Marine Photovoltaics: A review Of Research And Developments, Challenges And Future Trends.

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Abstract: Application of solar energy inthe marine power system is widely accepted as a promising solution for many countries to develop green ship.Proper integration of photovoltaic(PV) energy into the ship power system(SPS) requires a knowledge about the ship electrical power systems, and many other related concerns of the ship.This paper presents a brief review on the various aspects of solar PV application onboard ship.Finally the paper highlights the technical and economical challenges in integrating PV energy onboard shipsand also address future research possibilities in the PV integrated shipping industry. This review paper contributes to extend the realistic utilization of PV system and alsohelps as a reference for exploring the integration of PV systems in marine industry.

Index Terms: Marine photovoltaic, Photovoltaic ship power system, Marine Pollution, Power quality onboard,Renewable energy integration, Solar ship.

I. INTRODUCTION

The need of renewable energy system (RES) in shipping industry has been raised due to the increased fuel cost and marine pollution[1].Generally diesel engines are used to power many shipsand this release immensequantities of exhaust gases like carbon di oxide,nitrous oxide, sulphuroxide which pollute water and air,causing global warming and health hazards to humans[2]. By 2050, amount of green house gas emissions is predicted to increase to 17% [3].The main shipping supervisory body for shipping, International Maritime Organization (IMO) introduced some standards and regulations to increase environmental quality of worldwide shipping and the shipping industry was forced to find new solutions for reducing emissions[4]. The International Convention for the Prevention of Pollution from Ships (MARPOL)Annex VI [5] has introduced the Energy Efficiency Operational Index (EEOI) and Energy Efficiency Design Index (EEDI) [6], [7]as pointers for observing the CO2 emission and other greenhouse gas (GHG) emissions from ship.In order to deal with the strict demands of the regulations by IMO, all major shippingcountries in the world have implemented “green ships”exploiting renewable energy sources.As a part of reducing marine pollutionvariouspossible renewable energy sources such as wind energy, solar energy, biofuels, wave energy, tidal energy and liquefied natural gas (LNG)are used for power generation in marine applications.Development of All-Electric- Ships(AES) which uses electric motors for propulsion instead of internal combustion engine (IC engine) has alsogreatlyreduced exhaust gases from ships. Application of energy storage systems(ESS) along with the renewables helps to reduce the fuel consumption rate thereby reducing pollution.Several projects applyCarbon Capture and Storage (CCS) technique to reduce the carbon emission. CCS is aprocedure where CO2 is caught from fossil fuels and transferred to a storage spot using pipelines or ships, and collected it underground thuslowering pollution [8]. Other technologiesfor reducing the pollution includesfuel chemical treatment,waste heat energy recovery as well as increasing efficiency of the electro-generating systems.Among thevarious technologies available for green shipping, solar energy has been turned out to be a reliable solution in marine energy applications [9]. Solar ship developed by different countries integrates solar photovoltaic(PV) energy into ship power system. Solar energy is a clean fuel which is abundant in nature and available at free of cost. The advancements in the PV technology and the extensive electrification of the ships also boosted the development and research The remaining paper content is structured as follows: In section 2,a literature review is presented on the photovoltaic ship projects and developments that has been performed by different researchers in different areas of photovoltaic ship power system (PSPS).Section 3outlines the different aspects of solar integrated ship power systems.Comparison of PV integrated land system and PV integrated ship power system as well as role of ESSare also described. In section 4,photovoltaic ship powering system and different operation modes of solar powered ship power systems areparticularly reviewed.Section 5summarizes potential challenges and anticipatesfuture research needs in the application of PV onboard ships. Lastly some conclusions are extracted in section 6.

2. RECENT PHOTOVOLTAIC SHIP PROJECTS AND DEVELOPMENTS

Sun et al. examined the design and application of PV system on the ships [10].The transient characteristics were studied under two operating conditions: at sea and at port. When PV is integrated into the ship’s grid, a large amount of harmonic waves are produced. The economicviability of installing PV systems on merchant ships have been examined in [11].The practicability of using PV as a back up power for Auxiliary Engines (AEs) have beenstudied in [12]. Lee et al. assessedcalculationof stability and investigation of a hybrid PV/diesel ship system[13].Babu and Jain [14] examined the application of PV system for small distant-aquatic fishing boats in India.Cristea [15] presented the experimental results of PV panel installed on the ship “NS Mircea”. The effectiveness of PV systems for the Navy ships has been inspected in [16].Kobougias et al.researched the specifications of PV system for the ships [17]. Utama et al. studied the solar-powered catamaran fishing vessel [18].Yufang et al. described the fuel-free ship design based on the solar and wind energy [19]. Alfonsín et al. presented a theoretical prototype of hybrid hydrogen and renewable energyscheme to electric propulsion in sailboats [20].Cristeaet al. investigated the correspondence between simulated and actualPV system on the training ship named “Mircea” in naval conditions. They noticed that the horizontal installed PV panels are more efficient than the vertical type [21]. The capacity of using PV system on the ships as ansupplementary powerto trim down fossil-fuel utilizationhas been studied in [22].A case study regarding the installation of PV system for cruiser ships is presented in [23]. Peng et.al established a traditional ship power system simulation model and PV system simulation model inPSCAD software [24].Lan et al. propositioneda method fordeciding the optimum size of the PV/Diesel/Battery hybrid system for ship power systems tolessen the capital cost, fuel cost, and exhaust discharges [25]. He also conducted a study on the optimization of tilt angle of PV panels on abig oil truck ship. As the tilt angle rises, power production of PV panel falls according to the result of study [26].Tang et al.introduced a power administration system of "CoscoTengfei" ship, which is integrated in the PV system [27].Consequence oflow frequency shaking of ship on the output characteristics of PV cells under altered solar radiation has been studied in [28].Taking into account the movements of the ship,Wen et al. studied the PV/ESS/Diesel hybrid ship power system in [29]. Application of solar technology in an oil tanker ship is explained in[30].An electric boat charging station with grid-connected renewable energyhas been analysed in [31]. Using LabVIEW and MATLAB a simulation of ship power system is established in [32].Design of large scale photovoltaic arrays using advanced MPPT control has been performed in [33].A large scale solar photovoltaic system has been designed for "COSCO Tengfei" with a peak power of 143 kW in [34].In recent years a number of solar energy ships are developed and some major projects of different countries are given in the Table 1.

3. DIFFERENT ASPECTS OF SOLAR INTEGRATED SHIPS

The advancements in the area of land PV systems contribute much to the development of ship PV systems. But the peculiarities of ship electrical power systems, marine environment conditions, different requirements of the vessel as well as nature of ship loads increases the complexity in the application of PV in marine environment. Several aspects of solar integrated ships are discussed below.

3.1Terrestrial Electrical Power System versus Ship Electrical Power System

A comparison of the hybrid renewable-energy systems on the land and ship applicationsare detailed in [35], [36] and [25] and summarized as following.

1. The electrical power system on land is stationary; however, a ship electrical power system usually functions in a vibrant mode.
2. The ship electrical system has short distances between generators and consumers whereas it reachesa number of kilometers in land power system
3. Ship power system is a "weak grid", whereas terrestrial power systems are strong grids. In ship the loads are extremelylarge and dynamic in comparison with the generated power. This conditionoffers aconsiderable voltage dip.
4. The loss of load probability (LOLP) in a ship power system need to be zero. But it is not compulsory to confirm that LOLP is zero in the terrestrial power system .
5. The load almost always deviatesconstantly in the land power system. On the other hand, the total load in a ship changes with different working conditions such as sailing, anchoring, loading or unloading etc.

3.2 Comparison of Photovoltaic Systems Installed in Ships and Land

Photovoltaic system installation in ships faces some difficulties as compared to that installed in the land applications [37],[17]. Some aspects can be summarized as follows:

1. Solar tracking systems which can increase the power output from the solar panels could not perform well for the PV panels installed in the ship. Storms occurring at the sea could adversely affect the mechanical moving parts of solar tracking systems. Therefore the cost of tracking systems and cost of maintenance increases in the case of ship PV systems.
2. PV modules receive continuously varying solar radiation especially when the ships have different sailing routes. The irradiation profileforecast is challenging in ships as compared to land PV systems. As a result the yearly electric energy generation assessment is also difficult.

TABLE 1
SOME MAJOR SOLAR SHIP PROJECTS

Name and type of vessel	Year & Country	Remarks
'Solar Sailor' (twin-hull passenger ship)	2000(Australia)	world's first commercial solar/wind hybrid twin-hull passenger ship
'Euphony Ace' (vehicles carrier)	2005 (Panama)	solar panels and huge capacity rechargeable batteries are extensively installed on the ship.
'Sun 21' (catamaran for five to six passengers)	2006 (Switzerland)	First fully sun powered boat that sailed across the Atlantic. 2 solar modules having 5kW each.

'Auriga Leader' (cargo ship)	2008 (Singapore)	World's first solar hybrid huge cargo ship. PV array with 328 panels. Generate electrical power upto 40kW which could meet ship lighting plant (off-grid mode).
'ShangdeGuoShen' (passenger vessel)	2010(china)	Use PV energy and diesel as hybrid sources of powerwhich could reduce exhaust gases by more than 30%.
'Emerald Ace' (vehicle carrier)	2012(Japan)	768 panels(160kW) is installed
"Tengfei" (vehicle carrier)	2014 (Wuhan University of Technology and COSCO)	World's biggest solar ship hybrid PV power generation system and could generate 143.1 kWp of solar power.
Blue Star Delos (Ro-Ro/ passenger ship)	2014(Greece)	A part of a project to study the use of renewable energy on large ships.
MS Tueranor Planet Solar (passenger boat)	2017(Germany)	Largest fully solar-powered boat in the world. The 35-meter-long and 23 meters wide catamaran is covered with 537 m2 of solar modules with the totalpeak power of 935 kWp.
'Sarvekshak' (Research/Survey vessel)	2017 (India)	First ship of Indian Navy ever to deploy solar power. Installed 18 light weight flexible panels of 300W each, capable of generating 5.4 kW electricity.

3. The optimum tilt angle of PV panels can be specified on the land application to obtain maximum power output. But for the ship applications, zero tilt angle of PV panels or horizontally installed PV panels have found to be providing more efficiency than the vertically installed panels.
4. The fluctuations of the sea could change the angle of incidence between the solar radiation and PV module, whereas it is fixed on the land applications generally.
5. PV panels installed in marine applications should be tolerant to sea conditions like high humidity, salty environment conditions, and corrosion. Short-circuits and deterioration to the mechanical parts of the converters are caused by humidity and salt. Metal exteriorscan be galvanized or can be covered with antirust coatings. To prevent solar cell degradation due to any moisture penetration encapsulation materials like additional glass sheet or toughened safety glass can be used.
6. The sea water can be crashed onto the deck in a ship power system and it will disturb the efficiency of solar panels. This does not happen in the terrestrial PV system.
7. The PV systems installed in ships have tight area constraints as compared to land PV systems. It should be at anmanageable place so that their maintenance work is easy.
8. In marine applications the open spaces are limited and the nonstopfluctuations of the vessel position causes shading effects of solar panels. On the other side, in land photovoltaic systems, shading can be prevented to a larger extent by choosing open installation areas.

Output characteristics of PV cells are also manipulated by ship low frequency shaking whereas PV cells are static in terrestrial systems.Theinfluence of rainwater, seawater , salt particles layer detritus from sea birds, weed and algae can also cause a degradation of PV array onboard ship.

3.3 Different Configurations of Marine Dynamic Photovoltaic Arrays

Different existing configurations of PV arrays like central, AC module integrated, string as well as multi-string can be employed in marine photovoltaic systems.The drawback of partial shading on the PV panels can be lessened using modern dynamic photovoltaic arrays (DPVA) [38].A pattern is fashioned todeliver maximum power output by reconfiguring the module interconnections in real time for each instant.The power output from a PV array can be increased by different methodologies such as Irradiance Equalised DPVA (IEq-DPVA), the Adaptive Bank DPVA (AB-DPVA) and the Optimised String DPVA (OS-DPVA).The divergence in irradiance in marine environmental conditions can be alleviated using different classifications of dynamic array such as Fixed configuration DPVA, string configured DPVA and Total Cross Tied DPVA(TCT-DPVAs)[39].

3.4 Maximum Power Point(MPPT) Control of Ship PV System

Different MPPT control methodologies are currently available for tracking maximum power from PV panels. Online algorithms such as perturbation and observation (P&O), incremental conductance (INC) and offline control algorithms such as neural network, evolutionary algorithms, soft computing methods, model predictive control are some available MPPT methods. But the application of these methodologies in ship PV systems becomes complex as the marine environment is frequently varying. In large ships the PV panels are sometimes shaded by the different parts of the ship itself.The performance of typical MPPT methods deteriorateespecially when a large scale PV system is installed in marine vessels. Therefore the MPPT control methodologies for large ocean going ships isin an exploring stage.

3.5 Application of ESS in PV Integrated Ships

The unpredictability and variablilitynature of PV power demandsadoption of an ESS, for the satisfactory working of entire ship power system.Different energy storage technologies such as batteries,fuel cells, supercapacitors,flywheels and superconducting magnetic energy storage (SMES) systems,compressed air energy storage (CAES) are currentlyincorporated into ship microgrids to maintain the energy stability and todeliver supplementaryfacilities to the ship power system[40].Each technology has distinctive power density and energy density and therefore should be applied according to thenecessity of ship microgrid.Presently, batteries offers the largest portion of energy in marine applications and Lithium-Ion battery is the most generally used technology. Application of BESS in ships, it's benefits and drawbacks are introduced in [41]. Hybrid Energy Storage System (HESS)merges both energy density and power densitystorages . Combination of solar energy and HESS helps to exploit the PV power installed in marine applicationsin a more efficient method.In [42],a model is proposed to integrate a supercapacitor energy storage system (SCESS) into a ship-PV power system and found to be effective in leveling the grid-connected power, regulating the DC voltage and boosting the Low Voltage Ride Throughcapability (LVRT)of PV system.

3.6 Power Quality Aspects in PV Installed Ships

The marine power quality standards issued by the major shipping classifications are not less strict, or even stricter than the rules of overland power quality internationalstandards. Different international organizations have developed various standards for power quality tosafeguard the consistency and security of the ships. Most general standards are the IEC60092-101 [43], Lloyd's Register Standard [44], Military Agency Standardization for navy STANAG1008 [45], American Bureau of shipping (ABS) 2008 [46], and the IEEE Coordinating Committee Standard45-2002 [47]. Defining power quality in ships require describing set of parameters in all different operatingconditions of the ship like manoeuvring, sea going, at port, anchoring etc.According to the IEEE Std. 1159-1995, issued by the IEEE Coordinating Committee, power quality is defined as "The term of power quality refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system"[48]. Power quality indices for ship power systems relating voltage and frequency variations can be found in [49], [50]. The most important standards concerning the limits for voltage, frequency fluctuation as well asharmonic distortion limits in ship networks are given by [51] and shown as in Table 2.Integrating PV into the ship main AC bus power system also brings some power quality issues. When connecting the PV system to the ship's AC grid it requires an inverter, as the output of the PV is obtained as DC . Inverters generally introduces harmonics into the system to which it is connected. Different inverter topologies, MPPT control strategies, the number of inverters as well as the efficiency of inverter used also influence the amount of harmonics produced in the ship electrical system .When connecting PV into the ship AC bus, the ship grid voltage and frequency has to keep constant for the stable operation of the ship. Transient current arises at the moment when PV is connected into or disconnected from ship power system [52]. Since the PV output power is fluctuating it can cause voltage swell and voltage dip problems connected to the ship bus system. Additional regulation devices are required to meet the energy demand of the ship distribution system if it is grid connected.Majority of the power quality improvement methods have been restricted to overland PV networks and only a few studies about the power quality improvement in ship PV systems are available. Sometimes the solutions applied to overland PV networks is not found to be satisfactory due to the characteristics of marine electric networks.

TABLE 2

IMPORTANT STANDARDS CONCERNING THE LIMITS FOR POWER QUALITY IN SHIP

Main power supply	415 V,50Hz,3Ph
Voltage tolerance	5%
Voltage modulation	2%
Line voltage unbalance tolerance	3%
Voltage transient tolerance	+/-16 sec
Voltage transient recovery time	2 sec
Power factor	>80%
Total Harmonic Distortion(THD)	<5%
Individual Harmonics	3%
Deviation factor	5%
Frequency tolerance	+/-3%
Frequency modulation	+/-0.5%
Frequency transient tolerance	+/-3%
Frequency transient recovery time	2 sec

4. PHOTOVOLTAIC SHIP POWERING SYSTEM

Many of the ships with electric propulsion are depending AC main bus system and a block diagram representation of integration of PV into ship AC bus system is shown in Fig. 1. The major diesel generators are coupled directly to the AC bus. The AC propulsion systems and other AC loads can also be connected to the AC bus. The output DC of the PV system is fed to ship main AC bus system using inverter.In the upcoming period, the DC bus system is strongly recommended than the AC bus system [53,54]. Medium voltage DC (MVDC) from 1 kV up to 35 kV have been used as DC power for marine power systems[55].Better utilization of ship space and absence of harmonic issues are some of the advantages of ship DC bus systems. DC bus system eliminates need of synchronization based on bus frequency as well as enables easy integration of PV systems and ESS into ship power system. However, DC ship power systems and related machineries are in a developing stage in the area of marine industry. Block diagram representation of ship DC bus system incorporating PV is shown in Fig. 2. In DC distribution, diode rectifiers convert the AC power generated by diesel generators to DC power and then it is provided into the DC bus.

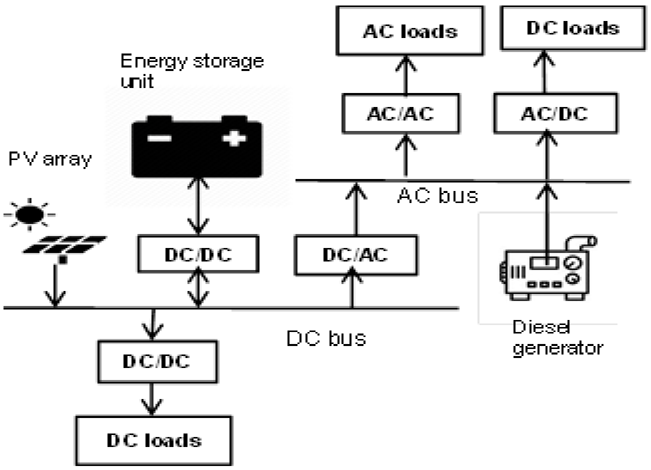

***Fig. 1**. Block diagram representation of integration of PV into ship AC main bus system*

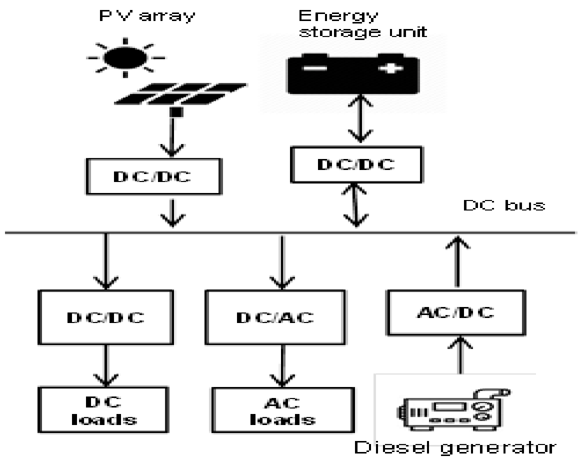

***Fig. 2.** Block diagram representation of integration of PV into ship main DC bus system*

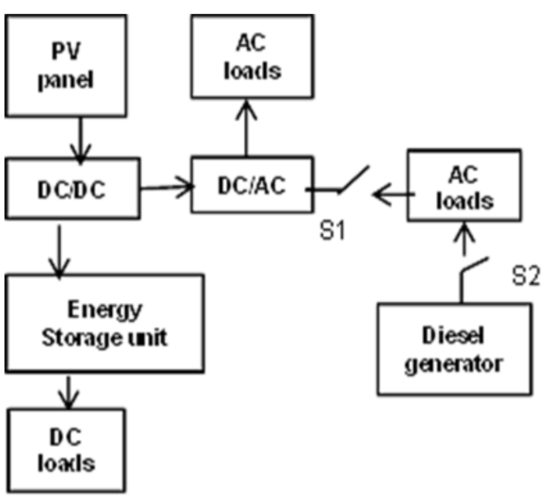

***Fig.3.**Block diagram of Offgrid connected mode*

4.1 Operation Modes of Solar Powered Ship Power Systems

Solar PV energy on ship can provide either main power energy or auxiliary energy for the ship. A few ships have effectivelyincorporatedsolar energy into ship power system that provide auxiliary energy only. Successful integration of PV for ship propulsion system such as in small vessels and recreational boats has also been performed by different projects. Application of solar energy as main power on ship implies that the ship's main propulsion plant is primarily powered by photovoltaic system. Application of solar energy as an auxiliary energy means it will power certain loads and the ship power system will have more than two varieties of power sources. This type of solar ships can be operated in three different modes like Offgrid mode, Grid connected mode and Hybrid off-grid / Grid connected mode [56]. Here the grid indicates the main bus of ship power system.

4.1.1 Off-grid mode

In this operation mode, PV system is not associated with ship main grid power system. It can be functioned as the stand alone mode of PV power system in land applications. An ESS is usually integrated into ship power system to overcome the severe fluctuation of PV plant. The DC output of PV arrays are stored in energy storage units such as battery banks. This batteries can provide direct supply to DC loads and also feeds AC loads of ship through a DC toAC inverter. But as far as the safety of ship is concerned it is normally provided with a diesel generator as a back up. Normally electrical loads are supplied by batteries when it has enough power (S1 closed and S2 open). But when it has not enough power to meet the load demands, the electrical loads are supplied by diesel generator (S1 open and S2 closed) as shown in Fig. 3. This type of configuration can reduce the capacity of battery banks and thereby reduces the investment cost. "Auriga Leader", the solar power assisted car carrier adopted off-grid mode which couldproduce that could meet the power requirement of ship lighting plant.

4.1.2 Grid connected mode

Conventional ship power system is considered as the main grid and solar photovoltaic plant is observed as a micro-grid. In grid connected mode PV system is connected to the ship main bus system. Ship AC loads and DC loads are connected to ship main AC bus system. Fig. 4 shows the block diagram of PV system integrated into ship's main AC bus system.

4.1.3 Hybrid grid connected/off-grid mode

In this operation mode ship power system can be operated in offgrid mode or grid connected mode by using a transfer switch as shown in Fig 5. Provision for preventing back flow of PV energy into the panels are also provided. Since offgrid mode is generally not able to supply the complete loads in a ship, only certain selected loads are connected to offgrid mode.

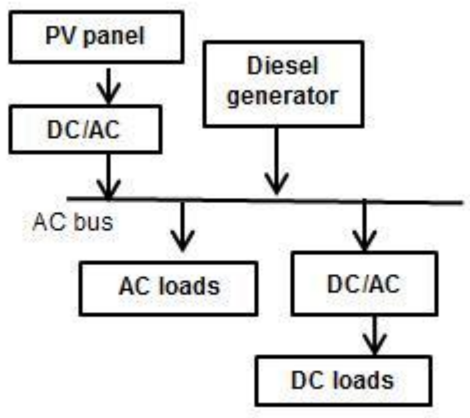

***Fig. 4**. Block diagram of Grid connected mode*

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5. CHALLENGES AND FUTURE RESEARCH NEEDS IN MARINE PHOTOVOLTAICS

The research challenges and some future trends in the area of solar integrated ship power systems over the next few years are summarized in Table 3. It is expected that through technological improvements, the renewable energy systems are expected to become more affordable with the present situation of marine vessels.

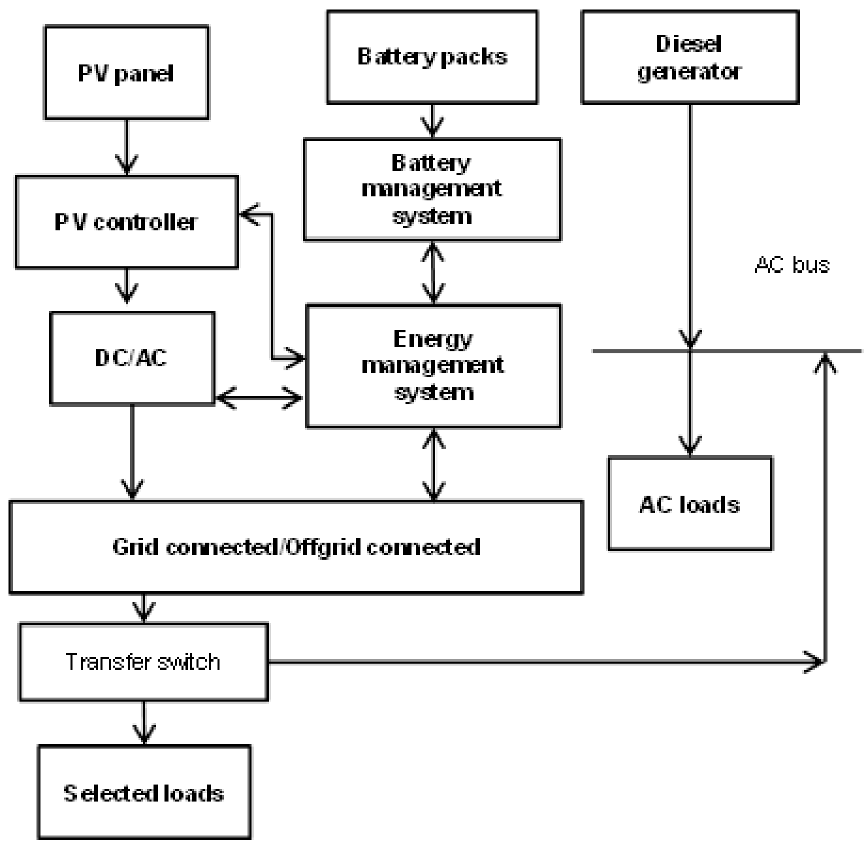

***Fig 5:**Block diagram of Offgrid/Grid connected ship power system*

TABLE.3
CHALLENGES AND FUTURE RESEARCH NEEDS IN MARINE PHOTOVOLTAICS

Research Area	Challenges	Future research needs(Prediction)
PV installation onboard ship	1. Ship reliability issues 2. full ship propulsion using solar PV 3. PV system integration to ship main bus according to the standard codes. 4. Energy management system 5. Ship Power system stability issues	1. Growth in on grid applications 2. Analysing the impact of PV penetration on protection coordination of ship systems 3. Advancements in Integrated power systems(IPS) for ship 4. Integration of PV into DC based power architecture of ship.
Design of marine solar panels:	1. Construction of marine compatible PV panels 2. Modelling of dynamic photovoltaic panels 3. Modelling of PV considering partial shading 4. wind pressure which cause uprooting of panels 5. Huge cost of PV panels 6. Reduction of total weight of PV generation systems. 7. Finding enough space for PV panel onboard ships.	1. Low cost PV panels 2. Light weight PV panels 3. Floating PV panels 4. Folding PV panels
Application of solar energy	1. Accurate PV forecasting 2. Solar energy for propulsion 3. Solar energy as an auxiliary supply. 4. Supplying non essential loads.	1. Increasing percentage of PV integration 2. Integrating PV into MVDC bus system of ship 3. Use of PV in Cold Ironing* process of ships
Allowable rating of PV in ships	Depends on 1. Capital investment 2. Available space 3. Ship load profile 4. Type of the generators used in ship	1. High voltage PV systems 2. Optimum space management
Energy Storage Systems	1. Battery Energy Management systems 2. Increasing the life span 3. Heavy weight of ESS 4. Space occupied by ESS 5. Vibration resistant batteries 6. Reduced cost 7. New materials to enhance energy density of batteries 8. Advancements in Bulk storage systems	1. Application of distributed storage such as use of supercapacitors and flywheels. 2. Economic dispatch of PV and ESS. 3. optimal size of the PV/Diesel/Battery hybrid system 4. Better control strategy for optimum power scheduling between PV and ESS. 5. Application of Ultrabatteries. 6. Low cost fire fighting system for batteries.
Impact of PV integration on the power quality	Rectifying PVgrid-connected issues such as 1. Harmonics 2. Interharmonics 3. Transients 4. power fluctuations 5. Voltage fluctuations 6. Power system stability issues 7. Ramp rate control of PV power output.	1. Mitigation of Transients 2. Harmonic suppression 3. Incorporating Flexible Alternating Current Transmission System(FACTS) devices 4. Design of Active filters 5. Mitigation of Interharmonics
Ship compatible PV inverters	1. Increasing efficiency of PV inverters 2. Optimizing MPPT controllers	1. Implementation of microinverter 2. Improved PV inverter control topologies. 3. Application of multilevel inverters. 4. Protection schemes for PV inverter against DC link overvoltage. 5. Application of smart inverters.
Standards for the interconnection of PV systems	Correction of ambiguities and inaccuracies in present standards	1. Reviewing power quality standards 2. for the interconnection of PV inverters. 3. Survey about the installed capacity of PV in marine applications.

6 .CONCLUSION

In this paper, an extensive literature review is conducted for photovoltaic ship power system. Some major solar ship projects and some major differences between terrestrial PV systems and onboard ship PV systems are reviewed. The three possible modes of operation of solar integrated ships, the role of ESS in marine PV applications, different power quality standards are also covered in this review. The marine PV system is not matured enough as the mainland PV system. Some future research directions are also recommended in this paper which helps more realistic utilization of solar integrated ships

REFERENCES

[1] R.E. Hebner, F.M. Uriarte, A. Kwasinski, A.L. Gattozzi, H.B. Estes, A. Anwar, P. Cairoli, R.A. Dougal, X. Feng, H.M. Chou, L.J. Thomas, M. Pipattanasomporn, S. Rahman, F. Katiraei, M. Steurer, M.O. Faruque, M.A. Rios, G.A. Ramos, M.J. Mousavi and T.J. McCoy, "Technical Cross-fertilization between Terrestrial

Microgrids and Ship Power Systems, " J. Mod. Power Syst. Clean Energy, vol. 4, no. 2, pp. 161–179, 2016.
[2] D.McCollum, G. Gould and D. greene, "Greenhouse Gas Emission Reduction Targets for International Aviation and Shipping," European Parliament, Brussels, 2009.
[3] M. cames, J. Graichen and V. Cook, "Emission Reduction Targets for International Aviation and Shipping," Technical Report, European Parliament, Brussels, November 2015. http://www.europarl.europa.eu/studies
[4] P. Bergmeijer: The international convention for the prevention of pollution from ships A2. Presented at the Dolman. 1992.
[5] MARPOL 73/78 Annex VI: Prevention of Air Pollution from Ships, International Maritime Organization, August 2004. http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx.
[6] Z. Soghomonian, J.M. Prousalidis, F. Kanellos, S.E. Dallas, D. Spathis, T. Kourmpelis, and G. Tsekouras , "The Role of Efficiency of Electric Machinery on Green Shipping, " Proc. Twenty second Int. Conf. Electr. Mach. ICEM,pp.2968–2974,2016, doi:10.1109/ICELMACH.2016.7732946.
[7] Guidelines for Calculation of reference lines use with the Energy Efficiency Design Index (EEDI), Resolution MEPC. 215 (63), IMO, EEDI London, Adopted on 2, March 2012. http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/231%2865%29.pdf.
[8] H. Wang, P. Zhou, and Z. Wang, "Reviews on Current Carbon Emission Reduction Technologies and Projects and their Feasibilities on Ships," J. Mar. Sci. Appl., vol. 16, no. 2, pp. 129–136, 2017.
[9] R.D. Geertsma, R.R. Negenborn, K. Zisser and J.J. Hopman, "Design and Control of Hybrid Power and Propulsion Systems for Smart Ships: A Review of Developments,". J.Appl. Energy vol.194 2017, pp. 30–54, https://doi.org/10.1016/j.apenergy.2017.02.060.
[10] Y.W. Sun, X.P. Yan, C.Q. Yuan and C.W. Lei, "Research Progress in Marine Grid-Connected Photovoltaic Technology," 47th Annual Conference of the Australian and New Zealand Solar Energy Society (ANZSES 2009),Zahedi A. Australia Townsville, 2009.
[11] A. Glykas, G. PapaioannouandS. Perissakis, "Application and Cost–Benefit Analysis of Solar Hybrid Power Installation on Merchant Marine Vessels," Ocean Engineering, vol.37, no.7, pp. 592-602, May 2010, https://doi.org/10.1016/j.oceaneng.2010.01.019.
[12] O. Sulaiman, "Feasibility of Using Solar as a Supporting Hybrid Power System for Marine Diesel Engine: UMT Vessel Experimentation Experience," Global Journal for Information Technology and Computer Science, vol.1, no.1, pp. 1-7, 2012.
[13] K.J. Lee, D.S. Shin, J.P. Lee, D.W. Yoo, H.K. Choi and H.J. Kim, "Hybrid Photovoltaic/Diesel Green Ship Operating in Standalone and Grid-connected Mode in South Korea – Experimental investigation," 9-12 Oct. 2012 IEEE Vehicle Power and Propulsion Conference(VPPC), vol. 49, pp. 580–3, doi:10.1109/VPPC.2012.6422691.
[14] S. Babu and J.V. Jain, "On-board Solar Power for Small-Scale Distant-Water Fishing Vessels," IEEE Global Humanitarian Technology Conference (GHTC), pp.1-4, 2013, doi:10.1109/GHTC.2013.6713644.
[15] O. Cristea, "Testing of PV module efficiency in naval conditions," 2013 8th International Symposium on Advanced Topics in Electrical Engineering (ATEE), pp.1-4, 2013. doi:10.1109/ATEE.2013.6563534
[16] J.P. Kirkpatrick, J.P. "An investigation of the effectiveness of solar power on Navy surface combatants," Naval Postgraduate School, Monterey, CA, 2013.
[17] I. Kobougias, E. Tatakis and J. Prousalidis, "PV systems installed in marine vessels: technologies and specifications, " Advances in Power Electronics, vol. 2013, ArticleID831560,8pages, 2013, https://doi.org/10.1155/2013/831560.
[18] I.K.A.P. Utama, P.I. Santosa, R.M. Chao and A. Nasiruddin, "New Concept of Solar-Powered Catamaran Fishing Vessel," Proc. 7th International Conference on Asian and Pacific Coasts (APAC 2013), Bali, Indonesia, September 24-26, 2013.
[19] Z. Yufang, Q. Peng, Y. Hong, "Fuel Free Ship Design for Next Generation," Eighth International Conference and Exhibition onEcological Vehicles and Renewable Energies (EVER), pp. 1-5, 2013.
[20] Alfonsín, V., Suarez, A., Cancela, A., Sanchez, A., and Maceiras, R., "Modelization of hybrid systems with hydrogen and renewable energy oriented to electric propulsion in sailboats," International Journal of Hydrogen Energy, vol.39, no:22, pp.11763-11773, 2014.
[21] O. Cristea, M.O Popescu and A.S Calinciuc, "A Correlation Between Simulated and Real PV System in Naval Conditions," Proc. IEEE Symp.Fundamentals of Electrical Engineering (ISFEE), pp.1-6, 2014, doi: 10.1109/ISFEE.2014.7050571.
[22] A.W. Hussein and M.W. Ahmed, "Solar Energy: Solution to Fuel Dilemma," International Journal of Research in Engineering & Technology, vol. 2, no. 8, pp. 99-108, 2014.
[23] M.M Moustafa and E.E El-bokl, "Solar energy for River Nile cruisers,".Brodogradnja, vol. 65, no. 2, pp. 61- 72. 2014.
[24] C. Peng, S. Shounan, L. Hai and Z. Qiang, "Modeling and Simulation of Ship Power System Integration of Solar Energy," 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), Beijing, pp. 1-5, 2014, doi: 10.1109/ITEC-AP.2014.6940746
[25] H. Lan, S. Wen, Y.Y. Hong, D.C. Yu and L. Zhang "Optimal sizing of hybrid PV/diesel/battery in ship power system," J.Applied Energy, vol.158, pp. 26-34, 2015, doi: 10.1016/j.apenergy.2015.08.031.
[26] H. Lan, J. Dai, S. Wen, Y.Y Hong, D.C. Yu and Y. Bai, "Optimal Tilt Angle of Photovoltaic Arrays and Economic Allocation of Energy Storage System on Large Oil Tanker Ship," J.Energies, vol.8, no.10, pp.11515-11530, 2015.
[27] X. Tang, T. Wang, C. Zhi and Y. Huang, "The Design of Power Management System for Solar Ship," 2015 International Conference on Transportation Information

and Safety (ICTIS), Wuhan, pp.548-553, 2015, doi: 10.1109/ICTIS.2015.7232182.

[28] Y. Zhang, Y. Sun, H. Luo and Y. Wang, "Study on Effect of Ship Low Frequency Vibration on the Output Characteristics of PV Cells under Different Solar Irradiation," 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, pp. 388-392, 2015, doi: 10.1109/ICRERA.2015.7418442.

[29] S. Wen, H. Lan, Y.Y. Hong, C.Y. David, L. Zhang and P. Cheng, "Allocation of ESS by Interval Optimization Method Considering Impact of Ship Swinging on Hybrid PV/Diesel Ship Power System," J. Applied Energy, vol.175, pp.158-167, 2016.

[30] Study on the Application of Photovoltaic Technology in the Oil Tanker Ship. Grant No. GK110900004. Execution period: January 2013-December, 2015.

[31] N.A.S. Salleh, W.M.W. Muda and S.S. Abdullah, "Feasibility Study of Optimization and Economic Analysis for Grid-Connected Renewable Energy Electric Boat Charging Station in Kuala Terengganu," 2015 IEEE Conference on Energy Conversion (CENCON), Johor Bahru, pp.510-515, 2015, doi: 10.1109/CENCON.2015.7409597.

[32] J. Jia and H. Dong, "Research on Ship Power Plant Simulation System Based on Labview and MATLAB Mixed Programming," 2017 IEEE 2nd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC), Chengdu, pp.72-75, 2017, doi: 10.1109/ITNEC.2017.8284888.

[33] R. li Tang, Z. Wu, and Y. jun Fang, "Design of green ships with large-scale photovoltaic arrays and intelligent MPPT control," Appl. Energy, 2017. 10.1016/j.apenergy.2017.04.076

[34] Y. Yuan, J. Wang, X. Yan, Q. Li and T. Long "A Design and Experimental Investigation of a Large-Scale Solar Energy/Diesel Generator Powered Hybrid Ship," J. Energy, vol. 165, pp. 965–978, doi:10.1016/j.energy.2018.09.085.

[35] F. Diab, H. Lan and S. Ali, "Novel Comparison Study Between the Hybrid Renewable Energy Systems on Land and on Ship", J. Renewable and Sustainable Energy Reviews, vol. 63, pp. 452-463, 2016.

[36] G. Sulligoi, A. Vicenzutti and R. Menis, "All-Electric Ship Design: From Electrical Propulsion to Integrated Electrical and Electronic Power Systems," IEEE Transactions on Transportation Electrification, vol. 2, no. 4, pp. 507-521, Dec. 2016, doi: 10.1109/TTE.2016.2598078.

[37] N. Papanikolaou, A. Kyritsis and M. Loupis, "Incorporating Power Converters for Energy Saving Marine Applications," 2014 International Conference on Electrical Machines(ICEM), Berlin, 2014, pp.2306-2311, doi: 0.1109/ICELMACH.2014.6960507.

[38] J. P. Storey, J. L. Hammond, J. E. G-H-Cater, B. W. Metcalfe and P. R. Wilson, "Modelling Dynamic Photovoltaic Arrays For Marine Applications," 2016 IEEE 17th Workshop on Control and Modeling for Power Electronics (COMPEL), Trondheim, 2016, pp.1-8, doi: 10.1109/COMPEL.2016.7556720.

[39] N. Papanikolaou, A. Kyritsis and M. Loupis, "Incorporating Power Converters for Energy Saving Marine Applications," 2014 International Conference on Electrical Machines (ICEM), Berlin, 2014, pp.2306-2311, doi: 10.1109/ICELMACH.2014.6960507.

[40] S. Jayasinghe, L. Meegahapola, N. Fernando, Z. Jin, and J. Guerrero, "Review of Ship Microgrids: System Architectures, Storage Technologies and Power Quality Aspects," J. Inventions, vol. 2, no. 1, p. 4, 2017, doi:10.3390/inventions2010004.

[41] K. Kim, K. Park, J. Ahn, G. Roh and K. Chun, "A Study on Applicability of Battery Energy Storage System (BESS) for Electric Propulsion Ships," 2016 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific), Busan, 2016, pp. 203-207, doi: 10.1109/ITEC-AP.2016.7512948.

[42] Y. Qiu, C. Yuan, and J. Tang, "Integrating SCESS into a Ship-PV Power System to Mitigate Power Fluctuations and Improve LVRT Capability," J. Arabian Journal for Science and Engineering (2019) ,vol.44, no.8, pp. 6769–6781, 2018.

[43] IEC 60092-101, Electric Installations in Ships-Part101: Definitions and general requirements. International Electric technology Commission 2002.

[44] Lloyd's Register of Shipping. Rules and Regulations for Classification of Ships, 2014, part 6.

[45] STANAG 1008:2004, Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies, NATO, Edition 9, 2004.

[46] ABS 0150 : 2006 "Guidance notes on control of harmonics in electrical power systems," American Bureau of Shipping.

[47] IEEE Recommended Practice for Electric Installations on Shipboard," in IEEE Std 45-2002 (Revision of IEEE Std45-1998) , vol., no., pp.1-272, 9Oct.2002, doi: 10.1109/IEEESTD.2002.94134.

[48] Inst of Elect & Electronic. IEEE 1159–1995, IEEE Recommended Practice for Monitoring Electric Power Quality; Inst of Elect & Electronic: Piscataway, NJ, USA, 1995.

[49] T. Tarasiuk, J. Mindykowski "Problem of power quality in the wake of ship technology development," J. Ocean Engineering. 2015, vol.107, no.1, pp.108–117, doi:10.1016/j.oceaneng.2015.07.036

[50] J. Prousalidis, E. Styvaktakis , I.K. Hatzilau, F. Kanellos, S. Perros and E. Sofras "Electric Power Supply Quality In Ship Systems: An Overview," Int. J. Ocean Systems Management 2008, vol.1, no.1, pp. 68–83. 2008.

[51] S. Puthalath and G. Bhuvaneswari, "Power quality enhancement and renewable energy integration in ship's distribution grid," 2018 IEEMA Engineer Infinite Conference (eTechNxT), New Delhi, 2018, pp.1-6. doi: 10.1109/ETECHNXT.2018.8385323.

[52] Y. Sun, Y. Qiu, C. Yuan, X. Tang, Y. Wang and Q. Jiang, "Research on the transient characteristic of photovotaics-ship power system based on PSCAD/EMTDC," 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, 2015, pp.397-402, 2015, doi: 10.1109/ICRERA.2015.7418444.

[53] B. Zahedi and L.E. Norum, "Modeling and Simulation of All-Electric Ships With Low-Voltage DC Hybrid Power Systems," IEEE Trans. Power Electronics, vol. 28, no. 10, pp. 4525-4537, Oct. 2013. doi: 10.1109/TPEL.2012.2231884.

[54] J.F. Hansen, J.O. Lindtjørn, T.A. Myklebust and K.Vanska, "Onboard DC grid– the newest design for marine power and propulsion systems," ABB Rev., no. 2, pp. 29–33, 2012. https://library.e.abb.com/public/b4f3f099e9d21360c1257a8a003beac2/ ABB%20Generations_20%20Onboard%20DC%20grid.pdf

[55] S. Ahmed, A. Castellazzi and A. Williams, "Technologies, Feasibility, and Management Strategies for On-Board Multi-Source Energy Networks," 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, pp. 1-6, 2016, doi: 10.1109/EEEIC.2016.7555683.

[56] Y. Qiu, C. Yuan and Y. Sun, "Review on the application and research progress of photovoltaics-ship power system," 2015 International Conference on Transportation Information and Safety (ICTIS), Wuhan, 2015, pp. 523-527. doi: 10.1109/ICTIS.2015.7232167

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