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Integrating Wind Electrical Energy for the Marine Electrical Power System

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***Abstract:** Utilization of renewable energy for the reduction of fuel consumption and green house gas (GHG) emissions in the shipping industry has been increased rapidly in the recent years. Wind energy is a clean renewable energy with no pollution which is abundantly available at sea. This paper proposes two different possible configurations of connecting wind power energy into the ship's main grid bus system . Wind electrical energy output has been connected to ship's main ac bus system in one configuration and it is connected to ship's main dc bus system. Even though Wind assisted ship propulsion (WASP) had been started already in the last decades in the form of wing sails, kites, Flettener rotor etc which could assist auxiliary propulsion of the ships, the application of wind power generator on the ship is not often applied. Therefore this paper has a relevant significance in applying wind electrical energy for the marine electrical power system needs. This paper also reveals the benefits and challenges in the area of onboard wind generation and opens future research possibilities in integrating wind energy into marine industry.*

***Keywords:** Wind energy conversion system (WECS), Horizontal axis wind turbine (HAWT), Vertical axis wind turbine(VAWT), wind assisted ship propulsion (WASP).*

I. INTRODUCTION

The wind energy available at sea can be utilized either directly as mechanical energy or indirectly by converting it into electrical energy. Wind turbines can, be installed on ships to generate electricity for electric propulsion and the forces generated by the blades of wind turbines could also be used to propel ships. But no projects under consideration within the industry would entirely replace a large ship's diesel engine, only complement it [1]. The applicability of wind turbines on ships is much more complicated than the application of marine photovoltaics. Application of wind power generators is only in a developing stage and has to overcome several hurdles. The main advantage of using a wind generator onboard vessel is the abundant wind resource available at sea. The generation efficiency of wind generator is much higher in the sea than on land. However, wind is well suited for smaller, slower-moving ships.

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The implementation of wind turbines in the small power range upto 1kW are generally used to meet the electricity needs of the ships such as lighting systems in ports or when moored. Japan Post Boat Company and Tung- Hai University has developed a wind power generator having maximum output power of 30kW and a 7 percent reduction of CO2 emission was achieved [2].
Another wind power generation system having four wind turbines each having a capacity of 5kw was used on "29004 pontoon" successfully in China [3].
An energy harvester system comprising solar panels and wind generator powered a refrigerator for a fishing boat in Indonesia [4]. A wind renewable power station system has been designed utilizing a vertical axis wind turbine for a water vehicle to give backup to main load of the vehicle [5].
The contents of the paper is structured as follows. Section II describes the principle of wind electrical power generation and proposes two different possible configurations of integrating wind electrical power system to the ship's grid. In section III, several aspects of connecting WECS onboard ships are presented. Section IV summarizes the challenges and predicts several future research areas in the integration of WECS in marine vessels. Finally some conclusions are drawn in section V.

II. APPLICATION OF WIND ENERGY CONVERSION SYSTEMS ONBOARD SHIPS

A. Principle of wind electrical power generation

Wind energy is converted to electrical energy using wind energy conversion system (WECS) and the main components of WECS is shown in the Fig 1**.** The important part of the WECS is the wind turbine which pick up the kinetic energy of wind and converts it to electrical energy using many subcomponents present inside the turbine. Fig 1. shows the main components of WECS. Wind makes the turbine blades to rotate thus converting the kinetic energy of wind to mechanical energy. The wind turbine rotor rotates and the rotor shaft is connected to generator shaft via a gear box. Gearbox increases the speed of the generator rotor to it's functional speed and the generator spins to create electricity. Thus generator converts mechanical energy of wind turbine rotor into electrical energy. DC generator, Permanent magnet synchronous generator(PMSG) and double fed induction generator(DFIG) are commonly used generators in the industry. Tower provides the support foundation for generator. Rotor over-speed can be regulated by pitch control system to avoid mechanical system failure. The maximum energy that can be bagged from the total kinetic energy of wind is 59.3% and this is known as Betz limit .It has been shown that the highest power coefficient (C_p) for an optimal modern turbine design can only reach up to 70 to 80% of the Betz limit.

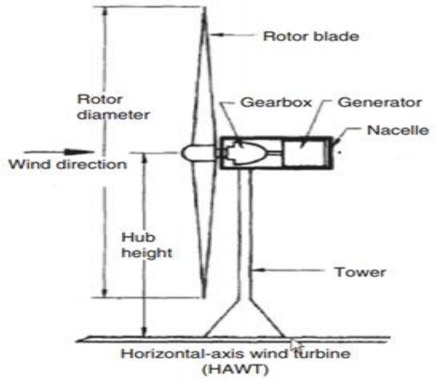

Fig 1. Main components of wind energy conversion system (WECS)

B. Proposed Methodology for integrating WECS into ship's power system

Ship main bus power system can be alternating current(AC) bus system or Direct current(DC) bus system. WECS can be connected either in two configurations. Fig. 2 shows first configuration in which WECS is connected with ship's main dc bus system. The output of the WECS is ac and then it is converted to dc using a rectifier and then fed to ship main dc bus system. Other energy sources such as fuel cells, photovoltaic panels, biodiesel etc can also be connected using suitable power conversion devices and the output energy can be fed to the same bus. The main power generating component of ship electrical system is a diesel generator and the ac output can be rectified to dc which could feed into the common dc bus. Energy storage devices like battery, flywheels can store energy and provides bidirectional flow of energy based on the requirements. Using an inverter dc is inverted to ac and could meet ship ac load demands. The common dc bus system can meet ship's dc load demands using a dc to dc filter. This architecture avoids the reactive power requirement and need of synchronization of bus frequency. This also helps to save space and weight onboard ships. The excess energy produced from WECS can be used by a dump load thereby maintaining the rated voltage level. Fig 3. shows second proposed configuration in which ship's main ac bus system incorporated with additional dc bus system. In this configuration output of WECS is smoothed using ac/ac filter and fed to ship main ac bus system. An additional dc bus system can meet the ship dc load demands.

Some projects have successfully integrated wind energy systems into ship power systems to meet ship auxiliary demands and some other projects used wind energy to assist ship propulsion. Wind energy conversion systems can be effectively utilized either by connecting it with ship's grid or operating stand alone. The best possible combination of wind energy along with other energy sources such as diesel generator, photovoltaic energy, fuel cell, batteries etc has to be identified based on the size and type of the vessel, economics, route of the ship etc.

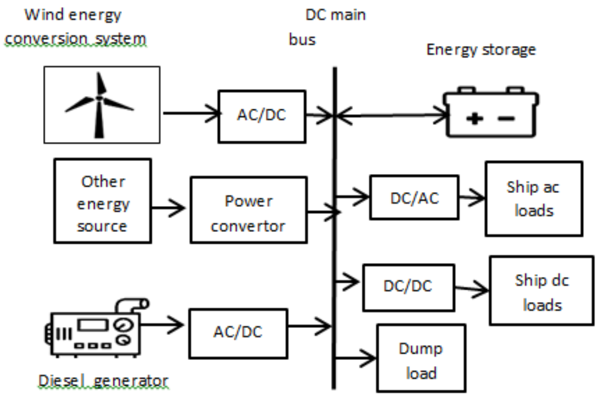

Fig 2. Wind energy conversion systems connected to ship's main DC bus

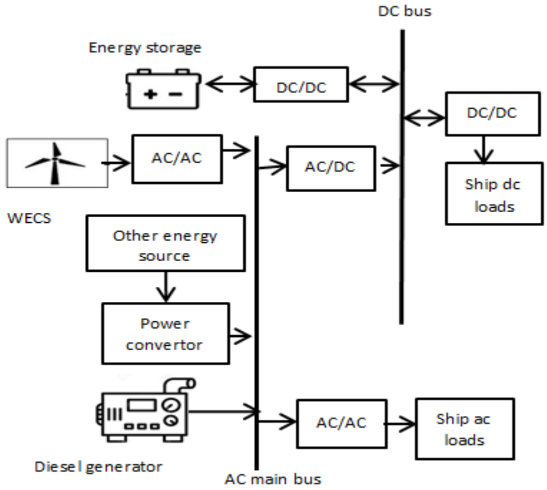

Fig 3. Wind energy conversion systems connected to ship's main AC bus.

III. DIFFERENT ASPECTS OF INTEGRATING WECS IN SHIP

Advancements of WECS in land based systems helped the application of wind turbines in marine vessels. But in order to cope up with the special requirements and functionalities of a ship**,** more attention has to paid and should consider several other parameters of the ship. Some aspects regarding with the integration of WECS onboard vessels are discussed below.

A. Vessel shipping routes

Different route of ship voyage have different wind velocities. Therefore the wind power output also varies according to that and vessel route optimization can be done for better fuel consumption.

B. Selection of wind turbine

Based on the airflow path relative to the turbine rotor upwind (The wind blades face the wind) and downwind wind turbines exist. On the basis of Power supply mode there are On-grid and Off-grid wind turbines. On-grid wind turbines are connected to the ship's grid which normally employs medium and large sized wind turbines.

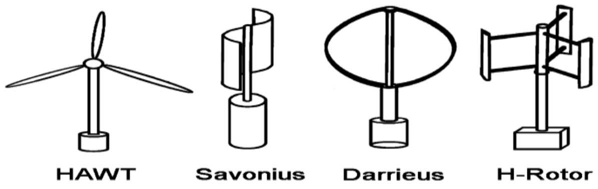

Fig 4. Different types of Wind turbine

They don't require energy storage elements. Off grid wind turbines are not connected to ship's grid which usually employs small wind turbines and normally used in connection with diesel generator or batteries. Based on the rotating axis of wind turbines, they are classified into Horizontal axis wind turbine (HAWT) and Vertical axis wind turbine(VAWT). In HAWT, rotating axis is parallel to the wind stream whereas in VAWT it is perpendicular to the ground as shown in Fig. 4. Higher power density, higher aerodynamic efficiency, lower cut-in wind speed and lower cost per unit output power are the highlights of HAWT. VAWT can be built lower and more stable since the centre of gravity is low, does not need yaw mechanisms, rudders, or downwind coning, easy to conduct maintenance work because the electrical generator can be put at a lower position, capable of catching wind from all directions, safer operation due to lower rotational speed, has low noise level (low tip speed ratio), does not suffer much from the constantly varying gravitational loads that normally would limit the size of horizontal- axis wind turbines and light enough to be carried on the roof or deck for mounting.

Ship implemented wind turbine should cope with turbulence and gusty wind, should have the optimum dimensions with respect to the energy demand, should be silent without vibrations, should have the ability to produce electricity at small wind speeds (3-5 m/s), has to be coated for marine environment, and should not harm the people or the birds. The vertical axis wind turbines especially the lift-type Darrieus is found to be more apt in this requirements. Savonious, Darrieus, H rotor are some other types of vertical-axis wind turbines which can also be used in ship with required modifications.

C. Turbine blades

For auxiliary propulsion of ships using wind turbine blades, the objective is to maximize the net forward force for the ship to propel. This results in the design of optimal blade design for wind turbine powered vessels and has shown higher fuel saving for the ship [6]. By providing additional elements such as flaps, vortex generators, flexible blades and slots, by modifying the blade shape, blade number, rotor aspect ratio and blade aerodynamic profile and by developing wind turbine self-starting solutions, the performance and the reduction of noise in a wind turbine can be improved [7]. The small power VAWTs are mainly manufactured by composite materials such as carbon fibre (CFRP) – being the lightest one in order to have a low moment of inertia or fibre glass (GFRP) that are heavier but are offering a higher flexibility.

D. Air draft limitation

Wind turbines onboard ships can increase the air drag force experienced on the ship . If the increased air draft exceeds the air draft limitation of the canal or bridges, the ship cannot travel through them thereby restricting the route of the travel. But the effect is less pronounced in most situations. When the turbine rotates**,** the air drag force on the vertically rotating turbine blades is only caused by the tower reference area, but does not increase much drag force to the ship. Below cut-in wind speed or above cut-off wind the turbine does not rotate and the turbine blade reference area will also contribute to the drag force to the ship. Generally the drag forces does not affect the ship resistance in both cases and was considered to be insignificant. But from the stability point of view, when the wind is from opposite direction , increase in drag force can increase the rolling or pitching motion of the ship.

E. Safety clearance

Depending on the size of the ship and the turbine, a minimum clearance should be provided from the blade tips to the freeboard of the ship to ensure the safety of human passageway. A safety clearance should also be provided around the wind turbine blade area to ensure the safety during the operation.

F. Stability of ship

The ship should have a stable equilibrium condition after the wind turbine system is loaded along with its necessary components [8]. Both the height and weight of the wind turbine would affect the ship's stability condition. The higher the height, the lower the stability. At the same time as the height increases, energy production increases. Therefore the optimum height of the wind turbine has to be designed that would complies with all of the ship stability criteria. As the centre of gravity of the ship get shifted due to the position of the wind turbine in the ship, the ship draught must also be checked in different loading conditions. The ship draught should be sufficient for the propeller to be immersed completely, thereby avoiding loss of vessel performance, overspeeding of the main engine or stress to the machinery.

G. Wind Generator Mounting

The wind turbines should not affect the functioning of vessel and the comfort of the crew member. Cruising vessels equipped with marine wind generators typically have a dedicated mast used as the mounting post for the wind generators. The vibrations generated by the wind generator's rotating blades will transfer down into the vessel's hull and can make living on board discomforting and un-pleasurable. A vibration absorbing material converting vibration into low grade heat which is the dissipated through the skin of the mast can be coated in the interior of the mast to eliminate unwanted sound and vibration. Additional rubber isolators provided with the mast mounting can also help to remove any latent vibrations before entering the hull. The other location for wind turbines is above mizzen mast. Especially for boats, with a second mast, mizzen mounts provide greater output by raising the wind turbine. Even though a raised wind machine increases the output power, it will increase the effects of pitch and roll.

In other installations, especially when the wind generator is permanently mounted on an arch, makes it more difficult to protect it from storm. Securing the wind generator-in-severe-weather conditions using a hook and tail is illustrated in [9].

H. Thermal management of wind turbines

Wind turbines installed in the ships are operating in the severe sea climatic conditions are experiencing large variations in environmental temperatures. Maintaining temperature levels inside the nacelle of wind generator within specified limits is important for ensuring safe and reliable operation of the turbine. Heat generated from electric/electronic devices and rotating mechanical components such as gearboxes and bearings result in various power losses. Wind turbine cooling includes wind generator cooling, electronic and electric equipment cooling, gearbox cooling, and other components/ subsystems cooling. The incoming wind can be utilized to cool the wind turbine .This wind assisted cooling system sucks in wind flow from an air inlet port on the top of the nacelle, fills the received airflow into the generator and finally exhausts at the front of the nacelle. Water or oil cooling can be applied for large wind generators with high thermal loads [10]. But adding such a complex cooling system brings lower reliability and higher cost. In addition, they must be protected from dusts and moisture, as well as electrical shocks from lightning. In cold climates, heating may be required for heating blades and hub to prevent them from icing over , warming up the lubrication oil in gearboxes, raising the temperature inside the control cabinets toward a desired temperature.

I. Braking of wind turbines

Wind turbines can be stopped under light winds or small short storms (normally under 15 mph) using the Dynamic or Electric braking mechanism. Generally wind generators are provided with Run/Stop switch. But beyond this wind speed, electric braking results in heat build-up in the generators stator winding, and can causes overheating of generator which ultimately results in expensive repair or complete failure. In such situations, a mechanical brake extreme wind speed condition is used to stop the turbine. But the mechanical brakes would wear quickly if used to stop the turbine from full speed. Under storm conditions greater than 30 mph including hurricanes and typhoons it is better to remove the wind generator from the mast or atleast the turbine blades in possible cases. The front of the wind generator should be sheltered from water by covering the axis bearings and nacelle with heavy duty plastic bag.

J. Grounding Wind Generator Systems on a Vessel

Wind generators and their related mast must be grounded to the ship's ground for the safe and reliable installation. Some wind generators make available a separate ground lead that connects the body of the wind generator to the ship's ground. Only a single ground wire should be connected from the wind generator structure to the ship's ground because multiple ground wires can give rise to current loops directing to hazardous voltages. If a rubber or nylon pad is provided for absorbing the mechanical vibration between the yaw mounting clamp and the mast, a small grounding jumper wire could take care of the electrical grounding path between them.

K. Marine turbulence and wind shear

Turbulence and wind shear can cause variations in the mechanical loading of the wind turbine which in turn affects the power production profile. It can also reduces the life time of wind turbine. Installing the turbine adequately high above the structures in the ship that disturb the free air flow can lessen marine turbulence and wind shear.

L. Fire protection of wind turbines

Fire can be caused in wind turbines due to lightning, application of a mechanical brake, heat surfaces at bearings, brake disk etc, ignition of leakage lubricants, solvents and dirt. Housing of the nacelle made of GRP- glass reinforced plastics, PUR –polyurethane or PS –polystyrene which provides sound insulation of the nacelle, oil in the hydraulic systems for pitch adjustments and braking systems are additional fire loads which increase the spread of fire. Burning parts falling down on the ship can extremely affects ships safety and the fire fighters. Wind turbines have to be equipped with lightning and surge protection. Use of non-combustible materials with high flash point, Automatic fire detection/alarm system, proper fire extinguishing systems, frequent maintenance, automatic switch-off of the turbines and complete disconnection from the power supply system in the case of fire risks being identified , training of employees for handling dangerous situations, installing trays for the immediate removal of leakages are some precautions that can effectively reduce fire spread.

M. Power Quality aspects

The irregular nature of wind and the application of power electronic converters in wind turbines introduces several power quality (PQ) problems. IEC 61400-21 defines power quality characteristics for wind turbines [11]. Operation of wind turbines can contribute several problems like voltage and current harmonic distortion, flicker, voltage fluctuations, voltage dip, voltage swell etc. The sudden change in wind speed, wind shear, yaw error, and tower shadow may cause a variation in the output power that results in voltage fluctuations and causes flickers in wind energy systems[12]. Flicker is a PQ problem in which the magnitude of the voltage or frequency changes at such a rate so as to be noticeable to the human eye[13]. Usage of the power electronics devices along with variable speed operation of wind turbine inject a considerable amount of current harmonics into the ship electrical networks. Harmonics are defined as multiple integer frequencies of the fundamental system frequency (typically 50 or 60 Hz) presented in electrical voltage or current waveforms Harmonics results in thermal overloading of lines and cables, overheating of transformers, nuisance operation of protection relays, decreased reliability and increased losses of ship power systems. Wind turbine operation may causes voltage unbalance and voltage drops in the line voltages of ship distributed systems. The irregular nature of the output power generated by the WTs plants could increase in maximum Short-circuit Current (SCC) in the network and therefore requires more expensive protective devices. SCC is a measure of the maximum fault current expected for a particular element.

IV. RESULTS AND DISCUSSION

Some significant research requirements along with the present hurdles in the area of wind energy integrated ship power systems are summarized in the Table 1. It can be anticipated that through further research developments, the wind energy systems can be expected to become more reasonable with the marine vessels.

Table- I: Present challenges and Research Trends in the Integration of Wind energy into ship power systems

Research Area	Challenges	Areas to be focused
Wind generator installation onboard ship	1. Ship reliability issues 2. Ship propulsion entirely by wind power 3. Ship stability issues 4. Hybrid energy management systems 5. Accurate Wind data collection 6. danger of rotating blades to the crew , cargo loading and unloading 7. noise produced by airflow over the blades 8. Increasing air draft 9. Have to withstand extreme environmental conditions (temperatures, wind speed fluctuations, humidity, dust, solar radiation, lightning, salinity and frequent rain, hail, snow, ice)	1. Development in ongrid applications. 2. Integration of wind energy into AC and DC ship architecture. 3. Deciding optimum vessel route 4. Construction of foldable turbine tower and blades without affecting the efficiency 5. Protection system of WECS against fault in ship's grid
Design of marine turbines	1. Huge cost of wind energy conversion components. 2. Modelling marine turbine generators 3. Deciding the location of wind turbine onboard ship 4. Reducing the weight of the wind turbine	1. Increasing the life time of wind turbines 2. Developing proper pitch control mechanism 3. Integration of MPPT controller for maximizing the WECS output.
Wind turbine blades	1. Optimal blade design shapes and size 2. Protection of turbine blades	1. Designing marine grade turbine blades 2. Increasing the strength of blades 3. Developing light weight blades. 4. Retractable wind blades. 5. Reducing the cost of turbine blades
Application of wind energy	1. Accurate wind forecasting 2. Using only wind energy for propulsion 3. Wind energy as an auxiliary supply	1. Increase in the percentage of wind energy penetration 2. Wind electricity for non essential loads, lighting 3. needs the cooperation between the ship owners, ship societies, manufactures of turbines, ship designing institutes 4. charging your batteries while the ship is at port.
Capacity of the wind turbine	Depends on 1. Capital investment 2. Type of the vessel 3. Ship load profile 4. Number of the diesel generators used in ship	High capacity wind turbines for ship's energy needs
Impact of wind power integration on the power quality	Rectifying grid-connected issues such as 1. Harmonics 2. Interharmonics 3. Transients 4. power fluctuations 5. Voltage fluctuations 6. Power system stability issues	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
Economics of installing wind turbine onboard ships	Reducing the cost of WECS	1. Increasing the profitability of investing wind generator 2. Reducing the payback period 3. Reducing the installation, operation, maintanence cost 4. Convincing the investors about savings in the fuel consumption by real time simulations 5. Expensive than installing solar panels 6. Indetermination about the anticipated profit
Interconnection Standards for connecting wind energy systems	No detailed rules for the application of wind power generation on the ship	1. Survey about the installed capacity of wind electricity in marine power needs 2. Review of the power quality standards for integrating WECS. 3. Finding the inaccuracies in the present standards

V. CONCLUSION

Application of wind electricity is definitely a promised solution for the energy crisis and green house gas emissions faced by marine industry. The additional weight of the wind energy conversion system installations is also possible to bring within reasonable limits to encourage potential investments in large vessels. Wind turbines mounted on ships require adequate differential wind speed over the turbine rotors and therefore the design of turbine blades may need some alterations to optimize ship performance. The wind turbines onboard ships also require further research and experiments, inorder to optimize the power production. By the proper management of the ESS and different sources of energy along with the wind energy systems could improve the efficiency and redundancy of marine vessels. Usage of wind electricity with the cooperation of ship societies, ship owners and manufactures, along with systematic engineering for the ship power needs would definitely be a solution for reducing green house gas emissions.

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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 Science from Cochin University of Science and Technology in 2012. She has been working as a faculty in the Department of Ship Technology at Cochin University of Science and Technology since 1990 and as currently Professor in the department. From 1987 to 1990 she was associated with the Department of Electronics, Cochin University of Science and Technology, as a Research Associate. She has 18 research publications to her credit and her research interests include validation and optimization of embedded software, motor control and power quality in electrical system.