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***Abstract*—This paper presents comparative evaluation and explores the different technologies suitable for the implementation of the Medium Voltage Direct Current (MVDC) electrical supplies for the marine on-board electrical distribution network. To realize the MVDC supply in the range from 5 kV to 25 kV, various technological choices are available during the design process and have a direct influence on the overall system performances. In this work we discuss different prime movers, choice of electrical generators and type of rectifiers. Different configurations are characterized with different metrics, in terms of commercial availability, quality of supply, efficiency, dynamic performance and volume. Multi-phase multi-pulse supply configurations are identified to provide high quality dc supply and recommended for marine MVDC distribution.**

I. Introduction

In the recent years, a possible replacement of the state-of-the-art on-board medium voltage ac (MVAC) electrical distribution systems for ships with medium voltage dc (MVDC) electrical distribution is being considered [1], [2]. The popularity of the on-board MVDC electrical distribution, as the future ship electrical distribution system, is primarily based on the improvements in the power electronic technologies that provide opportunities to achieve efficient fuel consumption, increased energy density and reduced footprint, and flexibility in the design process of the system [3]. The possible advantages, mentioned above, come with their challenges e.g., there is a lack of commercial MVDC equipment to fill in the gaps created by replacing the existing MVAC technology. In order to fully tap the advantages of MVDC electrical distribution system, there is a need to improve the existing diesel engines, gas turbines, electrical machines, medium voltage drives and rectifiers. At the same time, some technologies need development e.g., high power dc-dc converters, MVDC protection components, MVDC cables, energy storage and active and passive filters [2].

The state-of-the-art ship on-board MVAC electrical distribution systems consider fixed speed operation of the diesel engines and multiple synchronized synchronous generators. In case of the MVDC electrical distribution system, this will not be a requirement as the generators would be interfaced to rectifiers and will be expected to operate in an allowable frequency range, which will ensure overall efficient operation of the system. One of the challenges of the MVDC system implementation is the MVDC supply. Literature discussing different possible prime mover technologies, generators and rectifier configurations and topologies, for the MVDC systems, has been published [4]–[9]. The future dc systems on ships can provide possible fuel savings by utilizing variable speed operation of generators, as highlighted in [4] for a demonstrative low voltage dc (LVDC) electrical distribution system showing a fuel saving of up to 20%. A comparative analysis of MVDC and MVAC systems, carried in [5], predicts 7% fuel savings. In addition to the variable speed operation of prime movers, the MVDC systems also provide the opportunity to utilize high speed prime movers and generators, resulting in reduced footprint of installed equipment and increased energy density. An overview is provided in [6] covering different generator technologies spanning the existing low to high speed, and the future ultra-high speed generator solutions. Moreover, multi-phase generators can also be considered for MVDC systems, as they can provide higher voltages and redundancy in the system, as discussed in [7] and a prototype of a 12-phase high speed permanent magnet synchronous generator is presented in [8]. Furthermore, multi 3-phase generators can be interfaced with multi-pulse rectifiers and a scenario of series connected multi-pulse rectifiers is discussed in [9].

This paper discusses the possible MVDC supply technologies for marine applications for different MVDC distribution voltage levels from $5\,\mathrm{kV}$ to $35\,\mathrm{kV}$, which are recommended in [1]. A qualitative analysis is also carried out for commercially available prime movers, generators and rectifiers. Possible MVDC supply topologies are presented, based on the commercially available equipment, and discussed in terms of the impact of removal of the gearboxes and the voltage coordination transformers found in MVAC systems, utilization of medium to high speed prime movers, multi-phase generators and parallel/series multi-pulse rectifiers for better power quality and redundancy in the system.

This paper is arranged as follows: the different parts of MVDC supply technology e.g., prime movers, generators, transformers and rectifiers are discussed in section 2, followed by presentation of different system configurations for the MVDC supplies in section 3. Section 4 discusses the impact of these configurations on the electrical components, power quality and redundancy in the system. Section 5 provides the summary and conclusions of the paper.

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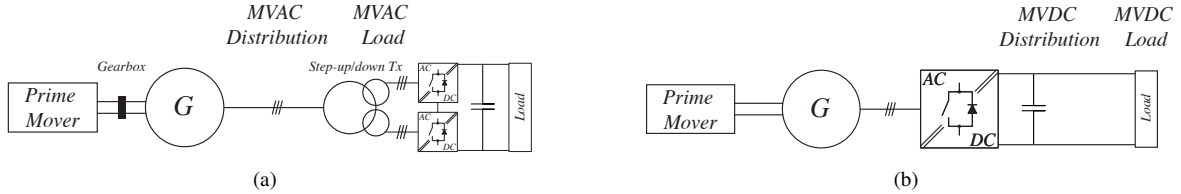


Fig. 1. (a) Simplified notional MVAC distribution with gearbox interfacing prime mover and generator, and voltage coordination transformer connected before the propulsion load. (b) Simplified notional MVDC distribution without gearbox and transformer.

II. Power Generation Technologies - An Overview

Power generation, in the future MVDC on-board electrical power systems, is expected to adopt different technologies from the state-of-the-art MVAC power systems. Among the major expectations from the MVDC systems, are the possibilities to remove gearboxes and voltage coordination transformers [2]. A notional MVAC system's expected evolution to a notional MVDC system is shown in Fig. 1. Currently, in MVAC power systems, fixed speed prime movers and alternators are producing the electrical power that is supplied to the different loads of the system through switchboards. Low frequency transformers step-up or down the voltage for connection with the propulsion loads. In case of the future MVDC power systems, a similar voltage class for generation, distribution and major loads e.g., propulsion motors is considered, therefore, ensuring the removal of the bulky transformers. A discussion is provided below on the various components of the supply system in light of the available industrial products and their role in the future MVDC power systems.

A. Prime Movers

The prime movers are primarily internal combustion engines (ICEs) running on diesel or heavy fuel oil (HFO) and are usually medium (400 rpm to 1000 rpm) to high speed (1000 rpm and above) [10]. Gas turbines, steam turbines or combined cycle turbines can also be found, wherever gas is available as a cheaper alternative e.g., for high speed vessels or LNG tankers [11]. Efforts are being made to optimize ICEs for fuel efficiency, but it is still around 40% and also the emissions are fairly high [5]. Variable speed operations of the prime movers, as suggested for dynamic ac (DAC) and dc on-board electrical power distribution, provide a way to make the operation of ICEs more efficient [12]. Demonstration ships having a low voltage dc (LVDC) electrical distribution systems, built by ABB and MAN, have shown that the variable speed operation of ICEs, possible under dc distribution, makes them more efficient and also reduces the operational cost [4]. Apart from the possibility of variable speed operation of the prime movers, dc distribution also does not require the generators to be synchronized to constant frequency (50/60 Hz) and opens up an opportunity to consider high speed ICEs and gas turbines, as the main prime movers for the main high speed generators to ensure energy density. This arrangement allows the removal of step up/reduction gearboxes, which have efficiency around 70% [13], interfacing the prime movers and generators. Gas turbines are also quite inefficient, around 40%, and expensive to run [14], but MVDC systems with high electrical frequency e.g., 1 kHz, could provide an ideal utilization of GTs interfaced with very high speed generators. Medium speed ICEs have the highest efficiency [15] and variable speed operation in dc distribution also provides an opportunity to improve their fuel consumption. Therefore, they can be considered as a possible prime mover candidate for the future MVDC systems, especially for large vessels.

B. Generators

The second part of the electric power generation are the 3-phase synchronous generators [11]. These are coupled to the shaft of the prime movers, rotating at a constant speed of 720/750 rpm, in case of the medium speed diesel engines, and up to 1800 rpm for high speed diesel engines. Brushless excitation is utilized in marine systems due to maintenance reasons. In order to maintain terminal voltage of the generators, the excitation current of the field windings is controlled using automatic voltage regulators (AVRs) with feed-forward measuring stator current. In most practical cases, a limit of $\pm$ 2.5% of nominal voltage, is imposed as a regulation limit at steady state operation, whereas, the transient voltages must not exceed -15% or +20% of the nominal generator voltage. Additionally, damper windings are present to damp the oscillations in the frequency and also the oscillations due to the load sharing among different generators and any variations in the load [11]. With the possibility of the dc electrical distribution for ships, the generators are not required to operate at a constant frequency and this has opened up opportunities to consider other high speed generator technologies e.g., permanent magnet synchronous generators (PMSG) [6], [8], which are mostly commercially available for wind power application [16]. Another possibility for generators are multi-phase machines, discussed since 1970s [17]. Their application and potential as generators for the MVDC ship on-board electrical power systems is analyzed in [6]. In [9], a re-configurable 12-phase synchronous machine is discussed and shown that increasing number of phases improves system fault tolerances and also the output dc current due to connection of multiple rectifiers. Commercial multi-phase SM and PMSM are available for drive operation but specialized generator technology does not exist. Additionally, multi-phase generators allow interfacing multi-pulse rectifiers and remove the transformers, reduce harmonics and increase reliability of the system.

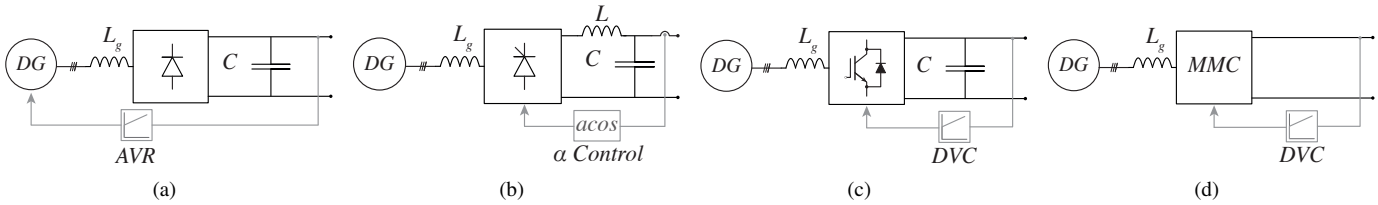


Fig. 2. 3-phase system configuration with different source side converters. (a) Diode rectifier. (b) Thyristor rectifier. (c) Multi-level active rectifier. (d) MMC active rectifier.

C. Transformers

In marine on-board electrical power systems, transformers are used for voltage coordination, galvanic isolation and sometimes for phase shifting [11]. These transformers are usually very bulky and use oil for cooling and insulation. Other types e.g., air-insulated or resin-insulated are also used depending on the requirements laid down by the shipyard [11]. Variable speed drives are usually fed with phase shifting transformers, in order to feed multi-pulse rectifiers to cancel the dominant current harmonics and reduce the impact of the distorted currents and voltages on the different components of the marine electrical power system e.g., generators. As discussed earlier, the multi-phase generators are expected to fulfill the role of the transformers of allowing the interface of the multi-pulse rectifiers.

D. Rectifiers

The move from the MVAC electrical distribution to the MVDC electrical distribution rectifiers will play a pivotal role as they will convert the ac voltage generated by the generators to dc voltage. State-of-the-art propulsion drives, used in the on-board MVAC electrical distribution systems in ships, have their own rectifiers e.g., [18] reports a 12-pulse rectifier. As discussed earlier, MVDC distribution systems provide an opportunity to utilize high speed generators and also the multi-phase arrangements that would require fast devices and also possibility to utilize multi-pulse rectifiers, which can be diode, thyristor, active (classical 2-level/multi-level topologies, MMC). These 6-pulse rectifiers can be connected in series or parallel, resulting in 12, 18, 24-pulse rectifiers, depending on the voltage or power requirements of the system [18]. The voltage blocking capability of the present semiconductor devices is not high enough for MVDC applications, therefore, multiple devices have to be connected in series that would result in increased design complexity of the rectifier systems. There are several rectifier configurations that could be used and a brief description of the different rectifiers is given below.

1) Diode Rectifier Unit: Diode rectifier unit (DRU), with a capacitive filter, is shown in Fig. 2(a). It is the simplest and cheapest of the rectifier technologies containing passive devices, but lacks direct regulation of the dc-side voltage or ac-side currents. In order to maintain the dc-side voltage, automatic voltage regulation (AVR) of the generator is required. The feedback from the dc-link is fed to the controller, which then controls the field current of the generator to increase or decrease its terminal voltage. The AVR control of generator is usually slow, with a bandwidth of around 1 Hz. The DRUs are employed in the present drive technology [18], especially for marine applications where no regeneration is possible, and are interfaced with input multi-secondary transformers in 12, 18 or 24-pulse series or parallel configurations. Additionally, DRUs provide good source-side dynamics for the marine MVDC distribution [19]. Therefore, they present an easy adaptation from MVAC to MVDC system especially when multi-phase generators are used.

2) Thyristor Rectifier Unit: Thyristor rectifier unit (TRU), shown in Fig. 2(b) with an LC filter, is deployed mostly in high voltage dc (HVDC) applications [20]. For MVDC systems, they can also be considered as a possible MVDC supply side converter as they provide possibility of regulating dc-link voltage in a narrow voltage band [19]. They are an expensive alternative to the DRUs. The control is based on the well known inverse cosine control, which corrects the firing angle to achieve desired voltages for the dc-side. The bandwidth of this control is usually of the order of 10 Hz [20]. In [21], fault clearing capability of TRUs using active foldback control is discussed. This provides an opportunity to explore TRUs further as MVDC supply side converters for marine applications and compare with DRUs, which are default rectifiers in commercial high power voltage source inverter (VSI) drives.

3) Active Rectifier Unit: ARU, the third type of rectifier (classical 2-level/multi-level topologies), with a capacitive filter is shown in Fig. 2(c). It is called as such for its ability to control ac-side current and dc-side voltage and allowance of bidirectional power flow. Here direct voltage control (DVC) is used with a bandwidth of 100 Hz [22]. Different topologies exist for active rectifiers e.g., classic 2-level voltage source converter (VSC) and multi-level like 3-L neutral point clamped (NPC), 3-L active NPC (ANPC), 4-L flying capacitor (FC) and 9-L cascaded h-bridge (CHB) that are also found in the commercial products. Among these topolgies, 3-L NPC is most widely used in MV applications [18]. The control of these rectifiers is usually fast and is only limited by the device switching frequency and sampling frequency. ARUs are relatively expensive compared to the DRUs and TRUs and their ability to allow bidirectional power flow is of limited use, in ship on-board electrical distribution systems, as the power cannot be regenerated to the generator. Modular multi-level converters (MMC), shown in Fig. 2(d),

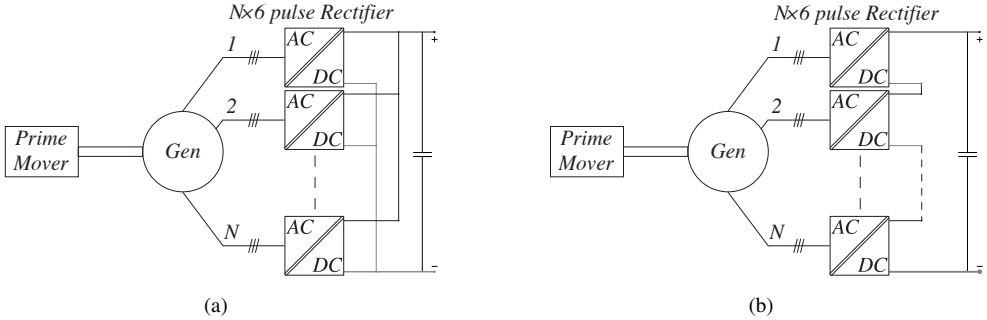


Fig. 3. N×3-phase system configuration. (a) Parallel connection of rectifiers. (b) Series connection of rectifiers.

another technology used in HVDC that is being considered for MVDC applications as it provides higher efficiency due to lower switching frequency, modularity, voltage scalability, reduced filtering effort due to the presence of sub-modules and have good fault clearing capability [23]. In case of availability of dc-breakers, adoption of MMC rectifiers may be overlooked because of their complex control and scalability for multi-phase generators.

III. MVDC Supply - N×3-phase, N×6-pulse

In the present drive systems, especially for the marine applications, multi-secondary transformers are used at input of the drives with the multi-pulse diode rectifiers to produce higher quality dc-side voltage, better quality ac-side currents and are easier to build. This configuration is preferred over the ARUs due to their lower cost and the lack of regeneration requirement in the marine systems [24]. As removal of transformers is being considered for the future MVDC systems, therefore, a high quality MVDC supply is possible with multi-phase generators interfaced to multi-pulse rectifiers. In this paper, the analysis is limited to N×3-phase generators. Multi-phase generators can be connected to multiple rectifiers and this arrangement makes the system fault tolerant for both the generator and the rectifier faults and also provides flexibility in selecting the generator and the load voltage class. Two possible arrangements of this configurations are given in Fig. 3 and discussed below.

A. Parallel Configuration

In parallel configuration, shown in Fig. 3. (a), the windings of the N×3-phase generator are rated to the full ac-side voltage e.g., 3.7 kV ac for 5 kV dc-side supply or 7.4 kV for 10 kV dc-side supply. The total current rating of the generator, for same power as 3-phase case, is divided among all the 3-phase winding sets i.e., $I_{ac,N} = I_{rated}/N$, here N is the number of 3-phase winding sets of the generator. Additionally, each rectifier is also rated to the full dc-side voltage. The ratings of the devices must be sufficient to block the dc-side voltage or if this is not possible (10 kV, 15 kV, ...) then a series connection of several devices is required and additional snubbers and voltage balancing circuits are also employed. The current through each rectifier is $I_{rec,N} = I_{dc,tot}/N$. Parallel connection requires the voltage class of the generators and the motors to be similar. In case of loss of any of the 3-phase sets or rectifiers, the system can continue operation in de-rated mode, where only critical loads are supplied and all non-essential loads are disconnected.

TABLE I
Rectifier module parameters considered in this study

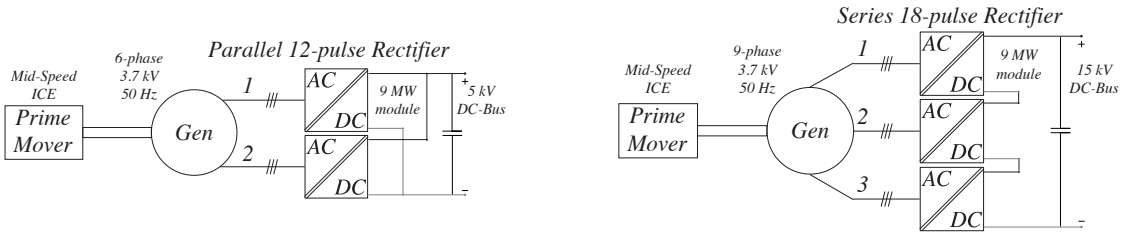
Module Parameters	
Rated Apparent Power (S_n)	10 MVA
Rated DC Voltage (V_{dc})	5 kV
Rated AC Voltage (V_{ac})	3.7 kV
Rated Frequency (f_n)	50 Hz
Generator Inductance (L_g)	$0.1 \times \frac{V_{dc}^2}{2\pi f_n S_n}$ mH

B. Series Configuration

In case of series connection of several rectifiers, as shown in Fig. 3. (b), the voltage rating of each 3-phase winding set and rectifier is considered $V_{N,ac/dc} = V_{tot,ac/dc}/N$. For the current ratings, each of the 3-phase winding set and rectifier are required to supply rated load current. The semiconductors employed in the rectifiers are of lower voltage blocking capability, compared to the parallel combination, but expected to block voltages of $V_{tot,dc}/N$ for a 2-level rectifier. Additionally, less auxiliary circuits e.g., snubbers and voltage balancing circuits are required. Series connected multi-pulse rectifiers provide flexibility when selecting the voltage classes of generators and motors i.e., generators with lower voltage ratings can supply loads with high voltage ratings without use of transformers. In case of loss of 3-phase winding set or a device or a rectifier, the system will not be able to supply the rated voltage and may be required to trip/shutdown to repair the faulty part.

IV. Multi-phase Multi-pulse MVDC Supply

Discussion on multi-phase multi-pulse MVDC supply, from previous section, is deepened here considering selection of prime movers, generators and design of rectifier modules for series/parallel connections. In this configuration, prime movers are driving multi-phase generators that are interfaced with multi-pulse rectifiers. In case of the prime movers, gas turbines and high speed ICEs have been proposed in the literature. The above discussion shows that the gas turbines and the high speed diesel engines are only slightly more energy dense



(a) (b)

Fig. 4. Proposed multi-phase multi-pulse configuration. (a) 5 kV, 18 MW, parallel 12-pulse rectifier based dc supply. (b) 15 kV, 27 MW, series 18-pulse rectifier based dc supply.

compared to medium speed ICEs, but are less efficient whereas the efficiency of the medium speed ICEs is around 48% [15]. Therefore, medium speed ICEs can be considered as prime movers and operated in DAC configuration to achieve maximum benefit. The second part is the type of generator, multi-phase synchronous generators can be considered as main generation units, as they provide possibilities to connect multi-pulse rectifiers. The third and last piece of the MVDC supply puzzle is the ac/dc converter, which is a multi-pulse diode rectifier especially as it constitutes a high quality dc supply and shows good dynamic response [19].

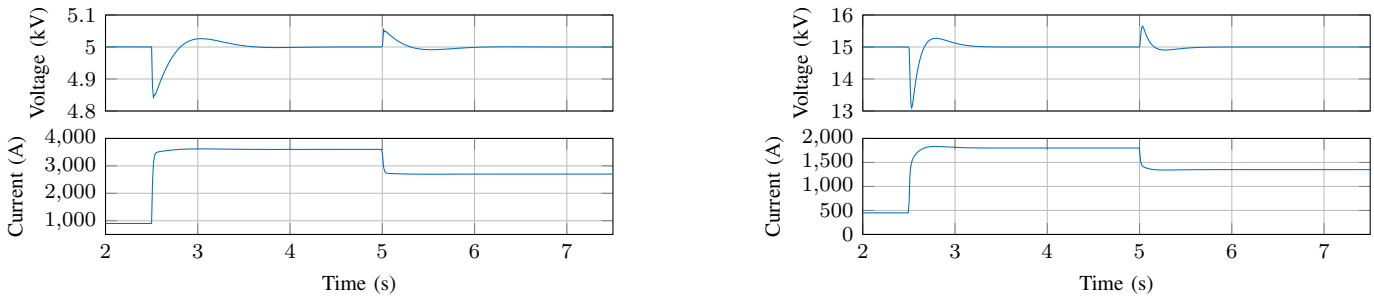
Two possible MVDC supply configurations are proposed and discussed here. The first case considers a medium speed diesel engine (720/750 rpm) driving a 6-phase generator (2×3-phase) interfaced to a parallel 12-pulse rectifier, as shown in Fig. 4. (a). Each 3-phase winding set of the generator is rated at 3.7 kV and 10 MVA. The voltage rating of the generator also defines its insulation requirements. In order to realize the dc supply, a 5 kV 6-pulse diode rectifier module is designed for parameters given in Table I, using ABB diodes rated at 6 kV blocking voltage [25]. The blocking voltage requirement for the devices is calculated using $V_{RSM} = \sqrt{2}V_{S,rms} \times k$, here V_{RSM} is absolute maximum rating of the diode, $V_{S,rms}$ is the rms value of the ac voltage and k is safety factor usually taken as 2.5 [26]. Here devices are required to block 13.1 kV resulting in connection of 2 devices in series per half leg.. The device parameters and losses for the rated power are given in Table II. The connection of 2 devices in series requires auxiliary voltage balancing circuits and snubber circuits. The connection of two 10 MVA rectifier modules in parallel generates a high quality 5 kV dc-side voltage and also provides redundancy and fault tolerance in the system when the total power requirement is 10 MVA. In case the system is rated to 20 MVA then for any generator or rectifier fault e.g., failure of one of the 3-phase winding set or rectifier module, the system can be operated in a de-rated mode i.e., non-essential loads can be disconnected from the system, while supplying only the essential loads. The LC-filter at the output of the rectifier are designed according to the steps highlighted in [20]. DC-side voltage and current for this system configuration supplying a 18 MW load are shown in Fig. 5. (a). The load is changed from 25% to 100% at 2.5s and then dropped to 75% at 5s. The only control working here is the AVR of the generator which corrects the voltage.

TABLE II
DESIGN OF 10 MVA 6-PULSE RECTIFIER MODULE.

Device	
Manufacturer	ABB
Model	5SDD06D600
V_{RRM} *(V)*	6000
$I_{f\,avg}$ *(A)*	662
$I_{f\,rms}$ *(A)*	1040
v_f *(V)*	1.066
r_t *(mΩ)*	0.778
Parameters	**6-Pulse Rectifier Module**
V_{RRM} *(V)*	**1310** @ 2 devices connected in series
$I_{d\,avg}$ *(A)*	599.4
$I_{d\,peak}$ *(A)*	1818
$I_{d\,rms}$ *(A)*	1037
No. of devices	**12**
Loss per device (W)	**1475**
Total Loss (W)	**17700**

The second system configuration also considers a medium speed diesel engine, but here it is driving a 9-phase generator (3×3-phase) interfaced to a series 18-pulse rectifier, as shown in Fig. 4. (b). Similar to the previous case, each generator 3-phase winding set is rated for a voltage of 3.7 kV and 10 MVA. The diode rectifier module designed earlier is used here as well and 3 of it are connected in series to realize a 15 kV dc supply rated at 30 MVA. As discussed earlier that series multi-pulse rectifiers provide flexibility when it comes to select voltage class of generators and loads e.g., here a generator rated at 3.7 kV can supply a propulsion motor rated at 11 kV without the requirement of a step up transformer. In case of any faults e.g., generator or rectifier side faults, this configuration requires the system to be shutdown and repaired before supplying the loads again. DC-side voltage and current for this system configuration supplying a 27 MW load are shown in Fig. 5.(b). The load is changed from 25% to 100% at 2.5s and then dropped to 75% at 5s.

The two notional systems presented here highlight the benefits of multi-phase multi-pulse dc supply. Parallel configuration improves the dc side supply, adds redundancy and fault tolerance to the system. Series configuration also improves the dc side supply and adds flexibility in choosing the voltage class of generators and motors. The choice between them depends



(a) (b)

Fig. 5. Simulation results for (a) 5 kV, 18 MW, parallel 12-pulse rectifier based dc supply. (b) 15 kV, 27 MW, series 18-pulse rectifier based dc supply.

on the system designers, system requirements and availability of the required equipment.

V. Conclusion

This paper analyses the available and proposed technologies for ship on-board power supplies and the practices followed in the state of the art MVAC electrical distribution systems in ships. The early adopters of MVDC electrical distribution are expected to consider commercially available technologies. In commercial drives, multi-pulse rectifiers are used to produce high power quality on the dc-side. As transformers are set to be omitted from the up coming MVDC systems, N×3-phase generation can provide the benefit of using the multi-pulse rectifiers to have high quality dc supply. Two high quality MVDC supplies configurations considering medium speed ICEs, operating in DAC mode, driving i) a 2×3-phase generator interfaced with parallel 12-pulse rectifier for a 5 kV dc distribution, and ii) a 3×3-phase generator interfaced with series 18-pulse rectifier for a 15 kV dc distribution, are proposed and analyzed. Multi-phase multi-pulse MVDC supplies also provide fault tolerance and redundancy, in case of parallel arrangement of rectifiers, and provides flexibility in choosing generator and load voltage class in case of series arrangement of rectifiers.

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