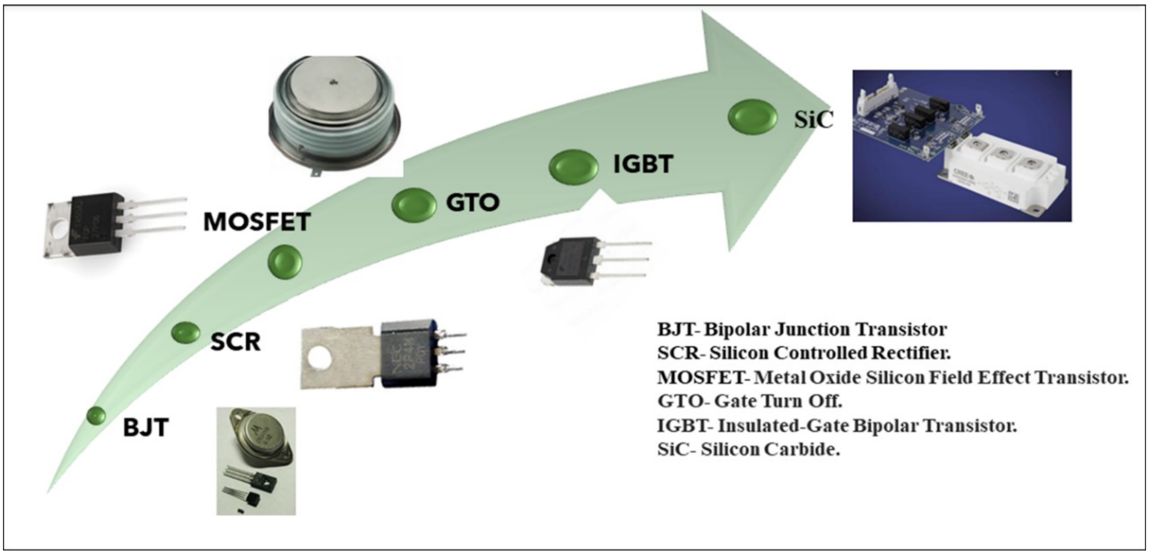


Figure 4. Evolution of switches in Marine Propulsion System(MPS).

2.1. Thyristor
The thyristor is locked with an impulse switch on the gate. ON low-voltage conductivity drops forward and does not turn off with pulse removal. Change needs a negative opening impulse. Normal used thyristors, line converters, and cycle converters are built without their own disconnect [26] capability, in which case the thyristor goes from its locked conduction state to a non-conductive condition, even if the current is zero in various directions. The approach results in a very effective solution and unity with the highest scores. Regarding high power converters are as follows.

- Gate Turn off (GTO)
- Integrated gate commutated thyristor (IGCT)
- MOS turn-off thyristor (MTO)
- Emitter turn-off thyristor (ETO)
- Super GTO (SGTO)[29]

2.2. Transistor
A transistor conducts a gate signal in its forward direction when the gate signal is turned off and on. A shutter has manual ignition; If the signal is less than what is needed for a full ignition, it will work as long as the anode remains at a partial cathode voltage [26]. This current limiting feature is an essential asset to transistors: it buys several microseconds of time, enough for protection purposes [29]. Nowadays mainly MOSFET and IGBT switches are being modified and used in most of the circuits due to its controlled cut-off maintaining features.

2.3. Power-Diode
A power diode is a two-terminal unit, where one is an anode and the other is a cathode. If the voltage of the anode is greater than the voltage of the cathode, then the diode is biased forward and the forward current flows through the diode [24]. Through this position the current rises gradually through the power diode, and the voltage increases as well. If the diode is biased in reverse, only a small current pass through the diode-this is called the leakage current [26]. In certain instances, this can be overlooked. The current is fairly insignificant in this role before some degree of reverse voltage occurs-this is called the voltage of breakdown.

2.4. SiC
Silicon carbide (SiC) chips can be used in principle to manufacture any of the devices mentioned above. The software offers advantages high voltage capacity (20 kV) of much lower switching losses (score per device) and high temperature [26]. Nonetheless, the hardware is expensive, the amount of small chips is huge. It must be connected in parallel, and the commercially available devices are around 1200 V and one hundred amps [29]. Although SiC devices are expensive, they have a very high impact on drive size, loss, weight, cooling requirements, and high PWM frequency potential [29].

3. Motor
The following table represents different types of motors that can be used in marine electric propulsion system. This table shows us a comparative study on the evolution of motors mainly dependent upon five factors: range of the motor, starting torque required by the motors , rating of converter associated with the motor and the efficiency of the motor, after the comparative study of different types of motor, DFA motor is found to be the best fit for usage in marine electric propulsion system due to the fact that it has partial power converter rating for the converter associated with it. This means that DFA motor can run at full capacity without burning up the power converter that is associated with it.

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Table 1. Comparison table of different types of motors.

Motors	Range	Starting torque	Rating of converter associated	Power rating	Efficiency
DC Motor	Wide-speed	High	Full rating of power converter		70 to 80 %
Synchronous Motor	No range (Sync speed)	Zero	Full rating of power converter	High power rating	High efficiency
Induction Motor	Runs at approx. synchronous speed	High starting torque	Full rating of power converter		85-97%
PMS Motor	Wide speed range	No starting torque	Full rating of power converter	High power rating	High efficiency
HTS Motor	Wide speed range	Good starting torque	Full rating of power converter	High power rating	High efficiency
DFA Motor	Wide speed range	High starting torque	Partial rating of power converter	High power rating	High efficiency

4. Power converter configuration in marine electric propulsion system.

The electronic power converter converts electrical energy in one way to electrical energy in a different way: AC to DC, AC to AC, DC to DC, DC to AC. Converters can adjust the power generated by source to an increasing voltage distribution; and load converters. The adjustment of voltage distribution depends according to the type of power supply that requires preparation. Resources can be configured to work at their best punctures [18]. The distribution and sharing of loads between active sources upgraded. Conversion point of use ensures loads are getting to their needed strength. Nearly every source and charge need today a conversion tool. Power and control circuits were special in the past and hardwired, unchangeable. Computer configurations are now made with Power Electronic Building Block (PEBB) can be used to produce variations during the design process miscellaneous products. In addition, these, with digital power products can be designed to operate the electrical selected functionality. The end result is therefore special and immutable like the corresponding wired converters. Today, digital control networks, a given PEBB configuration, can see their control algorithms modified to be delivered in the field [21]. This system can be used for many different functions. Different types of converters used in drives in electrical propulsion system (EPS) are Voltage Source Inverter (VSI) type converters for AC motors normally for asynchronous motors, cyclo-converters for AC motors normally for synchronous motors, Current Source Inverter type (CSI) converters for AC motors normally for synchronous motors and DC converters, or SCR (Silicon Controlled Rectifier) for DC motors[30].

Modern marine power electronic converters are Alstom series connected converters, voltage clamped converters and isolated voltage converters[30].

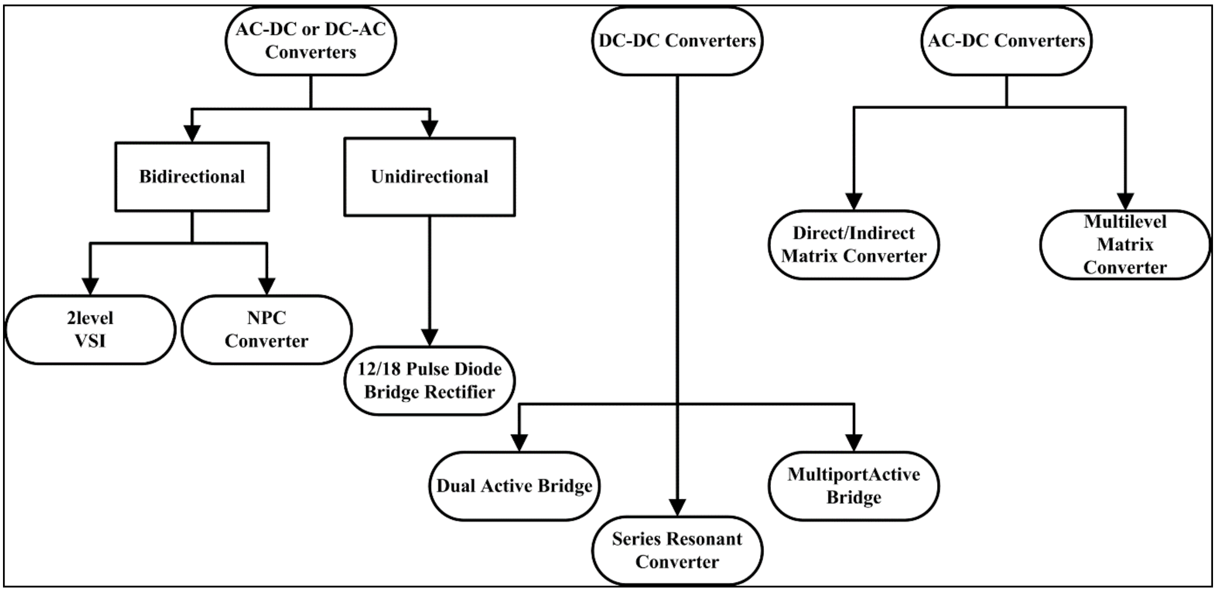

Figure 5. Power electronics converter classification tree.

4.1. Alstom Series Connected Converters

It is a multilevel inverter. It uses switches connected in series with flying capacitors connected in parallel to those set of series connected switches, the flying capacitor is used to cope up with the short circuits at the load or overvoltage problems. The Alstom series connected converter increases the power rating and maintains high quality of power and voltage without derating the motor.

These converters permit a rise in power rating and voltage while not sacrificing the purity of the voltage waveform and also the subsequent motor de-rating. Semiconductors need not be stratified and may be place in series with none preselection [21]. Finally, energy levels are minimized beneath fault conditions. The benefits of this device are no longer needed to be established for high-power variable speed drives. In the years to return, it will inevitably become the topology of alternative all told sectors of energy conversion [30].

4.2. Voltage Clamped Converters

DC–DC device with reduced reverse recovery current and switch-voltage stress, with an influence quality of low voltage and high current [18]. It will choose the switch with lower property voltage for assuaging the switch conductivity loss in order to use of voltage-clamped technique. In this case the extra capacitor is employed for providing the reverse current path of the electrical device to lift the utility rate of the core [30]. further snubber circuits for engrossing the voltage spikes within the diodes aren't needed to additional hamper the manufacture price.

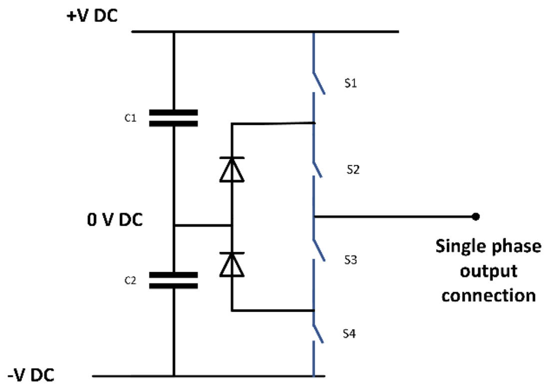

Figure 6. Voltage clamped converter.

4.3. Resonant Converters

Recently, resonant DC / DC converters have sparked considerable interest in analysis by tracking the progress of their applications. This increase in its industrial application has led to many efforts to improve smooth switching, smooth waveforms, high octane density, and high-power options for resonant converters. Its quality for high-frequency use and its ability to mitigate switching losses were attracted to industrial applications compared to typical hard-switched drives. Numerous studies have been carried out on the exchange of DC-DC converters to confirm that they meet the strictest criteria for the application of the philosophy of natural energy. The possibility of minimizing the switching losses and conductivity in the switching mode by increasing the switching frequency makes them very attractive. However, many switch topologies will achieve high octane transfer [1][2], but the problem is that the power switches (transistors), diodes, and passive energy storage components (capacitors and inductors) contained in the converter capacity structure, which affects its power. The idea is that an auxiliary circuit around the main power switch creates a resonant flow of current in the same circuit that forces the current or voltage of the switch to be around zero at all times switching interval [21]. In this way, the switching loss is essentially eliminated because the volt-amp product is also around zero. once this control is around zero, the circuit is assumed to resonate in current, on the contrary, once the voltage is controlled around zero, the circuit is assumed to resonate in voltage [30].

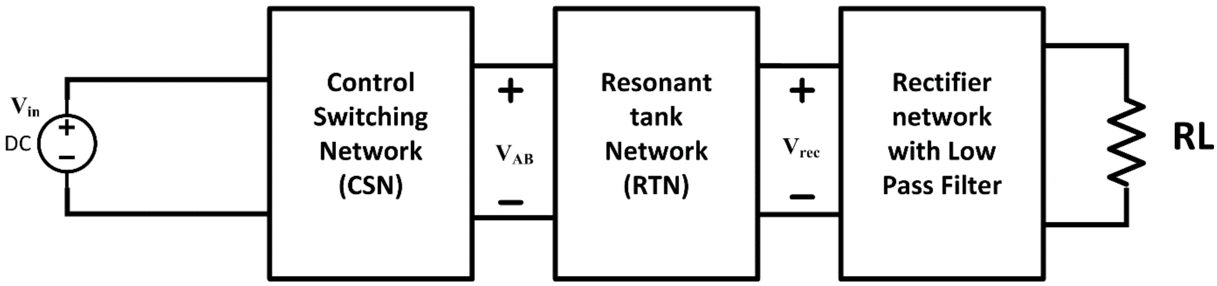

Figure 7. Resonant converter.

4.4. Isolated Voltage Converter

In terms of accuracy in output voltage regulation, isolated DC / DC converters generally fall into three categories: regulated, unregulated, and semi-regulated. In a regulated isolated DC / DC converter, the input voltage, load current, and shutdown temperature have an effect on the output voltage accuracy of unregulated isolated DC / DC devices[30]. For some applications that require specific output voltage and tight regulation, this is generally unacceptable and regulated isolated DC / DC devices must be used.

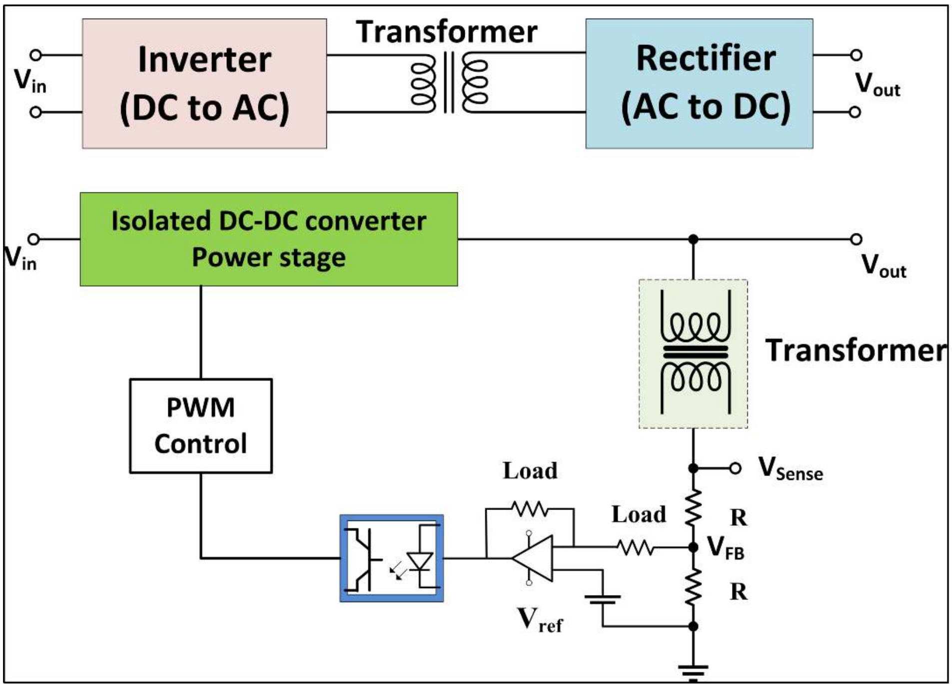

Figure 8. Isolated voltage converter.

4.5. Matrix Converter

A matrix converter is used to convert input voltage direct into an arbitrary AC voltage instead of converting that input voltage as DC voltage (as in case of inverters). This matrix converter has high efficiency, long life span, smaller harmonics and has high potential for completing the demands of today's market[21]. The matrix converter arranges the switches in matrix order and controls them to convert input voltage direct into an arbitrary AC voltage. Since there is no conversion into DC component therefore energy storage devices are not required [30].

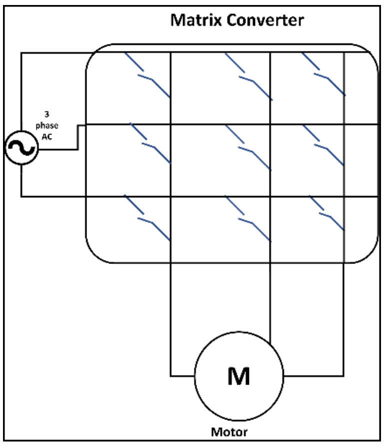

Figure 9. Matrix converter.

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The below table gives us a comparative study on the three different types of enhanced power converters. The comparison parameters for the power converters are mainly: number of switches used in the power converter, different types of configurations in which the power converters can be used and the most important parameter that is the MVA capacity of the power converters.

Table 2. Comparison table of modern converters.

Power Converters	No. of Switches	Modes of Output	Configuration	MVA Capacity	Year [citation]
Alstom Series Connected Converters	10	3	Transformers, Multilevel-Inverter, Motor-filter	25 MVA	2002 [30]
Isolated Voltage Converter	8	1	Refer diagram	10-11 MVA	2002 [30]
Voltage Clamped Converters	12	2	Refer diagram	5 MVA	2002 [30]

5. Control strategies for on board micro-grid system.

5.1. Primary Control

The primary control focus of a dc microgrid are dc voltage guideline and burden sharing. If the breakers are shut, the AC/DC converters associated with the generators are taking care of a solitary HV transport, in this way, the voltage of the transport and the power sharing of the two generators must be managed [21]. A few methodologies can be embraced to accomplish these objectives, and they can be separated into concentrated and decentralized methodologies. The best decentralized methodology depends on the hang control, looking like the controllers embraced in the inheritance framework. At the point when two DC/DC converters are working equal, their yield voltage is controlled to de-wrinkle relatively to the current [31]. This usage of the hang control impersonates the activity of a perfect voltage source with an arrangement resistor. On the off chance that the yield current builds, the voltage diminishes, taking into account the equal association of numerous voltage-controlled converters. The hang coefficient can likewise be named the virtual resistor for the voltage lease hang control. Different methodologies are conceivable, similar to the current/voltage hang (where the converter is worked with a present control conspire) or by utilizing the power rather than the current (power/voltage hang or volt- age/power hang) The decentralized controllers consider a basic execution; in any case, consistent state voltage blunders or soundness issues may emerge [29]. A voltage blunder shows up when the converter is preparing the most extreme current Imax diminishing the estimation of the virtual resistor R_v decreases the mistake however makes the power sharing less precise because of estimation blunders[30].

5.2. Secondary Controls

To settle the consistent state blunder because of the hang control, auxiliary circles are utilized. The thought is that a focal controller forms the estimations at every hub and afterward sends refreshed references for the hang control to re-establish the ostensible voltage condition [18]. This technique looks like the optional control of the heritage network, and it needs a low-transfer speed correspondence connect to play out the estimation and speak with the neighbourhood controllers. Techniques that don't require a correspondence interface however depend on improvement strategies are likewise professional presented to this point [21].

In an external adjustment circle is received to forestall the framework in-strength on account of little yield channels. An eye-witness based framework is along these lines proposed to play out the adjustment activity with-out the need of extra sensors [31].

5.3. Storage Management System
This control mechanism is most essential part of any system. Power required for all the equipment other than traction power comes from this system. It basically deals with the battery state estimation i.e. state of charge, state of health, state of life, and state of power estimation for the batteries. Overall supply of energy for all the systems at regular basis as well at the emergency state depends upon the wellness of the batteries that stores energy. All the supporting element gets power from this for operation.

5.4. Multi-objective global optimization
The heart of all control types. This keeps an eye on rest of the other control techniques for the smooth working of the equipment under desirable range. It's working ladder is based on the importance of equipment on the priority list for a particular work. It's feature for controlling the targets depending on the phase of operation makes it very compatible for installation to get better control over the equipment. But due to computational complexity it's establishments are affected.

Table 3. Comparison table for different control type.

Control type	Control targets	Features	Issues	Year [citation]
Primary	Load current and voltage DC or AC bus voltage	Local implementation of the inner controls Possibility to use solutions tested in other applications	Customization to the ship environment required.	2019 [21]
Secondary	Voltage restoration Stability improvement Power flow regulation	Improvement of the distributed control performance. Global network management.	Communication link must be established. Susceptible to single point failure. Several sensors needed.	2019 [21]
Storage Management System	State of charge Peak shaving Voltage control	Energy storage scheduling depending on the technology.	Many control targets makes the optimization difficult. Fault isolation required because of the risks.	2019 [21]

Multi-objective global optimization	All variables within the specified limits, load prioritization and storage management.	Better performance than distributed control. Possibility to adapt the control targets depending on the phases of operation.	Mismatch between predicted and actual mission profile. Computational complexity.	2019 [21]

6. Energy management strategies

Power age in transport microgrids are commanded by coordinated generators, which are controllable. Notwithstanding, the heaps are exceptionally powerful and, in specific cases, may contain quick changes. In this way, so as to oversee complexities and accomplished to control goals, the various levelled structure can be received for transport microgrids also. In addition, as clarified beneath, the current control advancements in transport power frameworks can likewise be portrayed in accordance with the various levelled control system. In various levelled control, the essential level goal is to accomplish load sharing among the power sources. The optional level control objective is to make sure about transport signals at their ostensible qualities. The tertiary level control is utilized to accomplish ideal activity with deliberate goals [32]. In this plan, the higher the degree of control, the more-slow the guideline it gives. Besides, the extent of the control augments as the level increments.

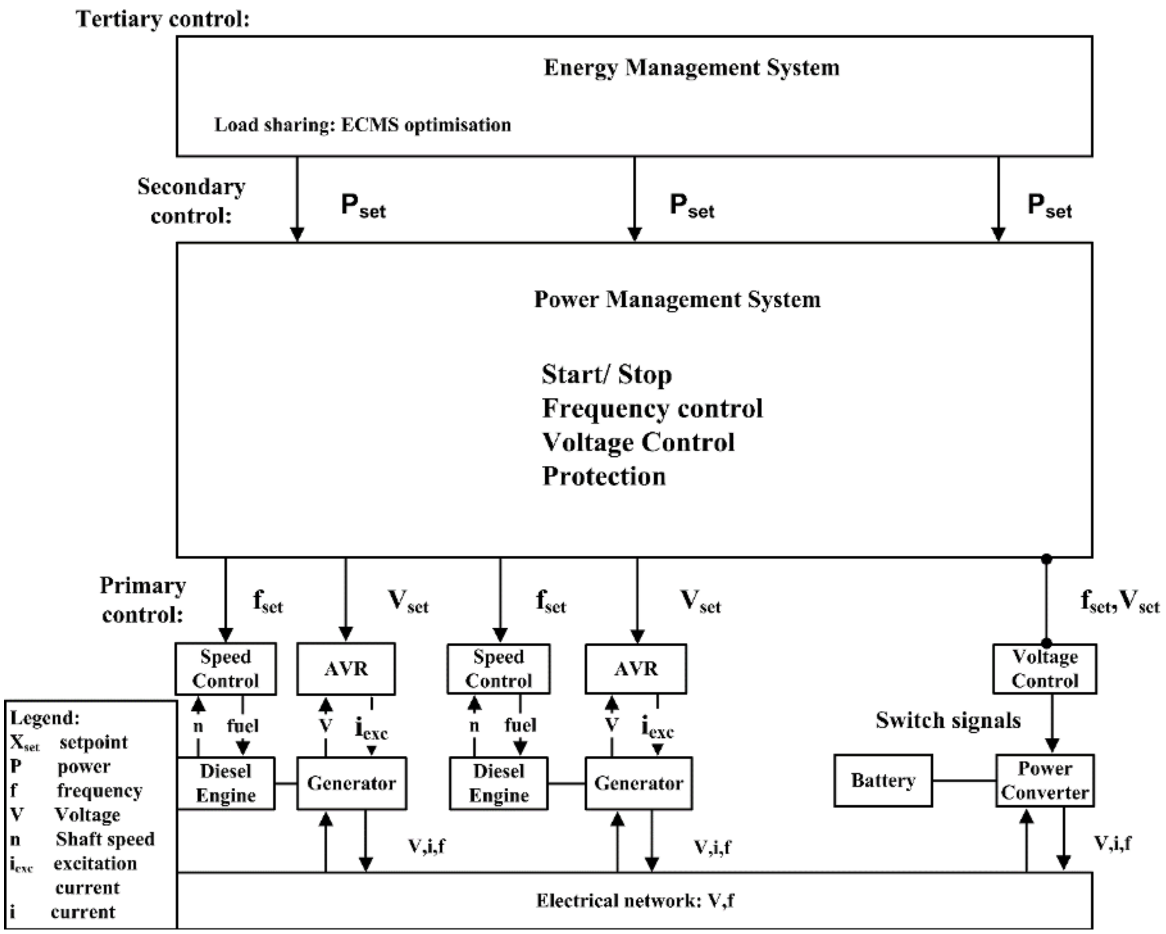

Figure 10. Different levels of control strategies and control techniques in MPS.

6.1. Isochronous Control

Most marine power scaffolds are AC flow scaffolds where repetition and tension are the two key parameters that must be met within certain limits. Since simultaneous generators for diesel engines or gas turbines are the sources normally used in this setting, the senator's controller manages the repeat while the automatic voltage controller (AVR) directs the voltage. The senator, supplied in the form of a hydromechanical or electronic control, correctly directs the fuel to the engine and therefore manages the speed (ω) of the rotor.[3] Delivered as an electronic controller, the AVR controls the current applied to the generator field turn, which manages the performance voltage[4].

Under isochronous control, generator voltage and repetition performance are maintained at fixed focal points, regardless of changes in the heap. Unlike different level control structures, isochronous control for a single generator falls into the area of essential and auxiliary levels, as it manages the transport voltage and repetition in fixed foci and at the same time provides the required force [18].

The previously mentioned isochronous control functions admirably for a solitary generator. On the off chance that at least two generators are associated with a similar power transport, one of the motors may attempt to take the whole burden while the others probably won't take the heap. This prompts dangers and may bring about power outage. In this way, so as to settle this issue, correspondence between the representative controllers, as a heap sharing line or a correspondence connect, for example, Controller Area Network (CAN) transport or Field transport, is required with the assistance of the correspondence interface, every motor can be set to take a particular portion of the heap without going into boundaries or insecurities[31]. In this setup, the Power Management System (PMS), decides the power reference for every motor, and can be ascribed to the tertiary degree of the various levelled control structure [19].

Despite the fact that isochronous burden sharing is equipped for controlling voltage and recurrence at set focuses, it has not gotten the well-known decision in transport microgrids, primarily due the cruelty of nature in ships, which unfavourably influences correspondences [8]. Additionally, so as to execute isochronous force sharing, all the senator controllers ought to be perfect, and a large portion of the cases should originate from a similar maker, which may not be conceivable at times [31]. Despite the fact that arrangements, for example, propelled generator oversight have been created to forestall power outage in flawed circumstances, isochronous control is as yet not the mainstream decision with regards to huge shipboard force frameworks.

6.2. Droop Control

Contrasted with isochronous control, hang control is the mainstream decision for power partaking in multi-generator shipboard power frameworks, as it doesn't require correspondence between the representative controllers. As opposed to the fixed recurrence and fixed voltage activity in the isochronous control, hang control lets the recurrence and voltage differ with respect to the dynamic, (P), and receptive force, (Q), requests of the heap. Where the speed and voltage references are diminished directly as the dynamic and responsive power requests increment.

The droop control matches with the intrinsic P/f droop nature of simultaneous machines where stacks on the electrical side hinders the rotor and thus, speed drops [3][4][5]. The senator infuses more fuel in light of the speed drop and subsequently, the generator set gets steady at another recurrence, which is lower than the ostensible recurrence, fundamental frequency (f_o). The recurrence as well as the voltage settles at another incentive similarly when there is an adjustment in the responsive power request [18]. In a multi generator framework, every senator detects the speed drop, supplies more capacity to the matrix lastly settles at another recurrence. The measure of intensity provided by each generator set relies upon the hang settings of the genset. In the event that the settings are equivalent, all the generators set similarly share the heap. Additionally, the hang control can also be applied for power converter-based frameworks. Also, it may be, independent of the framework, hang based power sharing falls inside the extent of the essential reaction in the progressive control plot.

In a multi-generator framework, the auxiliary control can be accustomed to take the recurrence back to the ostensible worth, by adding a counter-balance to the speed reference, ω ref. This is known as the optional reaction that can be credited to the level 2 control of the various levelled control plot. Further changes can be made to the hang controller by changing the hang gain, kp, which changes the force levels of every motor to their most ideal levels under the given condition. This tertiary reaction has a place with the level 3 control of the progressive plan. Like the previously mentioned speed, hang controllers work dependent on the responsive force request. As indicated by the guidelines of the majority of boat arrangement social orders, the proportionality of burden sharing needs to biggest generator should be inside the scope of ±15% of the evaluated dynamic force and ±10% of the appraised receptive intensity of the biggest generator. As opposed to isochronous control, hang control requires just neighbourhood estimations of voltage and recurrence, and in this manner, it permits different generators to share the heap without chasing and without the need between unit correspondence. This makes hang control strong, exceptionally solid, and adaptable in including/expelling the generators of various power evaluations to the network [7][8]. By the by, since the dynamic and receptive force provided by generators rely upon recurrence and voltage deviations , huge burdens bring about expanded deviations, and this is an innate exchange off of hang control.

7. Result

The space required for installation of electrical propulsion machinery is very less and compact as compared to conventional system. There is no direct connection of propeller shaft and prime mover, and hence transmission of severe stresses such as torsional and vibration is restricted. Environmental benefits from lower fuel consumption and emissions.

Whereas the efficiency of the electrical plant is less than that of a conventional system. The installation cost of electrical propulsion plant is much higher. Different and improved training for ship's crew as the system is completely different from mechanical system and involves major automation.

8. Conclusion

At present, electric propulsion is applied mainly in following type of ships: Cruise vessels, ferries, DP drilling vessels, thruster assisted moored floating production facilities, shuttle tankers, cable layers, pipe layers, icebreakers and other ice going vessels, supply vessels, and war ships. There is also a significant on-going research and evaluation of using electric propulsion in new vessel designs for existing and new application areas. The development of offshore electrical power systems has been extremely strong in the past two decades and this is due to advances in topology and the construction of independent electronic switches and power converters. This paper compared various converters used in marine propulsion and saw various power switching devices and also various control strategies. Electric propulsion systems are majorly dependent on power electronics sources and devices which is depicted above in this paper. Large and small ships will greatly bee benefited from continuous improvements in devices and controls in the area of power electronics. Space and weight are always a very important on board a ship, so current developments will result in devices that significantly reduce the cost, size, weight, and losses of power electronics.

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