International Journal of Advanced Technology and Engineering Exploration, Vol 9(93)
ISSN (Print): 2394-5443 ISSN (Online): 2394-7454
http://dx.doi.org/10.19101/IJATEE.2021.875595

Research Article

Impact of online PPL accommodation on quality of power in an AES' MVDC distribution system

Remna Radhakrishnan[1*] **and Mariamma Chacko**[2]
Research Scholar, Department of Ship Technology, Cochin University of Science and Technology , Kochi, Kerala 682022, India[1]
Professor, Department of Ship Technology, Cochin University of Science and Technology, Kochi, Kerala 682022, India[2]

Received: 06-March-2022; Revised: 22-August-2022; Accepted: 26-August-2022

Abstract

Quality of electrical power onboard ships is an important area, since there are stringent power quality standards set by the classification societies. In an all-electric ship (AES) with alternating current distribution, the power quality issues become more serious similar to those in inland power systems. Recent trend in modern AES is to utilize the medium voltage direct current (MVDC) distribution system. The presence of power electronic converters in the DC distribution system, and their high frequency switching creates voltage ripple and noise at the direct current (DC) bus. There evolves the importance in the effective analysis on MVDC bus voltage quality, since quality of power and its continuity is utmost important onboard ships. This paper focuses on the simulation studies of a 6 kV MVDC distribution system onboard ship with propulsion motor, pulsed power loads and some service loads operated. Each load is energized in a particular sequence to identify their impact on the DC bus. Quality of power at the DC bus is analysed as per the standards set by the IEEE 1709. Also the impact of online accommodation of pulsed power load (PPL) on DC bus voltage and its stability is examined. Simulation results and their analysis can be useful for the design of pulsed load profile in certain situations and for the design of proper filters and sufficient energy storages in some other cases. With the pulsed power load deployment in online mode, the DC bus voltage crosses the permitted tolerance which comes around -13.98%, and the angular velocities of generators have reduced by 3 to 4%. Results show that, with the pulsed power load operation, the quality and stability of the DC Bus voltage is deteriorated.

Keywords

MVDC distribution system, All electric ship, Quality of power, Pulsed load, DC voltage ripple.

1.Introduction

Medium voltage direct current (MVDC) distribution systems [1, 2] are nowadays replacing the conventional alternating current (AC) distribution in the marine electrical system. Power distribution through common direct current (DC) bus and the power electronic converters drastically reduces the volume of components that must be installed in the main switchboard room. It also enables upgrading of the system with energy storage or renewable energy sources, which can be connected directly to the grid through DC-DC converters [3]. The main benefits [4, 5] highlighted such as space and weight savings, decreased fuel consumption, improved power stability and quality, higher energy efficiency etc. are attractive to civil and military shipyards.

IEEE standard 1709 defines two main topologies for the MVDC next generation integrated power system (NGIPS): the radial distribution and the zonal distribution. Among the already established voltage classes as specified in [6], there is not much research work carried out on voltage classes above 5kV. This research work goes through simulation studies of a 6 kV MVDC radial distribution system onboard and analyses some of the challenges faced by MVDC distribution systems, especially the DC bus voltage quality and its stability. Apart from the propulsion motor which draws the majority of the generated power, low power service loads and high-power pulsed loads are also considered for the simulation. High power pulsed loads implicate some naval weapons such as rail guns, laser weapons, aircraft launch etc. Like all other organizations naval ships

---

[*] Author for correspondence

are nowadays shifting from mechanical to all-electric control of these high-power pulsed loads.

As far as quality of power is concerned, it is very strict to follow the standards, as continuity and quality of power is utmost important onboard ships. Among the major harmonic producing loads, deployment of pulsed power loads (PPL) in the DC grid system plays a major role in the deterioration of the quality of power. So it is important to analyse the impact of these high power pulsed loads on DC bus's voltage quality and stability, since they are supposed to carry high current for a very short duration. This motivated the development of an onboard MVDC distribution system accommodating an online PPL and analysing its impact on the DC bus voltage quality.

Even though there are certain solutions put forward by researchers for PPL accommodation onboard all-electric ship (AES) power systems, they haven't considered the impact of other loads, especially propulsion loads. Moreover there is less research carried out in the online deployment of the PPL, which is the main challenge in this area. The control implementation of the propulsion motor and isolated DC-DC converters were the major challenges faced during this work.

The objectives of this work include

- Modelling a 6 kV MVDC AES electrical system, including generators, propulsion motor and its control, DC as well as AC service loads and pulsed power load (PPL).
- Simulation of the MVDC AES electrical system in MATLAB Simulink using Simscape toolbox.
- Analysis on the impact of online PPL accommodation on DC bus voltage quality based on the IEEE standard.

The main contributions of this work are: modelling and simulation of AES power system with 6 kV MVDC distribution system containing generators, propulsion load, AC and DC service loads and PPL; Percentage evaluation of the DC bus voltage variation due to the online PPL operation is calculated through the fast Fourier transform (FFT) window and is analysed with the standards set for the MVDC distribution onboard; Effect of online PPL deployment in generator angular velocity is analysed and calculated the percentage variation of the same.

The paper is organized as follows: Literature review briefing is done in section 2. Section 3 describes the system considered for simulation with each module explained in subsections. Section 4 details how the simulation is carried out and the results obtained, ending with an analysis on the same in section 5. Finally the paper is concluded in section 5.

2.Literature review

Bash et al. [7] constructed a low power medium voltage direct current test bed (MVDCT). The DC zonal system described, includes two generating systems, power supply module, six converter modules, ship propulsion system, pulsed power load, etc. The testbed provides a complete documented system for the entire research community. Test results show the behaviour of the system during steady state and transient conditions. Sulligoi et al. [8] reported the design, development and validation of an advanced prototype of naval package 2 MVA generation equipment for MVDC integrated power system. The developed prototype is a 12-phase alternator feeding converters, including uncontrolled rectifiers and choppers. Bosich et al. [9, 10] describes the power system distribution and voltage control and stability aspects of the large ship research. They also specify the change in future ship design with MVDC distribution that reduces the space dedicated for electrical equipment onboard. MVDC onboard system modelled by Shi et al. [11], by combining synchronous machine dynamic model and different load models. The efficiency of the modelling is justified and verified against the conventional Simulink model.

Vu et al. [12] presented a distributed adaptive control architecture applied to a zonal medium voltage DC ship power system. Javaid et al. [13] investigated the effect of three different source-side converters on the MVDC distribution grid and their interactions with the constant power loads (propulsion drives). Investigation shows that an excellent fault current withstand capability can be achieved by appropriate semiconductor devices along with fast acting fuses. Zhu et al. [14] developed an end to end mathematical model of an MVDC shipboard power system (SPS) and simulated the same to capture the system behaviour for ship-wide system-level studies.

Hasanzadeh et al. [15] addressed the analysis of active and passive rectification systems within an MVDC ship power generation unit, showing that the dynamic and transient performance of the input and output voltages of the three phase diode-bridge rectifier present better results when the diode-bridge's output DC voltage is fed back to the AVR.

Stubban et al. [16] reviewed the interaction of different loads and filter configurations on a shipboard microgrid with a medium voltage DC distribution bus. The study has shown that high power quality at the load can be achieved without high power quality at the generation source and MVDC transmission bus. Kourmpelis et al. [17] experimented on an MVDC bus feeding a buck converter and a propulsion load to evaluate the harmonic distortion at both AC and DC sides. The result shows that the percentage of harmonic presence is very high and is a lot higher from the limits that the regulations define. Whaite et al. [18] reviewed the major power quality issues in DC distribution systems as: current harmonics and circulating currents that arise on a DC bus from nonlinear effects of the various power electronic converters, inrush current drawn by the filter capacitor at the load side and fault current through converters or from energy resources or capacitance directly on the DC bus.

Farasat et al. [19] introduced a novel approach to voltage control in AES power systems to minimize switching losses in power electronic converters feeding the loads in a MVDC Ship Power System. Jeung et al. [20] introduced a feedback linearization control strategy of active DC filters (ADF) to compensate for the harmonic ripple voltage in a medium-voltage DC shipboard power system. Jin et al. [21] put forward a novel mitigation method using negative virtual inductance loop for the voltage instability on DC bus. Sources of frequency content on MVDC bus listed by Engelhart et al. [22] are ripple generated from active rectifier, low dynamic response of turbine-generator set and harmonic components from power electronic loads. Also an MVDC series DC active filter is designed by the authors to attenuate the ripple generated from MVDC active front end rectifier and hence to improve the power quality of the system. Yun et al. [23] specifies that regardless of the output voltage of the generator, the PWM technique applied to the active front end rectifier can regulate the DC bus voltage. Maximum power per ampere operation of the generator is utilized to regulate the DC bus voltage.

Kulkarni and Santoso [24] list the sources of transients present onboard in both AC and DC as: single phase and three phase AC faults, DC faults, switching of equipment, lightning strikes, pulsed loads etc. Among these, pulsed load transients are unique with two classifications based on the duration of the operation. Medium frequency transients are produced by the operation of the pulsed loads in millisecond range and high frequency transients in the microsecond range. The authors also specify that it needs much more work to verify this kind of behaviour of pulsed loads. Effect of pulsed load operation on the ship power system, with and without flywheel energy storage system (FESS) are analysed in [25]. Results show that without FESS, there is significant variation in angular speed of the alternator and hence frequency, which may adversely affect the other connected loads. On the other hand, FESS acts as a buffer between pulsed load and other connected loads to provide better results compared to the system without FESS. Propagation of pulsating power into the input power supply can be prevented by adding a storage unit to compensate for the pulsed power. A bidirectional buck boost converter is used by Huang et al. [26] for the above purpose. Propagation of low frequency transients are reduced or even removed with the feed forward control scheme applied to the bidirectional buck boost converter.

Usually an energy storage system (ESS) is connected at the output terminal of the pulsed power supply, in order to balance the instantaneous power difference. Pulsed power loads are classified as online PPL accommodation and offline PPL accommodation, depending on whether the ESS is connected to the ship power system during their deployment or not. Offline accommodation requires a charged ESS as an energy source for the PPL. ESS is charged online and discharged offline to the PPL. In online strategy, PPL is always connected to the ship power system. In Huang et al. [27] adopted an active capacitor converter under current reference feed forward control in place of storage capacitor, which will regulate its terminal current to provide the pulsed current except the DC component.

Fan et al. [28] introduced an adaptive control algorithm for fast charging of flywheel ESS, which acts as an intermediate ESS for PPL accommodation. The algorithm provided a guaranteed transient response with minimum disturbance to the system frequency. Duan et al. [29] introduced a neural network based control algorithm for onboard pulsed power load accommodation. Xie et al. [30] coordinated multiple pulsed loads on AES in the online mode by formulating an optimal coordination problem and proposed a decomposition algorithm. Even though the algorithm is effective for online use of pulsed loads, the authors claim that some uncertainties exist under certain situations in the operation of the ship.

Eldeeb and Mohammed [31] implemented a control technique to improve the voltage stability of an MVDC onboard distribution system having three synchronous generators interfaced via bidirectional DC-DC converters as well as pulsed load. Simulation results show that the intervention of the pulsed load at any terminal of the MVDC ship-board will result in a voltage dip. The problem is mitigated by activating an ultra-capacitor whenever the voltage at any MVDC terminal goes lower than the pre-set value. Mardani et al. [32] proposed a model predictive controller for the energy storage converter of a DC microgrid system consisting of a single generator, PPL and hybrid storages. With the control strategy authors were able to ensure voltage and current constraints during PPL deployment. But they haven't considered any other loads onboard or their changes, which may degrade the system performance. Dong et al. [33] have maintained the shipboard DC grid power system stability and suppression of power fluctuations due to pulsed loads by using batteries and capacitors through simulation studies. Impact of pulsed load parameters such as peak power, pulse duration and pulse number are analysed by Xu et al. [34] for single and multiple pulsed loads in an onboard DC microgrid system. There was significant voltage variation in either case. Salama et al. [35] proposed a fuzzy logic control to the DC-DC converter and the ESS that supplies the PPL in an AC distribution system to mitigate the voltage and frequency fluctuations at the point of common coupling. Tu et al. [36] introduced an optimal control solution for online PPL accommodation. A bidirectional DC-DC converter along with a supercapacitor acts as the ESS. With the optimal control applied to ESS, it was able to achieve fast charging of ESS, regulated DC bus voltage and minimized generation cost during PPL deployment. Along with the PPL, they have taken other loads in a single unit for simulation. A hybrid ESS with the battery and ultra-capacitor was presented for pulsed power loads by Wasim et al. [37]. The simulation results show an improved battery life and reduced battery capacity. Posam et al. [38] implemented a logistic regression algorithm to identify the shunt faults in PPL. In order to analyse the dynamic voltage and frequency during deployment, a large signal model of PPL was proposed in [39] based on some nonlinear differential algebraic equations. Considering the high frequency nature of the PPL, a High Frequency Lumped circuit model was proposed and developed in [40] by Rajabi-Nezhad and Razi-Kazemi.

Literature review discussed the design and development of the MVDC distribution system onboard, including mathematical modelling, overview of the suitable power converters etc. Coming to the power quality aspects, several researches have been carried out to identify the power quality issues in such a distribution system. Major issues identified are DC voltage instability due to harmonic currents and inrush currents from various converters and filter capacitors, fault current, low dynamic response of turbine-generator sets etc. Several mitigation methods have also been invented or adopted by the researchers. The voltage instability problem is mitigated by minimizing the converter switching losses, PWM switching applied to active front end rectifiers, providing a negative virtual inductance loop etc. Some active and passive filters are also introduced with different control strategies to attenuate the ripples from active front end rectifiers. Another major power quality issue associated with the AES electrical system is the pulsed load switching. The intervention of the pulsed load at any terminal of the system may result in voltage dip. Hence it is a usual practice to place an ESS at the output terminal of the pulsed power supply. Research work has been carried out for AES with pulsed load alone supplied from a DC source and the dip in voltage has been reduced to an extent by placing ultra-capacitor, flywheel ESS, super capacitor etc. in place of ESS. In all these works, the PPL is deployed in offline mode. Now it has become a recent trend in researchers to go with power electronic devices such as active capacitor converter, buck boost converter etc. for minimizing the voltage dip caused by pulsed loads. Also from the literature itself, it is clear that PPL deployment in online mode requires more and more research yet to be conducted to get a feasible mitigation on this pulsed power propagation into the DC bus as well as the generators. In the AES' MVDC systems with PPL accommodation described in literature, all other loads onboard are not considered independently. Since more than 50% of the power generated onboard is used for propulsion, it is important to consider the propulsion load and their changes as far as an AES is concerned. Along with that voltage transients produced by online PPL accommodation and its impact on other loads connected to ship power systems need more attention and research since they cause some major issues as far as DC bus voltage quality is concerned. In this paper, instead of considering the entire load as a single unit, each individual load, including PPL, propulsion loads and service loads are modelled independently and analysed the impact of online PPL accommodation in an AES' MVDC power system through simulation studies.

3.Method

3.1MVDC distribution system

The Onboard MVDC distribution system under consideration for simulation and power quality analysis is shown in *Figure 1*. Among the topologies for the next generation integrated power system, radial distribution has been chosen here for simulation studies because of its similarity with the medium voltage alternating current (MVAC) Distribution system. Moreover, radial distribution systems provide unidirectional power flow, better voltage regulation and higher efficiency in terms of design and operation. Two Synchronous generators, one rated at 30 MVA and the other at 5 MVA are used for the power generation. Six pulse diode rectifiers convert the generated AC into DC, so that an established medium voltage class of 6 kV as recommended by IEEE std1709 [6] appears at the DC Bus capacitor. Critical loads in naval power systems such as propulsion motor, PPL, low voltage direct current (LVDC) service loads and low voltage alternating current (LVAC) service loads are connected to the same DC Bus, either through inverters or through power conversion modules. Isolated DC-DC converters are used as power conversion modules, to reduce the bus voltage into required voltage levels, since all other loads except propulsion motors are designed to work under reduced voltage levels.

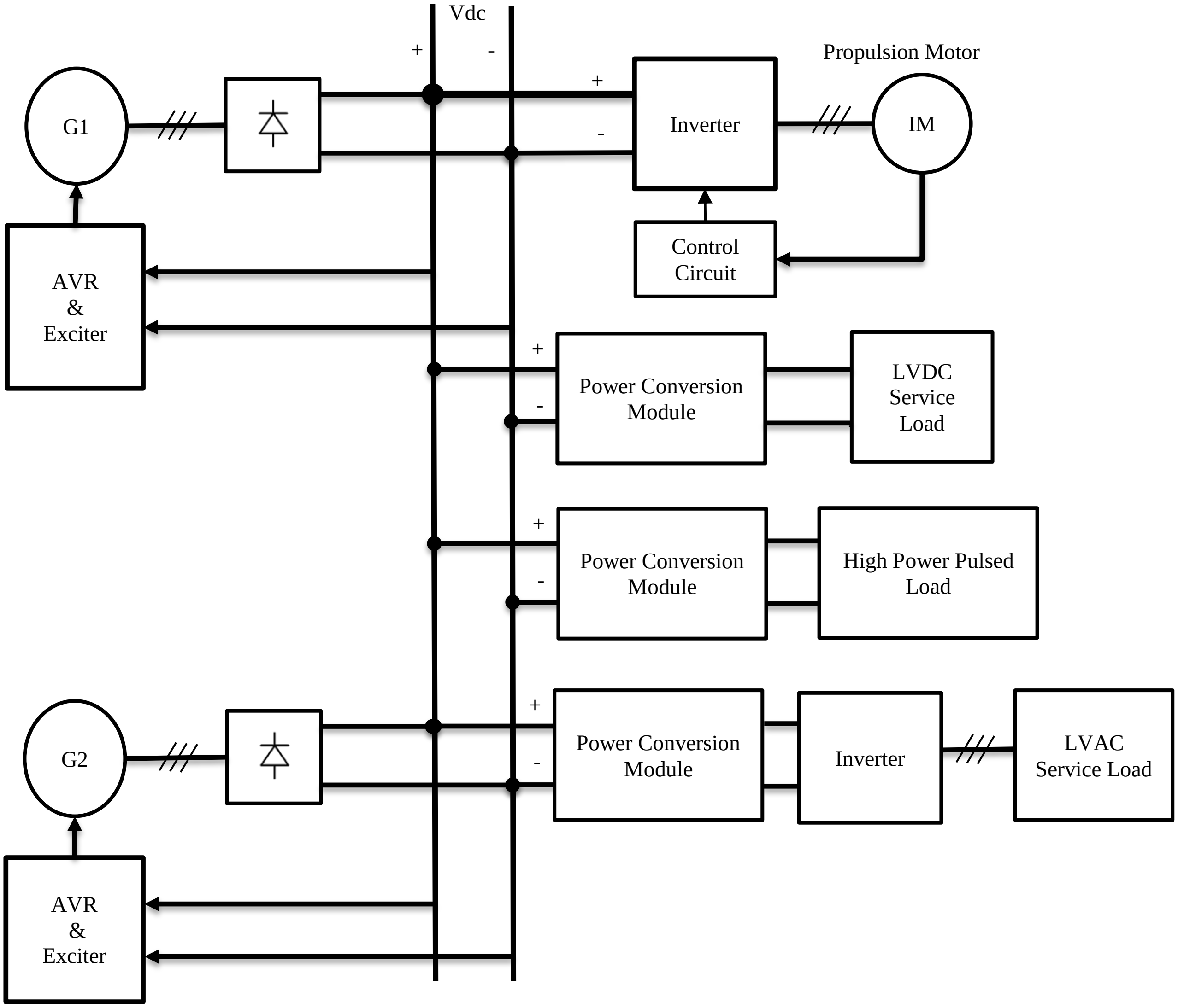

Figure 1 Onboard MVDC Distribution system under consideration

3.1.1Power generator

Power Generators are the main source of power that is required onboard. Here G1 is a gas turbine driven round rotor synchronous machine and G2, a diesel engine driven salient pole synchronous machine. Field excitation of these generators is provided by automatic voltage regulators (AVR). With the terminal voltage and a desired voltage, AVR generates the excitation voltage to the field windings of the synchronous generators. The power generator block diagram is shown in *Figure 2*.

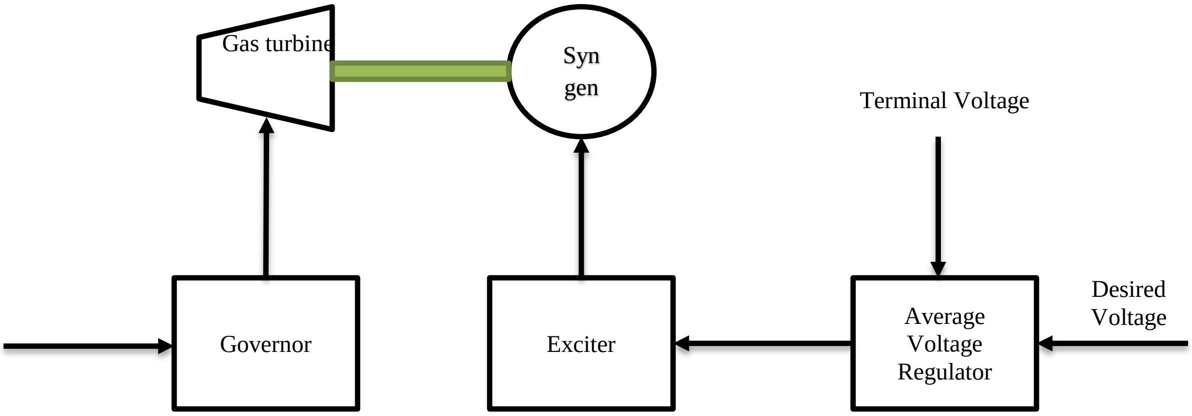

Figure 2 Power generator block diagram

3.1.2Propulsion motor

Propulsion motor is directly connected to the MVDC bus through variable frequency drive as in *Figure 3*. An induction motor rated at 19 MW, used as the propulsion motor drives the propeller. For simulation purposes the propeller is modelled by a load torque demand. Also with the direct torque control strategy applied to the propulsion motor drive, it is able to provide the load torque demanded by the propeller.

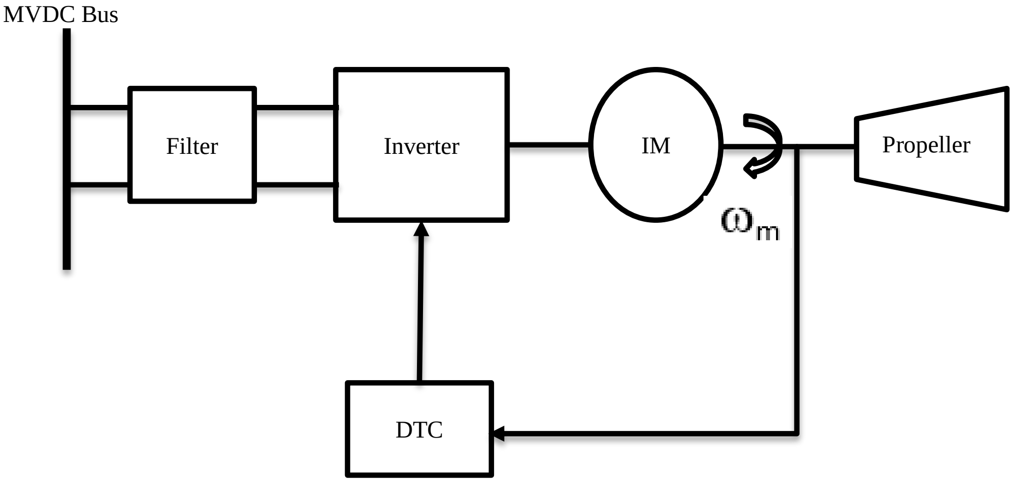

Figure 3 Propulsion motor control

3.1.3Power conversion module

The loads are connected to the DC bus through isolated DC-DC converters, whose main role is to change DC voltage levels. Converters with galvanic isolation are preferable for onboard applications. The DC-DC converter topology [41] shown in *Figure 4* with transformer primary current peak control is adopted for the simulation. Service loads and high power pulsed loads are connected to the DC bus through the same DC-DC converter topology, but with different component values since each load is at different voltage levels.

The control diagram of the DC-DC converter is shown in *Figure 5*. The output capacitor voltage, V_{of}, of the DC-DC converter is controlled by regulating the maximum transformer primary winding current, i_{pmax}, using PI control with anti-windup. The voltage command is denoted by V^*. To prevent the control output from saturation, voltage command is slew rate limited. The difference between this slew rate limited command voltage and the measured voltage V_{of}, at the output LC filter capacitor, is the error signal. This error signal is given as input to the PI controller with anti-wind up. The output of the PI controller is the maximum transformer primary current, i_{pmax}. PWM switching signals are generated for the H bridge inverter based on i_{pmax}.

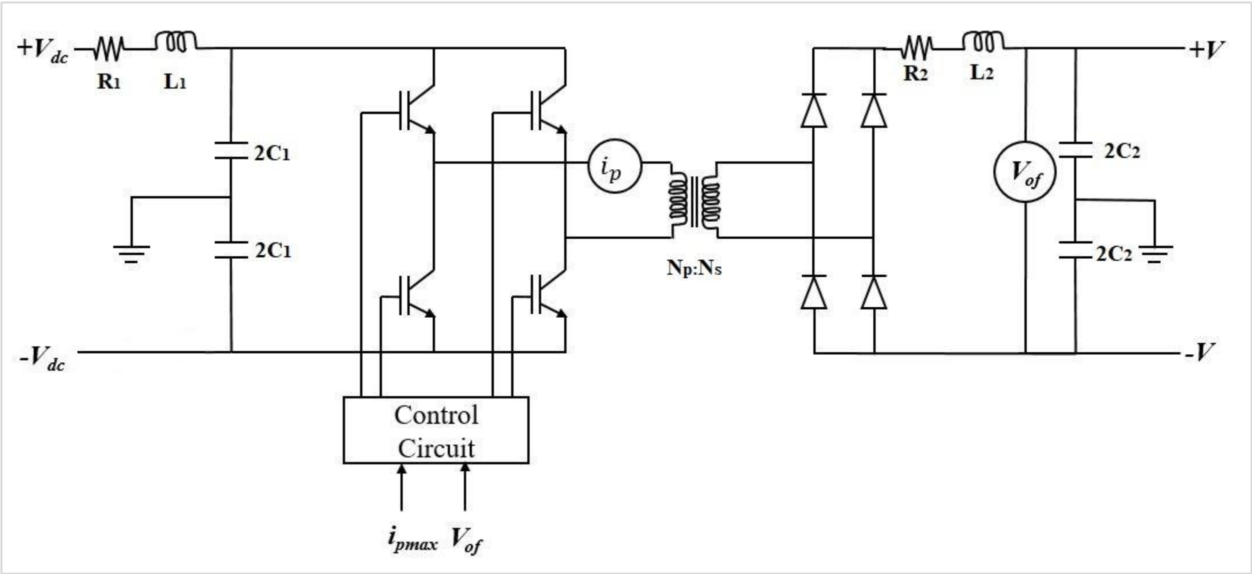

Figure 4 Isolated DC-DC Converter

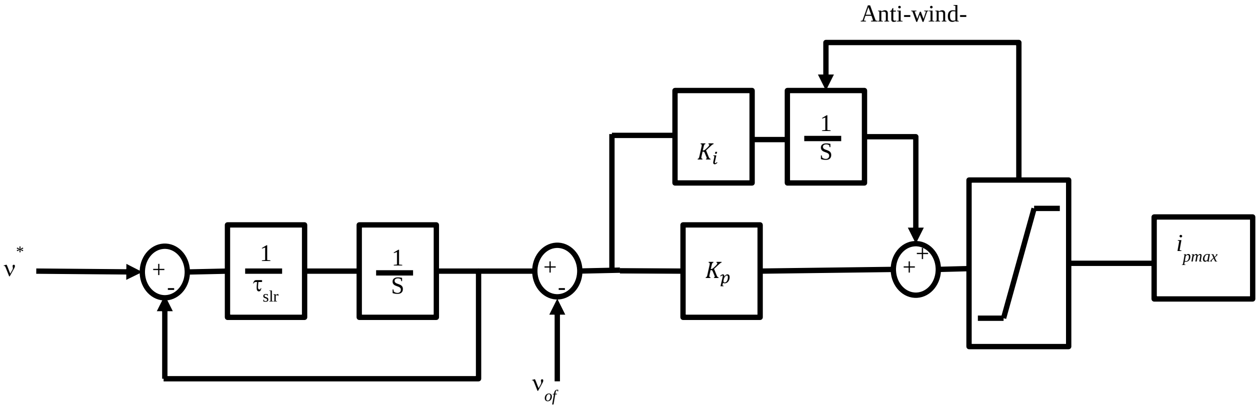

Figure 5 Isolated DC-DC converter control

In future, AESs are expected to carry a variety of electrical power loads. Here, we consider two types of common onboard loads: Ship service loads and PPL, such as electromagnetic aircraft launch system and laser weapons.

Ship service loads are mainly classified as LVDC and LVAC service loads. Each DC load is represented by their Norton equivalent. LVDC service loads are modelled as in *Figure 6(a)*, consisting of a resistor in parallel with a controlled current source (CCS). They are designed to work at a DC voltage level of 220 V. The power conversion module described above is used to convert the 6 kV DC bus voltage to 220 V. The current, i flowing through the LVDC service load is given by Equation 1.

$$i = (V_{LVDC}/R_{LVDC}) + (P_{VLDC}/V_{LVDC}) \quad (1)$$

Three phase star connected load realizes the 3ϕ load for simulation which is designed to work at 400 V AC. *Figure 6(b)* represents the corresponding model for LVAC service loads. Power conversion module along with a three phase inverter will do the necessary voltage conversions.

Generally PPL is that kind of load, which carries a very high value of current for a short duration. So a general model of a PPL as in *Figure 6(c)* is taken here for simulation. There are two resistors, one with very high value R_{High} and the other one with a very low value, R_{Low} connected in parallel. Normally R_{High} will be connected to the circuit and is switched to R_{Low}, whenever a pulsed current load is operated. Pulsed current can be represented by Equation 2.

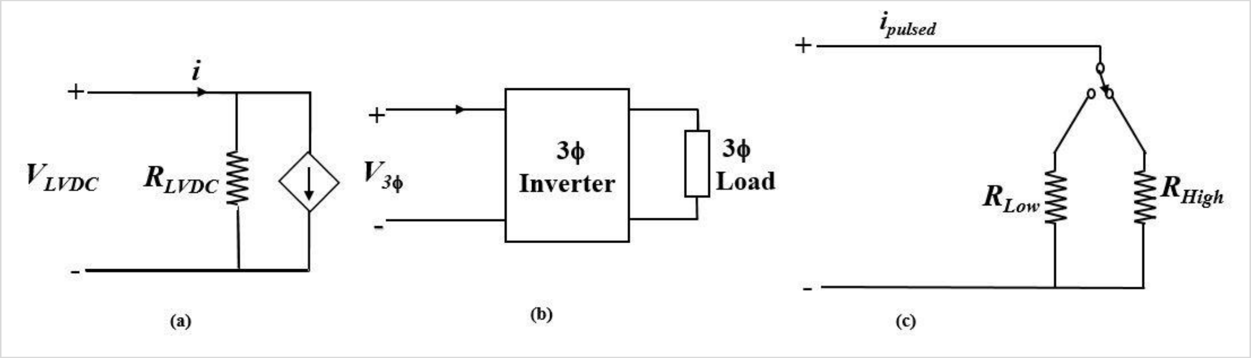

Figure 6 (a) LVDC Service Loads; (b) LVAC Service Loads; (c) PPL

4.Results

4.1Simulation results

In this section, the performance of the system is validated through simulation. MVDC onboard distribution systems with critical nonlinear loads described above are simulated in the MATLAB Simulink platform using the Simscape tool box. MATLAB model of the MVDC distribution system is given in *Figure 7*. Two synchronous generators along with the uncontrolled rectifiers, an MVDC class voltage of 6 kV Bus is generated. Propulsion motor is connected to the DC bus through an Inverter module. The propeller load torque profile is designed as the load torque demand to the induction motor. The direct torque control strategy is applied to the Induction motor to provide the required torque demand. Isolated DC-DC converters do the respective voltage level (as specified in *Table1*) conversions for all other loads. LVDC service loads are simplified by their Norton equivalent for simulation. LVAC service loads resemble some high power AC service loads. Three phase load of 10 MW is used as LVAC load here. PPL is designed in such a way that under normal operation, a very small amount of current flows through a very high value of resistance. *Table 2* lists the values of each parameter of DC-DC converters of service loads and PPL. Whenever a situation like a battle occurs and an aircraft gun or missile is to be operated, the circuit switches to a very small resistance, so that a heavy current flows through the circuit. *Table 1* details the power and voltage ratings of the generators and all other loads that are considered for the simulation.

Table 1 Power and voltage ratings

S. No.	Item	Rating
1	Synchronous Generator (G1)	30 MVA, 4160 V, 2 pole, 60 Hz
2	Synchronous Generator (G2)	5 MVA, 4160 V, 8 pole, 60 Hz
3	Propulsion Motor	19 MW, 4160 V, 12 pole, 60 Hz
4	LVAC Service Loads	10 MW, 400 V
5	LVDC Service Loads	360 kW, 220 V
6	PPL	4 MW, 3000 V

Table 2 Parameter values of DC-DC converters

S. No.	Parameter	Value (LVAC)	Value (LVDC)	Value (PPL)
1	L1	3.64 µH	3.64 µH	3.64 µH
2	C1	8.9 mF	8.9 mF	8.9mF
3	L2	0.128 µH	171.3 µH	27 µH
4	C2	2.5 mF	5.69 µF	17.7 µF
5	Switching	100 kHz	100 kHz	100 kHz

S. No.	Parameter	Value (LVAC)	Value (LVDC)	Value (PPL)
	Frequency			
6	N_s/N_p	0.08	0.06	0.65

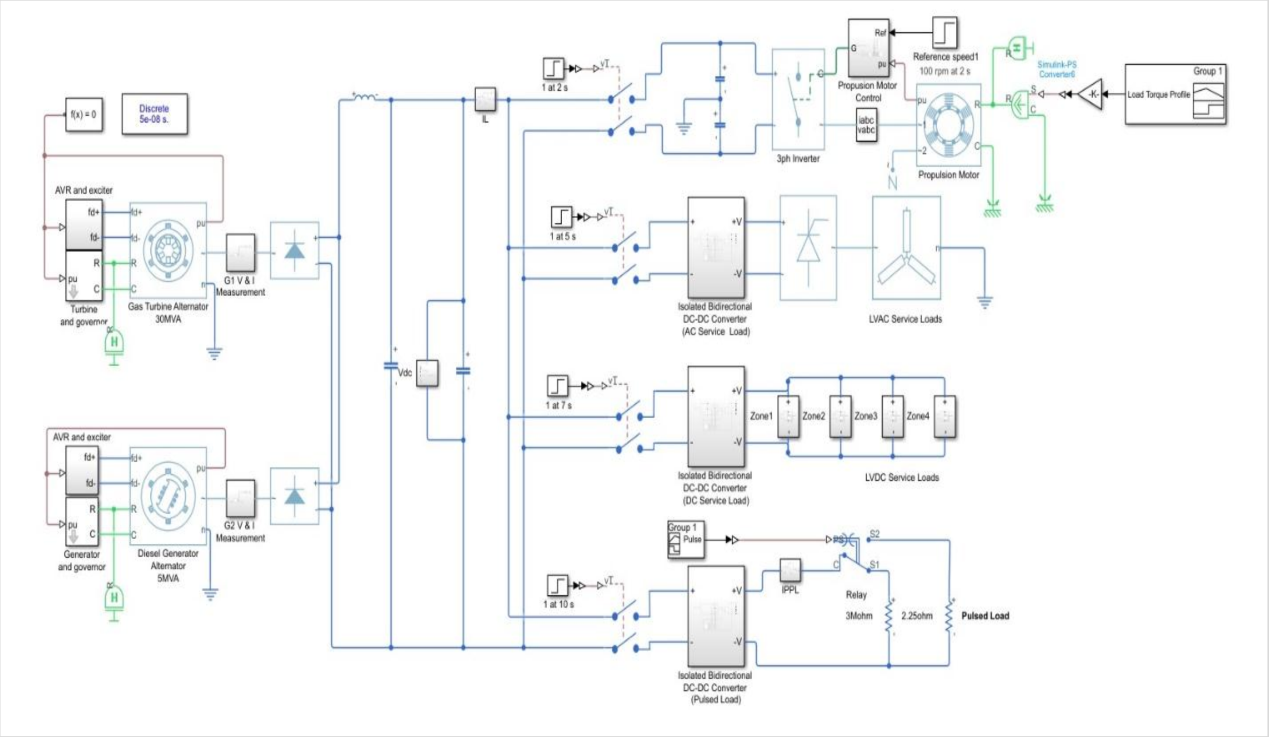

Figure 7 MATLAB model of the onboard MVDC distribution system

Each load is connected to the DC bus through a DC disconnect switch. Initially the two generators are started under no load. Simulation is performed in such a way that each load is energized by closing the respective DC disconnect at specific intervals.

4.1.1Case 1: Initialization of propulsion motor

Propulsion motor is energized under no load by closing the corresponding DC disconnect switch at time t=2 sec. Gradually the motor is loaded with a propeller torque profile as in *Figure 8*. The propeller is set to run at a speed of 100 rpm to provide a load torque requirement of 2.5 kNm. Suddenly the load torque demand is raised to 5 kNm by around 20 sec. At the time of closing of the DC disconnect switch, a transient dip in DC bus voltage is noticed in *Figure 9*, which takes around 4 msec to settle down.

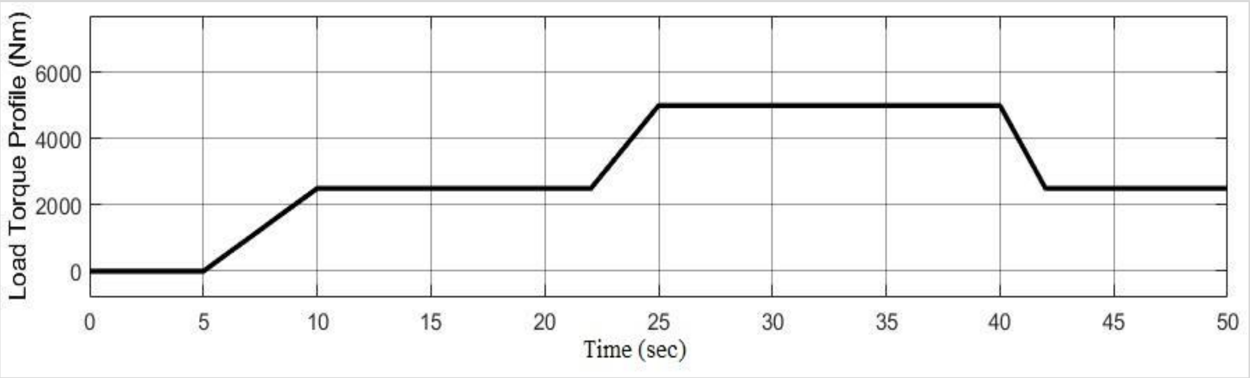

Figure 8 Propulsion load profile

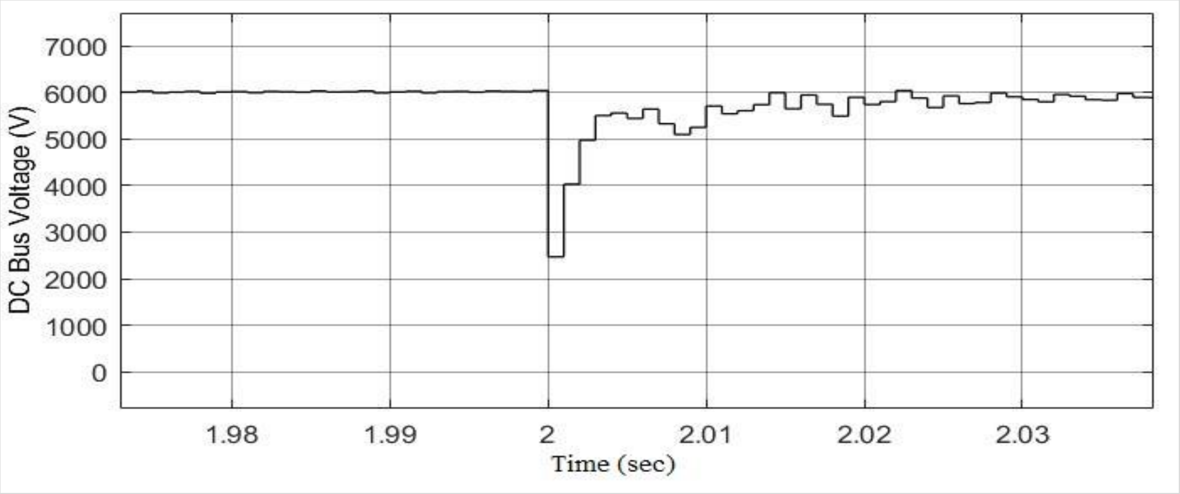

Figure 9 DC bus voltage at the time of propulsion motor initialization

4.1.2Case 2: initialization of service loads

Service loads are connected to the DC bus after the propulsion motor. Corresponding DC disconnect switches of LVDC and LVAC service loads is closed by 5th and 7th seconds respectively. LVDC service loads of 360 kW rated at 220 V is designed with current controlled sources. These loads are assumed to be distributed over different zones. 10 MW LVAC service loads at 400 V are represented with a three phase star connected load. Transient dip in voltage is found during the switching of the service loads also and they last for 4mSec for settling. Corresponding DC bus voltage is given in *Figure 10.*

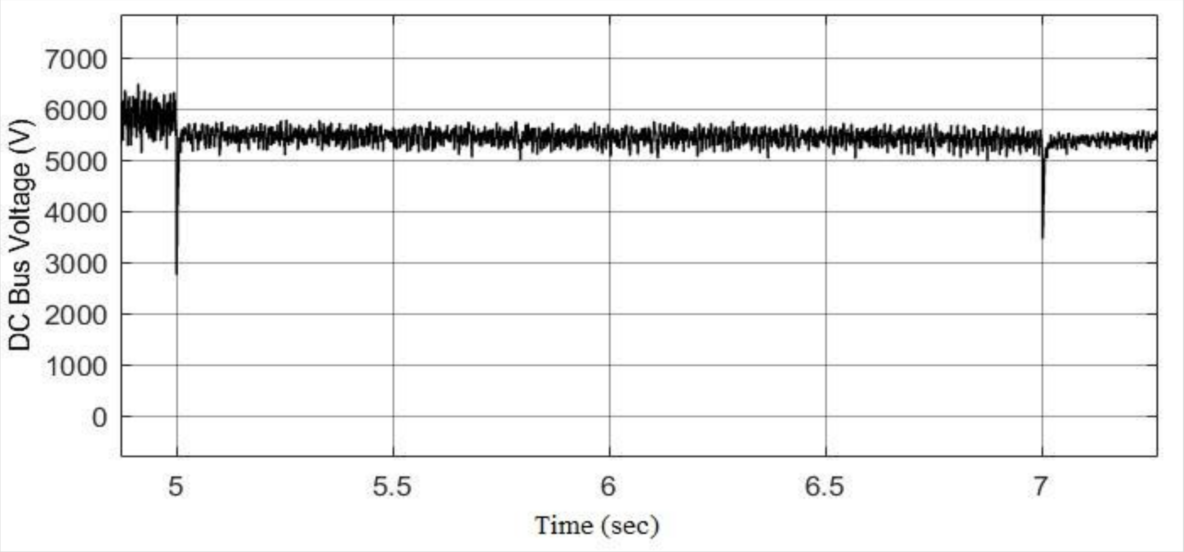

Figure 10 DC bus voltage at time service load initialization

4.1.3Case 3: initialization of high power pulsed loads

Finally, PPL circuit is enabled at the 10th sec of the simulation, so that the load R_{High} draws a very small current. R_{Low} corresponds to the 4 MW high power pulsed loads. Assuming the sudden rise of propeller torque demand by 20 sec as given in *Figure 8*, as a battle condition, large pulsed currents are drawn by the low resistive path ie, R_{Low} of the online PPL circuit path.

Scenario 1: Pulsed Currents of same pulse width

In this analysis, pulsed currents of each 2 sec duration are assumed to be drawn by the online PPL. PPL currents and the corresponding variation on the DC bus voltage due to the pulsed current flow is shown in *Figure 11.*

Scenario 2: Pulsed Currents of different pulse width

Simulation is again carried out to analyze the impact of pulsed Currents of different pulse amplitude and pulse width on the DC bus voltage. With the same load initialization as in the previous scenario, pulsed currents of different pulse width and varying amplitudes as in Figure 12 are drawn by the online PPL. PPL currents and variation on the DC bus voltage due to the pulsed current flow is shown in *Figure 12*.

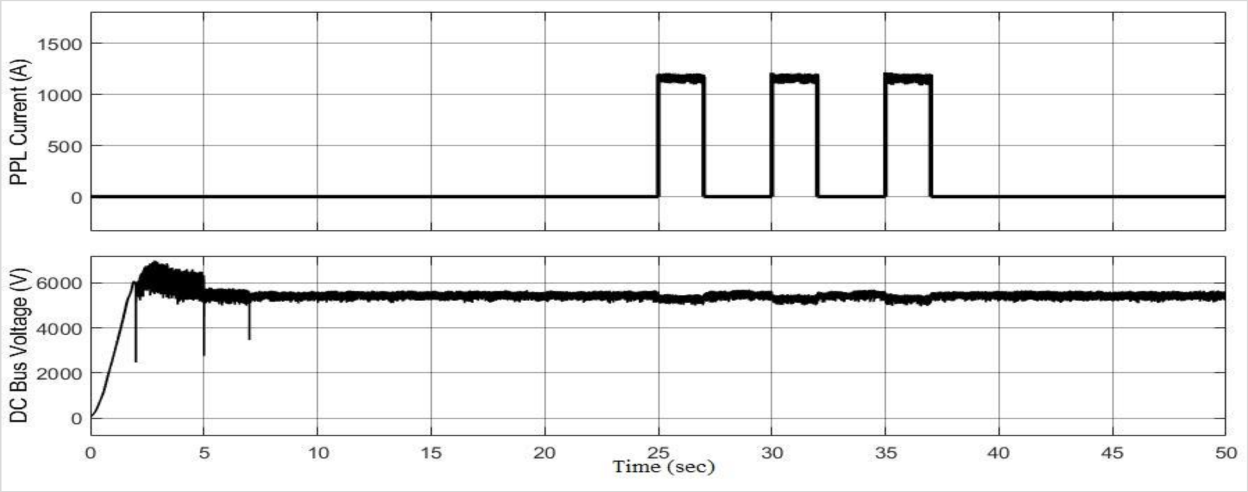

Figure 11 PPL current and DC bus voltage for same pulse width

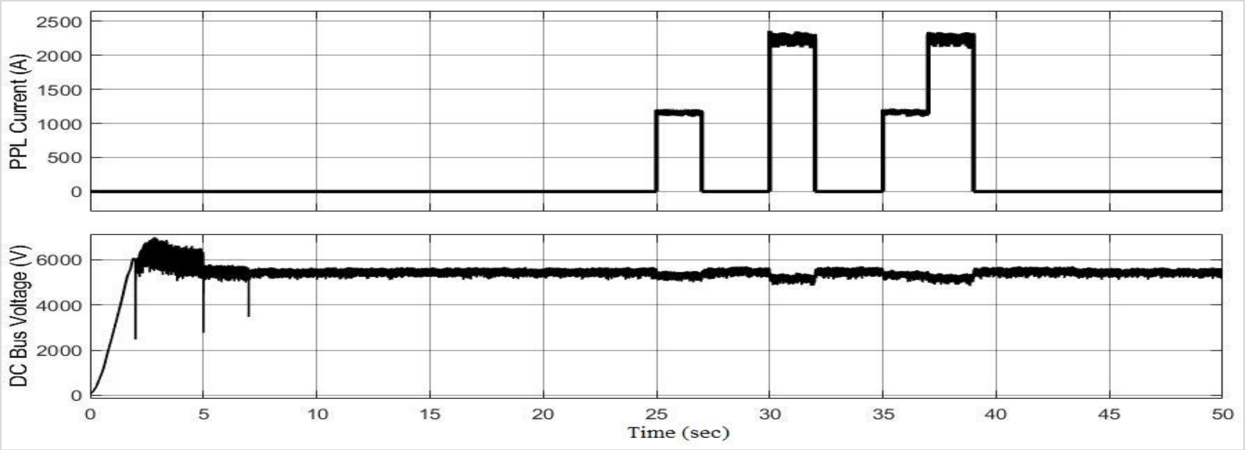

Figure 12 PPL current and DC bus voltage for different Pulse width and amplitude

5.Discussion

The impact of online PPL accommodation on DC bus voltage, that is the variation and the stability of the DC bus due to the different kinds of pulsed loads can be well analysed with the help of FFT taken relative to DC component at different operating intervals. DC bus voltage FFT during normal operation i.e. when pulsed power loads are not activated is given in *Figure 13*. Within the selected FFT window, it shows an average DC value of 5475 V and a total harmonic distortion (THD) of 4.55%. As per IEEE Standard 1709 [6], for any MVDC class, acceptable root mean square value of ripple voltage and load induced noise should not exceed 5% and the steady state DC voltage tolerance limits should be ±10%. Voltage tolerance as specified by IEEE Standard 45.1 [42] is the permitted departure from nominal voltage during normal operation, excluding transient and cyclic voltage variations, which include variations such as those caused by load changes, environment and switchboard meter error. Here the THD obtained can be considered as a representation of voltage ripple which shows that it is within the set standard.

Also the average DC value marked in the FFT window is well within the standard.

But the injection of pulsed currents has crossed the tolerance limit of ±10%. The FFT window corresponding to scenario 1, i.e. impact of pulses of same width is given in *Figure 14*. Even though the THD value, 2.98% is within the set standard, DC bus voltage average value, 5296 V is beyond the tolerance limit of ±10%, which comes around -11.7% . From the FFT window of the DC bus voltage for different pulse width and amplitude as described in scenario 2, average voltage obtained is 5161 V as mentioned in *Figure 15*. THD in this case has not much variation as it is 2.87%. But the DC bus voltage average value 5161 V has again crossed the voltage tolerance set by the IEEE which is close to 13.98%. This implies that, the increase of pulse amplitude and frequency has resulted in more deviation to the DC bus voltage which is far above the permitted tolerance. From the above results it can be concluded that, even though the bus voltage ripple i.e. THD is within the standard set by the IEEE, voltage tolerance goes beyond the permitted standard once the PPL is in action. In fact high power pulsed loads, their high current and frequent switching are the reasons for this voltage instability.

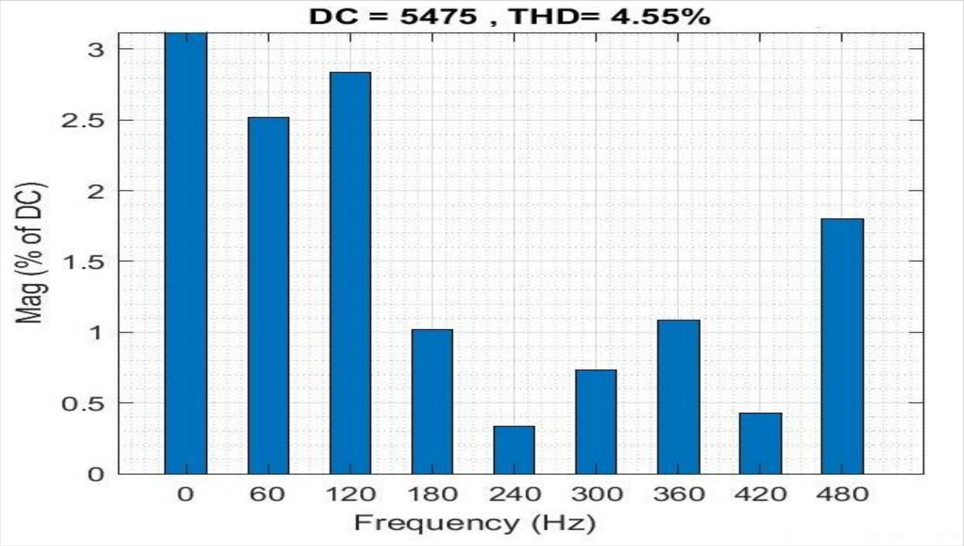

Figure 13 DC Bus Voltage FFT during normal operation

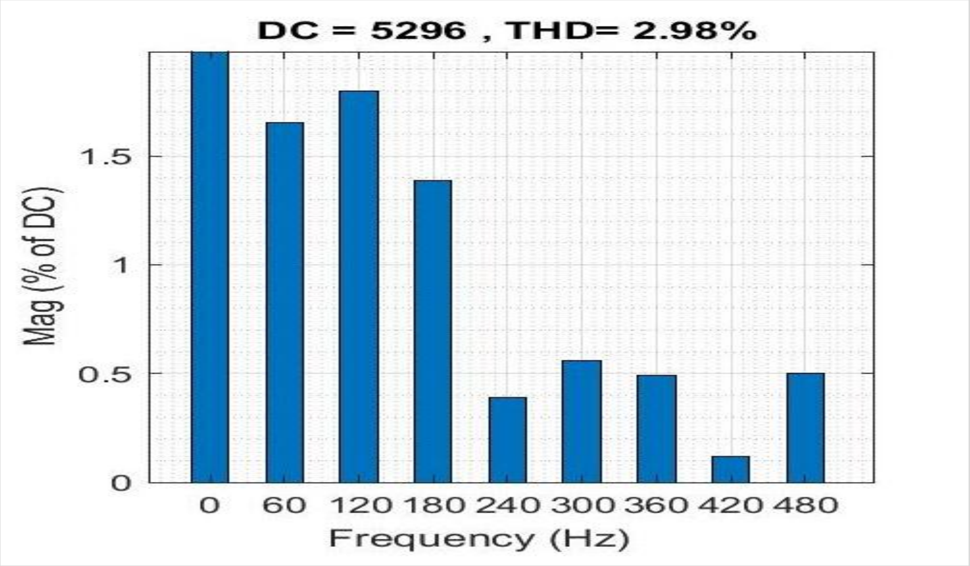

Figure 14 DC bus voltage FFT: same Pulse width and amplitude

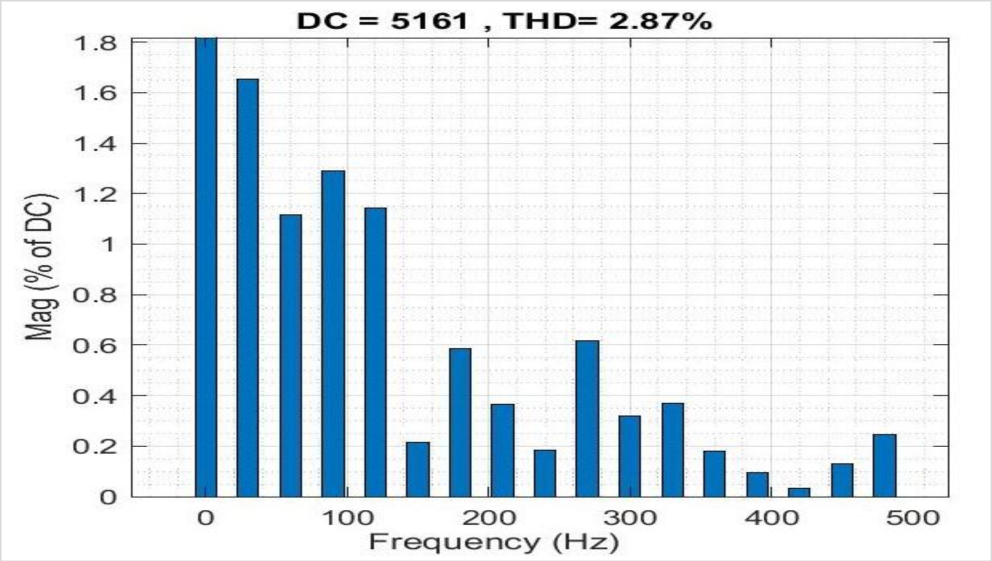

Figure 15 DC bus voltage FFT: different pulse width and amplitude

5.1Impact of online PPL to other connected loads

It is already explained in *Figures 9* and *10* that, there appears a transient dip in voltage during the energization of propulsion motor, and service loads. Apart from that the average DC bus voltage is reduced during the pulsed current injection. This reduced bus voltage will reflect at all other load terminals. With respect to the designed voltages of DC-DC converters as mentioned in *Table 1*, deviations in their output voltages at the service loads as well as PPLs in either scenario under consideration are shown in *Figure 16*. So it is clear from the results that the DC bus voltage is not at all stable at 6 kV. Also the increase of pulse frequency and amplitude makes the other load terminal voltages to intolerable limits.

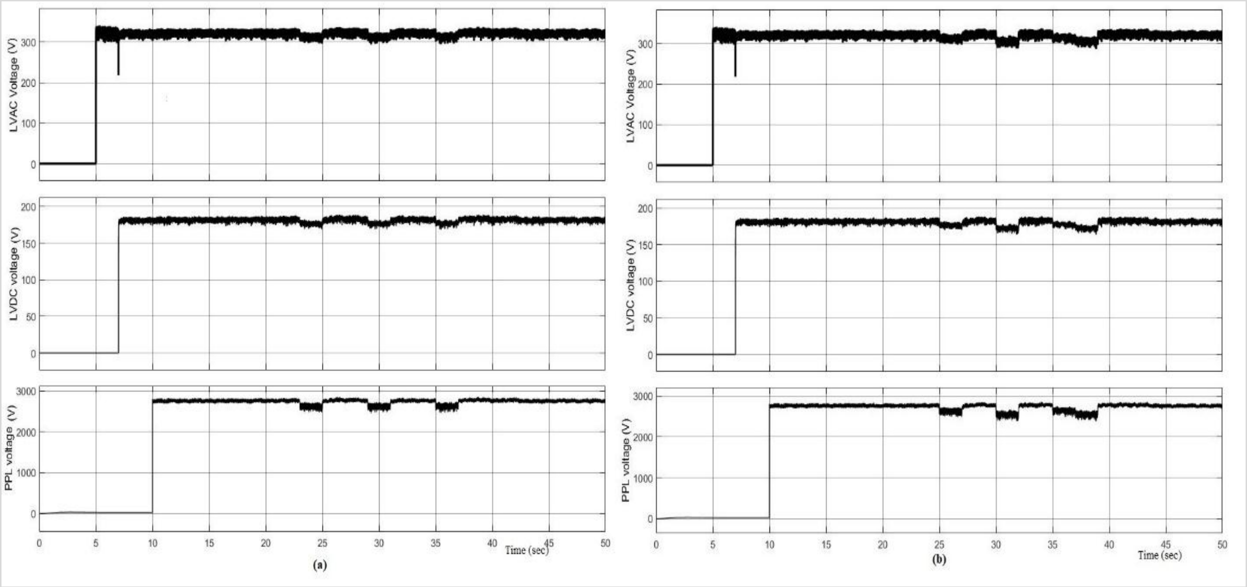

Figure 16 Power conversion module output voltages for LVAC, LVDC and high power PPL: (a) Scenario 1 (b) Scenario 2

5.2Impact of online PPL to generator sets

Again, this pulsed current may affect the operation of generators G1 and G2. Variations in angular velocity of both the generators G1 and G2 are shown in *Figure 17* for either scenario under consideration. It is clear from the figure that the angular velocity has reduced by 2 to 3% in scenario 1 and by 3 to 4% in scenario 2, during the respective time durations of pulsed current injection affecting the stable operation of generators.

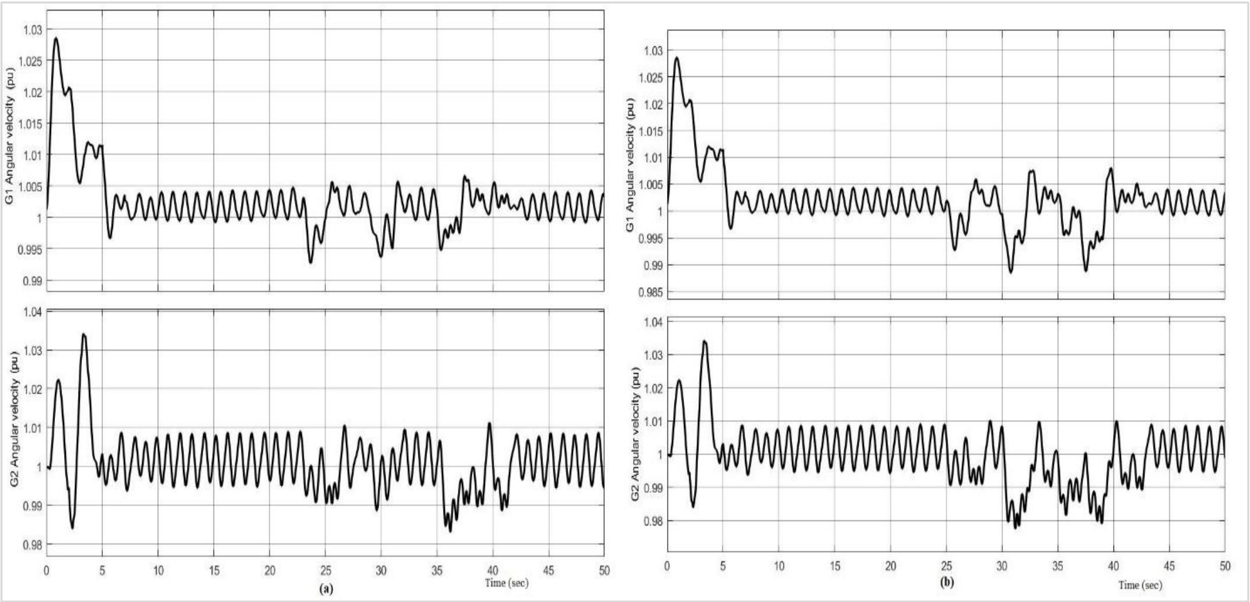

Figure 17 Angular velocity of G1 and G2 in per unit: (a) Scenario 1 (b) Scenario 2

Loading of the propeller, low voltage service loads and especially the PPL make not only the DC bus voltage unstable but also affects the entire power system adversely. Since the quality and continuity of power onboard ships are very important, stability of DC bus voltage becomes a major issue as far as MVDC distribution onboard ships are concerned. This paper goes through an analysis on the quality of power in an onboard DC grid corresponding to the operation of high-power pulsed loads. Simulation results provide a study on the impact of PPL towards the stability of DC grid. In pulsed loads like, where we can design the load profile earlier, this analysis will be useful, i.e. by considering the instability conditions, load profile can be designed accordingly. But in some other high power pulsed loads like naval weapons and all, which operates unexpectedly, where the earlier design of load profile is not practical, this analysis will be helpful in designing proper passive/active filters and sufficient storage elements. Since 6 kV distribution system under consideration is not practical to implement, only simulation studies and analysis is performed in this paper. So, hardware implementation is a major limitation of this work. A complete list of abbreviations is shown in *Appendix I*.

6.Conclusion

An MVDC Onboard power system of a naval ship with propulsion motor, PPL, and service loads are simulated in MATLAB Simulink platform using the Simscape tool box. As per the recommended standards set by IEEE 1709, the DC bus voltage must be stable at respective voltage classes with a ripple or noise of the 5% limit. Here the simulation results show that the operations of the propeller, LVDC service loads, LVAC service loads and online PPL deployment have reduced the average DC bus voltage to a value lower than 6 kV. Specifically, the pulsed current injection has further crossed the bus voltage by -13.98%, which is beyond the tolerance limit of ±10%, set by the IEEE standard 1709. Above all online PPL has affected the stable operation of even generators showing a 3 to 4 % reduction in angular velocity during the pulsed current injection. Thus, the unstable DC bus voltage is a major issue associated with MVDC onboard, as this reduction in bus voltage may adversely affect all other connected loads. This analysis on the impact of online PPL on the quality of power will be useful for the designers to decide the pulsed load profile in certain situations and to design of proper filters and sufficient energy storages in some other cases.

Since Quality and continuity of power supply is utmost important onboard ships, these issues must be taken care of more seriously and some mitigation technique has to be adopted which is being pursued.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Remna Radhakrishnan: Conceptualization, Collection of data, simulation, modelling, analysis, interpretation of results, paper writing. **Mariamma Chacko:** Interpretation of results, review and editing.

References

[1] Doerry N, Amy J. The road to MVDC. In ASNE intelligent ships symposium 2015.

[2] ABB, Onboard DC Grid -The step forward in Power Generation and Propulsion, 2011.

[3] Remijn N, Krijgsman B. Advantages of common dc busses on ships. In 2010 3rd international symposium on electrical and electronics engineering 2010 (pp. 177-82). IEEE.

[4] Kim K, Park K, Roh G, Chun K. DC-grid system for ships: a study of benefits and technical considerations. Journal of International Maritime Safety, Environmental Affairs, and Shipping. 2018; 2(1):1-12.

[5] Coffey S, Timmers V, Li R, Wu G, Egea-alvarez A. Review of MVDC applications, technologies, and future prospects. Energies. 2021; 14(24):1-36.

[6] Khersonsky Y, Ericsen T, Bishop P, Amy J, Andrus M, Baldwin T, et al. IEEE recommended practice for 1 KV to 35 KV medium-voltage DC power systems on ships. Institute of Electrical and Electronics Engineers. 2010.

[7] Bash M, Chan RR, Crider J, Harianto C, Lian J, Neely J, et al. A medium voltage DC testbed for ship power system research. In IEEE electric ship technologies symposium 2009 (pp. 560-7). IEEE.

[8] Sulligoi G, Tessarolo A, Benucci V, Trapani AM, Baret M, Luise F. Shipboard power generation: design and development of a medium-voltage DC generation system. IEEE Industry Applications Magazine. 2013; 19(4):47-55.

[9] Bosich D, Sulligoi G, Mocanu E, Gibescu M. Medium voltage DC power systems on ships: an offline parameter estimation for tuning the controllers' linearizing function. IEEE Transactions on Energy Conversion. 2017; 32(2):748-58.

[10] Bosich D, Vicenzutti A, Pelaschiar R, Menis R, Sulligoi G. Toward the future: the MVDC large ship research program. In 2015 AEIT international annual conference 2015 (pp. 1-6). IEEE.

[11] Shi J, Amgai R, Abdelwahed S. Modelling of shipboard medium-voltage direct current system for system level dynamic analysis. IET Electrical Systems in Transportation. 2015; 5(4):156-65.

[12] Vu TV, Gonsoulin D, Perkins D, Papari B, Vahedi H, Edrington CS. Distributed control implementation for zonal MVDC ship power systems. In IEEE electric ship technologies symposium 2017 (pp. 539-43). IEEE.

[13] Javaid U, Freijedo FD, Dujic D, Van DMW. MVDC supply technologies for marine electrical distribution systems. CPSS Transactions on Power Electronics and Applications. 2018; 3(1):65-76.

[14] Zhu W, Shi J, Abdelwahed S. End-to-end system level modeling and simulation for medium-voltage DC electric ship power systems. International Journal of Naval Architecture and Ocean Engineering. 2018; 10(1):37-47.

[15] Hasanzadeh A, Edrington CS, Soto DM, Rivera GM. Comparative study of intensive pulse load impact on active and passive rectification system in MVDC ship power generation unit. In 2013 international electric machines & drives conference 2013 (pp. 1326-32). IEEE.

[16] Stubban JP, Johnson BK, Hess H. Comparing point of use power quality to system level power quality in a shipboard MVDC distribution system. In electric ship technologies symposium 2013 (pp. 203-8). IEEE.

[17] Kourmpelis T, Prousalidis J, Spathis D, Dallas S, Kanellos F, Korn M. Power quality analysis for the highly-electric asset with DC power distribution. In 2015 international conference on electrical systems for aircraft, railway, ship propulsion and road vehicles 2015 (pp. 1-7). IEEE.

[18] Whaite S, Grainger B, Kwasinski A. Power quality in DC power distribution systems and microgrids. Energies. 2015; 8(5):4378-99.

[19] Farasat M, Arabali AS, Trzynadlowski AM. A novel control principle for all-electric ship power systems. In electric ship technologies symposium 2013 (pp. 178-84). IEEE.

[20] Jeung YC, Lee DC, Lee HH. Feedback linearization control of series active DC filters for MVDC shipboard power systems. In European conference on power electronics and applications 2014 (pp. 1-9). IEEE.

[21] Jin Z, Meng L, Guerrero JM. Constant power load instability mitigation in DC shipboard power systems using negative series virtual inductor method. In IECON 2017-43rd annual conference of the IEEE industrial electronics society 2017 (pp. 6789-94). IEEE.

[22] Engelhart BR, Bazzi AM. Design and control of a series DC active filter (SDAF) for MVDC marine applications. In transportation electrification conference & expo 2020 (pp. 948-53). IEEE.

[23] Yun J, Son YK, Cho HJ, Sul SK. DC bus voltage regulation strategy in maritime DC power system for minimized converter loss. IEEE Transactions on Power Electronics. 2021; 36(11):13225-33.

[24] Kulkarni S, Santoso S. Estimating transient response of simple AC and DC shipboard power systems to

pulse load operations. In electric ship technologies symposium 2009 (pp. 73-8). IEEE.
[25] Kulkarni S, Santoso S. Impact of pulse loads on electric ship power system: with and without flywheel energy storage systems. In 2009 IEEE electric ship technologies symposium 2009 (pp. 568-73). IEEE.
[26] Huang X, Ruan X, Du F, Liu F, Zhang L. High power and low voltage power supply for low frequency pulsed load. In applied power electronics conference and exposition 2017 (pp. 2859-65). IEEE.
[27] Huang X, Ruan X, Du F, Liu F, Zhang L. A pulsed power supply adopting active capacitor converter for low-voltage and low-frequency pulsed loads. IEEE Transactions on Power Electronics. 2018; 33(11):9219-30.
[28] Fan B, Wang C, Yang Q, Liu W, Wang G. Performance guaranteed control of flywheel energy storage system for pulsed power load accommodation. IEEE Transactions on Power Systems. 2017; 33(4):3994-4004.
[29] Duan J, Xu H, Liu W, Peng JC, Jiang H. Zero-sum game based cooperative control for onboard pulsed power load accommodation. IEEE Transactions on Industrial Informatics. 2019; 16(1):238-47.
[30] Xie R, Chen Y, Wang Z, Mei S, Li F. Online periodic coordination of multiple pulsed loads on all-electric ships. IEEE Transactions on Power Systems. 2019; 35(4):2658-69.
[31] Eldeeb HH, Mohammed OA. Control and voltage stability of a medium voltage DC micro-grid involving pulsed load. In international conference on environment and electrical engineering and 2018 IEEE industrial and commercial power systems Europe (EEEIC/I&CPS Europe) 2018 (pp. 1-6). IEEE.
[32] Mardani MM, Khooban MH, Masoudian A, Dragičević T. Model predictive control of DC–DC converters to mitigate the effects of pulsed power loads in naval DC microgrids. IEEE Transactions on Industrial Electronics. 2018; 66(7):5676-85.
[33] Dong Z, Cong X, Xiao Z, Zheng X, Tai N. A study of hybrid energy storage system to suppress power fluctuations of pulse load in shipboard power system. In international conference on smart grids and energy systems 2020 (pp. 437-41). IEEE.
[34] Xu L, Wei B, Yu Y, Vasquez JC, Guerrero JM. Simulation assessment of the impact of pulsed loads in DC shipboard microgrid. In IECON 2021–47th annual conference of the IEEE industrial electronics society 2021 (pp. 1-6). IEEE.
[35] Salama HS, Bakeer A, Vokony I, Chub A. Mitigation of pulsed power load effect on power system using FLC-SMES. Energy Reports. 2022; 8:463-71.
[36] Tu Z, Fan B, Zhang W, Peng J, Liu W. Optimal state-constrained control of DC shipboard power systems for online pulsed power load accommodation. IEEE Transactions on Smart Grid. 2021; 13(1):96-105.
[37] Wasim MS, Habib S, Amjad M, Bhatti AR, Ahmed EM, Qureshi MA. Battery-ultracapacitor hybrid energy storage system to increase battery life under pulse loads. IEEE Access. 2022; 10:62173-82.
[38] Posam L, Ma Y, Corzine K. DC fault detection of shipboard pulsed power loads using logistic regression. In applied power electronics conference and exposition 2022 (pp. 2040-3). IEEE.
[39] Yan J, Wang J, Chen Y, Huang K, Shen C. Large-signal model of pulsed power load for analysis of dynamic voltage and frequency. IET Generation, Transmission & Distribution. 2020; 14(12):2271-81.
[40] Rajabi-nezhad A, Razi-kazemi AA. A new approach on modeling of pulsed-power loads. IEEE Transactions on Power Delivery. 2021; 37(2):727-35.
[41] Suryanarayana H, Sudhoff SD. Average-value modeling of a peak-current controlled galvanically-isolated DC-DC converter for shipboard power distribution. In electric ship technologies symposium 2013 (pp. 152-61). IEEE.
[42] Line OT. IEEE recommended practice for electrical installations on shipboard. IEEE, IEEE Std 45. 2002.

Remna Radhakrishnan was born in 1984 at Thalassery, Kannur, India. She received her Bachelor’s degree in Electrical and Electronics Engineering from Kannur University in 2005 and Master’s degree in Industrial Drives and Control from Mahatma Gandhi University in 2012. She is currently a research scholar at Department of Ship Technology, Cochin University of Science and Technology since 2016.
Email: remna@cusat.ac.in

Dr. Mariamma Chacko was born in 1961 at Changanacherry, India. She received her Bachelor’s degree in Electrical Engineering from University of Kerala in 1985, Master’s degree in Electronics from Cochin University of Science and Technology in 1987 and PhD in Computer Engineering from Cochin University of Science and Technology in 2012. She joined the Department of Ship Technology, Cochin University of Science and Technology as lecturer in 1990 and currently working as Professor there. From 1987 to 1990 she was associated with the Department of Electronics, Cochin University of Science and Technology, as a Research Associate. She has more than 30 research publications to her credit and her research interests include validation and optimization of embedded software, motor control, big data, and power quality in the electrical system.
Email: mariamma@cusat.ac.in

Appendix I

S. No.	Abbreviations	Description
1	AES	All-Electric Ship
2	AC	Alternating Current
3	AVR	Automatic Voltage Regulator
4	CCS	Controlled Current Source
5	DC	Direct Current
6	ESS	Energy Storage System
7	FESS	Flywheel Energy Storage System
8	FFT	Fast Fourier Transform
9	LVAC	Low Voltage Alternating Current
10	LVDC	Low Voltage Direct Current
11	MVAC	Medium Voltage Alternating Current
12	MVDC	Medium Voltage Direct Current
13	MVDCT	Medium Voltage Direct Current Testbed
14	PPL	Pulsed Power Load
15	THD	Total Harmonic Distortion