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Enhanced Efficiency Wind Energy Conversion System for Ship Propulsion Applications

Evangelos Tsioumas, Nikolaos Jabbour, and Christos Mademlis
School of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Greece

Corresponding author: Christos Mademlis, mademlis@auth.gr
Speaker: Christos Mademlis, mademlis@auth.gr

Abstract

This paper examines the potential of adopting environmentally friendly energy sources to power the electric microgrid system of a ship so that decrease of fuel consumption and thus, reduction of CO_2 emission can be attained. The research is focused on adopting wind power electrical generation on board by a wind energy conversion system (WECS) and a properly selected battery storage system (BSS). Specifically, an enhanced efficiency WECS with squirrel cage electric generator (SCIG) is proposed that attains minimum power loss of the electrical generator, maximum harvesting of wind energy, and highly accurate yaw control so that the nacelle is correctly aligned to the wind direction. The BSS consists of Li-ion batteries properly controlled by an energy management system so that maximum utilization of the generated electrical energy by the wind is accomplished and also, smooth power and energy performance of the ship's electric microgrid is ensured by absorbing any potential fluctuations of electric energy generated by the wind turbine and electric loads on board. Selective simulation results are presented to validate the satisfactory performance of the suggested combined scheme of WECS-SCIG and BSS for ship applications.

1 Introduction

All energy sources have environmental impacts. However, more harm is caused by fossil fuels, such as coal, oil and natural gas compared to renewable energy sources (RES) with respect to air and water pollution, health, wildlife, etc. The exact environmental impact and its intensity depend on the used technology, location, and several other factors. Among the RES, the wind power is one of the clearest and most sustainable technology, since it does not produce toxic pollution or harmful air pollutants and on the other hand, the primitive source is inexhaustible, abundant, and affordable [1].

In the maritime sector, International Maritime Organization (IMO) contributes to the global effort for protection of the environment and adopted several measures under the international convention MARPOL [2] in accordance with the ship's energy efficiency design index (EEDI) and energy efficiency management plan (SEEMP) [3]. Particularly, IMO strategy for greenhouse gas (GHG) decrease in international shipping aims to at least 40% reduction of CO2 emissions per transport work by 2030. Moreover, IMO strategy includes the adoption of near-zero or zero GHG emission technologies of energy sources for the 10% of the energy needed in international shipping by 2030 [4].

A WECS is a strong clean energy candidate for powering the ship propulsion system and its electric microgrid. Thus, several analyses have been conducted on the techno-economic aspects of this issue and various types of WECSs have been developed for the maritime industry that depend on the ship's size and type [5]. Also, several issues in respect to vessel's manoeuvrability and stability, navigation, vibration, noise, cargo loading and unloading, etc. have been studied and solutions have been proposed [6].

Therefore, a highly efficient combined control scheme of a WECS with a BSS that can be used for ship applications may be a suitable solution for the shipping sector objectives. The WECS can be realized with a SCIG for cost-effectiveness, and it can attain through the proper control system electric power loss minimization of the generator, maximum harvesting of the wind energy, and highly accurate yaw control of the nacelle so that is always aligned to the wind direction.

An investigation with respect to the use of wind power

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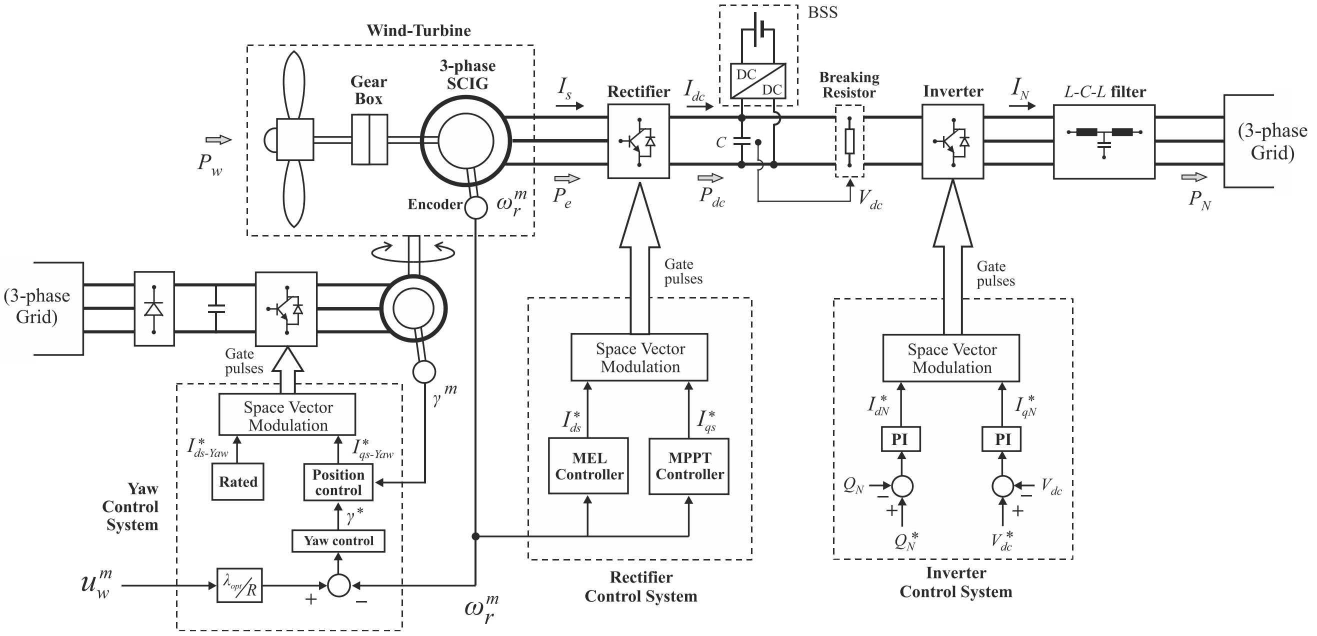

Fig. 1. Structure overview of the improved efficiency and accurate yaw controlled WECS with a SCIG and a BSS.

as the essential service system onboard has been provided in [7] and the benefits and limitations have been discussed in [8]. The economic and environmental analyses of a hybrid wind, PV, and fuel cell energy system for ships has been performed in [9] and also, ship propulsion strategies by using wind energy have been examined in [10]. The design and control of a combined scheme of sail and wind power technologies has been examined in [11]. The control technology for a sailing drone that is powered by a wind system has been proposed in [12]. Specifically, a study based on the Monte Carlo method with a stochastic dynamic programming technique has been conducted for the proper control of a robotic sailboat aiming to the improvement of the control accuracy. Similar research work has been conducted in [13] where it is mainly focused on the aerodynamic design of the wing.

The conceptual design and the technical construction of an autonomous vessel propelled by a combined scheme of wind turbine and PVs have been proposed in [14]. This vessel is more suitable for sailing in shallow waters. Finally, the exploitation of wind power generation technology and the analysis and design of the electrical generator for electric ships have been examined in [15].

From the above reference analysis, it is concluded that the research on the exploitation of the wind energy for ship propulsion has been mainly focused on the investigation of strategies, performance analysis, and proper design of the wind energy conversion system. Also, the issues of efficiency improvement and proper control of a WECS for ship propulsion applications were partly investigated in technical literature and only for some sectors of the problem. On the other hand, the problem of efficiency improvement for inland and offshore WECS installations has been extensively investigated [16], [17] and several control methods for various electrical generators have been proposed [18]. Therefore, there is a need for the development of a properly adapted control method of WECS to the specific needs of ship propulsion applications.

Thus, the aim of this paper is to fill this research gap and to propose a combined control scheme for a WECS with SCIG that can be used in ship propulsion applications and attains the aforementioned objectives. The above system is supported by a BSS that can be used for temporary storage of the excess energy produced by the wind turbine that cannot be absorbed by the ship propulsion system. Thus, both energy saving and high reliability of the respective electric microgrid can be accomplished. The proposed integrated control scheme combines the SCIG control system and the yaw control methodology that has been developed by the authors ([19] and [20], respectively) as well as the BSS energy management methodology that has been proposed by the authors in [21] for a WECS with a doubly fed induction generator.

Therefore, the novelty of the paper is a comprehensive WECS control scheme with a SCIG of maximum efficiency and reliable operation properly designed for the exact needs, technical requirements, and energy demands of the ship electric propulsion electric microgrid. The operating improvements and the effectiveness of the suggested control system have been verified with a simulation analysis in MATLAB/Simulink and selective

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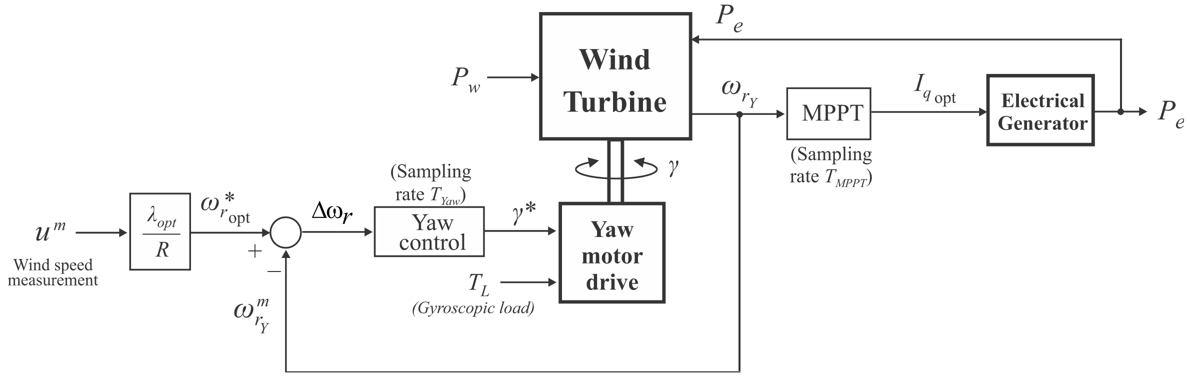

Fig. 2. Overview of the block diagram overview of the combined yaw and MPPT control system.

simulation results are presented to demonstrate the accomplishment of the aforementioned objectives.

2 Configuration of a WECS with a SCIG

The block diagram of the optimal efficiency and yaw controlled WECS with a SCIG is shown in Fig. 1. The mechanical energy provided of the wind turbine is conveyed to the electrical generator by means of a gearbox that can set up the lower rotor speed of the wind turbine to the higher speed of the generator.

Two converters in back-to-back connection operated with the vector control technique are used. The inner current controlled converter behaves as a rectifier and the field-oriented control technique is adopted to regulate the d- and q-axis components of the generator stator current. Through the d-axis current control, the efficiency of the SCIG is maximized by utilizing the minimum electric loss (MEL) controller, while through the q-axis current control, maximum absorption of the mechanical power of the wind is attained that is realized by the maximum power point tracking (MPPT) controller. Both MEL and MPPT controllers have common input the rotor speed ω_r of the generator.

For the outer controller, the voltage-oriented control technique is applied to regulate the d- and q-axis output current components. Specifically, through the control of the d-axis currents, the dc-link voltage is kept constant and thus, the active power at the common-coupling point with the ship's microgrid is controlled, while through the q-axis current control, the power factor at the common-coupling point with the ship's microgrid is regulated to supply to the ship's microgrid the required reactive power.

An LCL filter (Inductance-Capacitance-Inductance) is installed between the ship's microgrid and the inverter to reduce the voltage and current harmonics of the generated power that is injected to the microgrid. A BSS through a DC/DC converter is applied at the dc-link to store the excess electric energy that cannot be injected to the ship's microgrid in case of low energy demand. A braking resistor is also installed at the dc-link for emergency reasons to absorb the energy that cannot be consumed by the ship's microgrid or stored into the BSS.

An active yaw system is utilized to automatically orient the nacelle and the rotor shaft to the wind direction. It consists of a worm-gear-reduction drive with a rack-and-pinion gear to increase the torque and respectively decrease the speed of the nacelle rotation [20]. The yaw control system regulates the rotation angle γ of the nacelle by controlling the yaw motor drive utilizing the space vector technique. The command yaw angle position γ^* is estimated by the yaw control algorithm that aligns the nacelle to the wind direction. The block diagram of the yaw control system is illustrated in Fig. 2.

It should be noted that the concept of yaw control has two conflicting aims. On the one hand, it should effectively respond to eliminate the yaw error and on the other hand, to avoid small movements of the nacelle so that the lifespan of the mechanical parts is protected. Therefore, an optimal balance between the above objectives by considering the turbine technical characteristics and the wind conditions.

3 WECS optimal efficiency control

The power captured by a wind turbine is

$$P_W = \frac{\pi \rho C_P R^2 u^3}{2} \tag{1}$$

where u is the wind speed, R is the radius of the blades, C_p is the aerodynamic coefficient of the wind turbine, and ρ is the air density. The shaft speed of a wind turbine, at which at a given wind speed MPPT is attained, is given by

$$\omega_{opt} = \frac{u \lambda_{opt}}{R} \tag{2}$$

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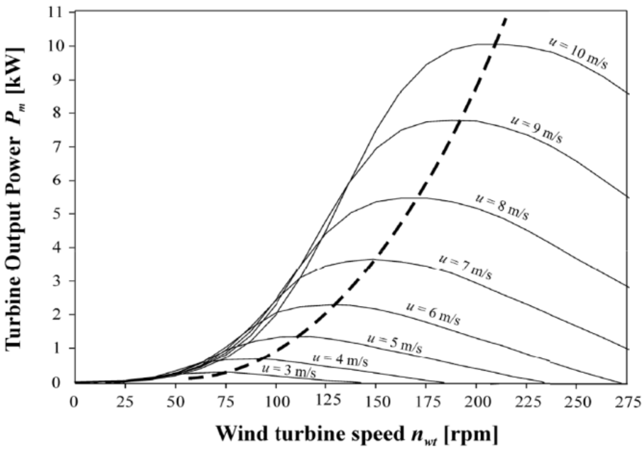

Fig. 3. Power-speed characteristics of a three-blade horizontal axis wind turbine for various wind speeds and zero blade pitch angle.

where λ_{opt} is the tip speed ratio that is constant for all the operating point of the turbine that maximum power is attained. Fig. 3 illustrates the turbine output power versus rotor speed for a 3-axis horizontal axis wind turbine with radius blades 3.5m, for zero degrees blade pitch angle.

The electric loss of a SCIG in a WECS can be minimized with respect to the d-axis stator current by

$$\left.\frac{\partial P_{loss}}{\partial I_{ds}}\right|_{\omega_e=\text{const.}} = 0 \quad (3)$$

and after several mathematical manipulations the following equations have been resulted that can act as the optimal conditions, for the d-axis stator current [19]

$$I_{ds_{opt}} = \omega_r \sqrt{G_d G_q}\left[\frac{1+T_a^2\omega_e^2}{1+T_b^2\omega_e^2}\right]^{0.25} \quad (4)$$

which is realized by the minimum electric loss controller (MEL) and for the q-axis stator current

$$\left|I_{qs_{opt}}\right| = \omega_r \sqrt{\frac{G_q}{G_d}}\left[\frac{1+T_b^2\omega_e^2}{1+T_a^2\omega_e^2}\right]^{0.25} \quad (5)$$

which is realized by the maximum power tracking controller (MPPT) where G_d, G_q, T_a, and T_b are parameters that can be determined experimentally.

Since the magnetic inductance L_m may vary due to saturation and the stator and rotor resistances may vary due to temperature, the G_q gain may be accordingly affected. Thus, the above MEL and MPP conditions are given, respectively, by

$$I_{ds_{opt}} = \omega_r \sqrt{G_d\left(G_{q1}+G_{q2}\omega_r\right)}\left[\frac{1+T_a^2\omega_e^2}{1+T_b^2\omega_e^2}\right]^{0.25} \quad (6)$$

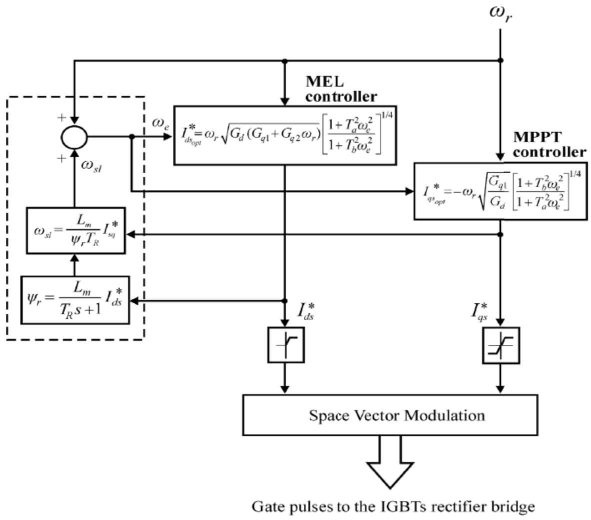

Fig. 4. Control algorithm for the rectifier converter of the optimal efficiency WECS.

and

$$\left|I_{qs_{opt}}\right| = \omega_r \sqrt{\frac{G_{q1}}{G_d}}\left[\frac{1+T_b^2\omega_e^2}{1+T_a^2\omega_e^2}\right]^{0.25} \quad (7)$$

To maximize the efficiency of the whole WECS by minimizing the SCIG's electric losses and attaining MPPT in the wind turbine, the respective optimal conditions of (6) and (7) should be simultaneously satisfied. In Fig. 4, the control algorithm flowchart of the optimal efficiency controlled WECS is provided.

4 WECS yaw control

In case of a yaw angle error γ, the aerodynamic coefficient of the wind turbine is reduced as given below

$$C_p(\lambda,\beta,\gamma) = C_p(\lambda,\beta)\cos^h\gamma \quad (8)$$

where h is a parameter with typical values 2.0-3.0, depending on the wind turbine construction [22].

The relationship between the power of the wind turbine under yaw error P_{wt_γ} and the power of the aligned turbine to the wind direction $P_{wt_{opt}}$ is given by

$$P_{wt_\gamma} = P_{wt_{opt}}\cos^h\gamma \quad (9)$$

and after several mathematical manipulations, it results that the wind turbine speed under yaw error in respect to the optimal speed of MPPT control when the turbine is aligned to the wind direction is

$$\omega_{r_\gamma} = \omega_{r_{opt}}\cos^{h/3}\gamma \quad (10)$$

and thus, the yaw angle can be determined by [20]

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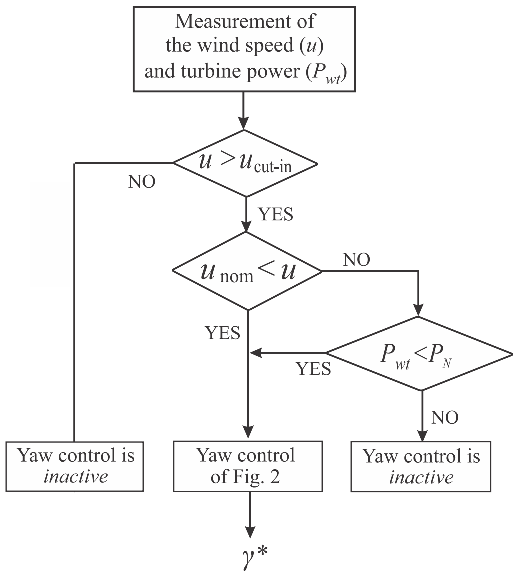
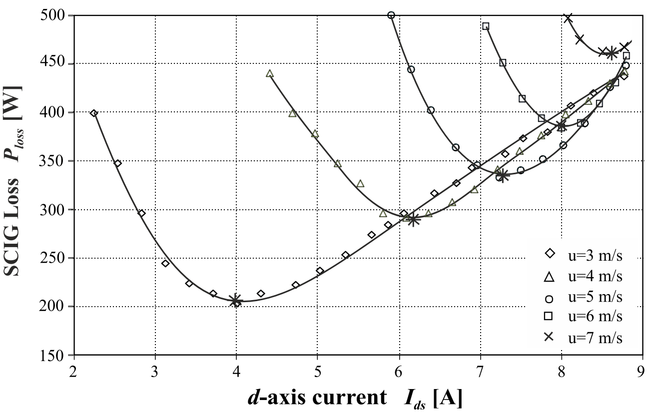
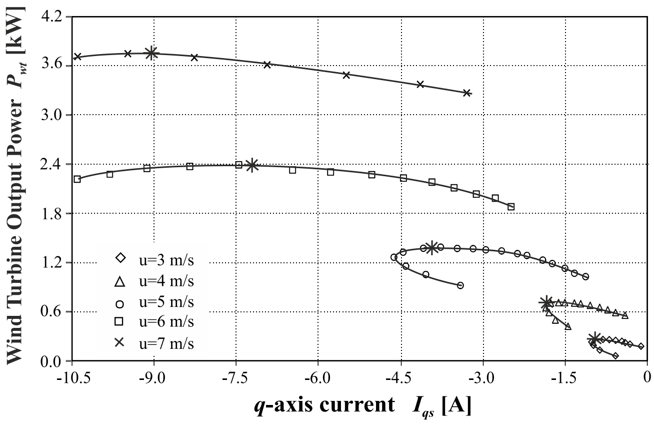


Fig. 5 Flow chart of the yaw control algorithm.



(a)



(b)

Fig. 6 Variation of: (a) SCIG loss versus I_{ds} stator current for various wind speeds (at each wind speed, the generator rotor speed corresponds to maximum power of the wind turbine) and (b) wind turbine output power versus I_{qs} stator current of the SCIG for various wind speeds (I_{ds} stator current is equal to the nominal value).

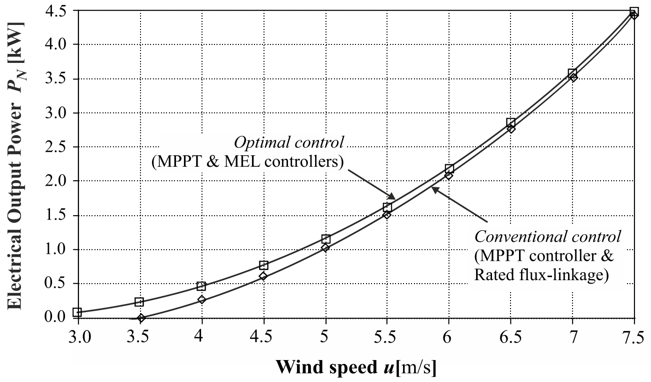


Fig. 7 Comparison of the electrical output power versus wind speed of the WECS with the proposed scheme against the conventional control system.

TABLE 1

3-PHASE, 10-kW, SCIG AND OPTIMAL CONTROLLER PARAMETERS

V_s= 400 V (rms)	I_s= 21 A (rms)	
f_e= 50 Hz	$2p$= 4 (number of poles)	
R_s= 0.7 Ω	R_r= 1 Ω	
L_m= 0.2 H	L_{ls}= 0.01 H	L_{lr}= 0.01 H
G_d= 1.558	G_{q1}= 2.23·10^{-2}	G_{q2}= 2.9·10^{-4}
T_a= 2.51·10^{-3}	T_b= 1.82·10^{-2}	

$$\cos\gamma = \left(1 - \frac{\omega_{r_{opt}} - \omega_{r_\Upsilon}}{\omega_{r_{opt}}}\right)^{3/h} \tag{11}$$

where ω_{r_Υ} is the real shaft speed of the turbine commanded by the condition (7) and $\omega_{r_{opt}}$ is the optimal speed of the shaft with which the turbine should operate. The condition (11) can be considered as the optimal condition that the yaw controller should realize.

Note that the yaw controller operates only when the wind speed is lower than the nominal value and greater than the cut-in value. The operation of the yaw control algorithm is described in Fig. 5.

5 BSS in the WECS

A dual role has the BSS in the proposed optimal efficiency WECS, on the one hand to smooth the generated energy and power and on the other hand, to maintain constant the dc-link voltage. Thus, it can offer ancillary services for keeping constant the frequency and voltage of the electric microgrid propulsion system and moreover, to enhance the fault-ride through capability of the WECS [21].

The dc-link voltage is regulated through the proper control of the DC/DC converter. The BCC can be realized with Li-ion batteries or supercapacitors since they provide satisfactory dynamic performance, high energy density, and high discharge/charge current capability.

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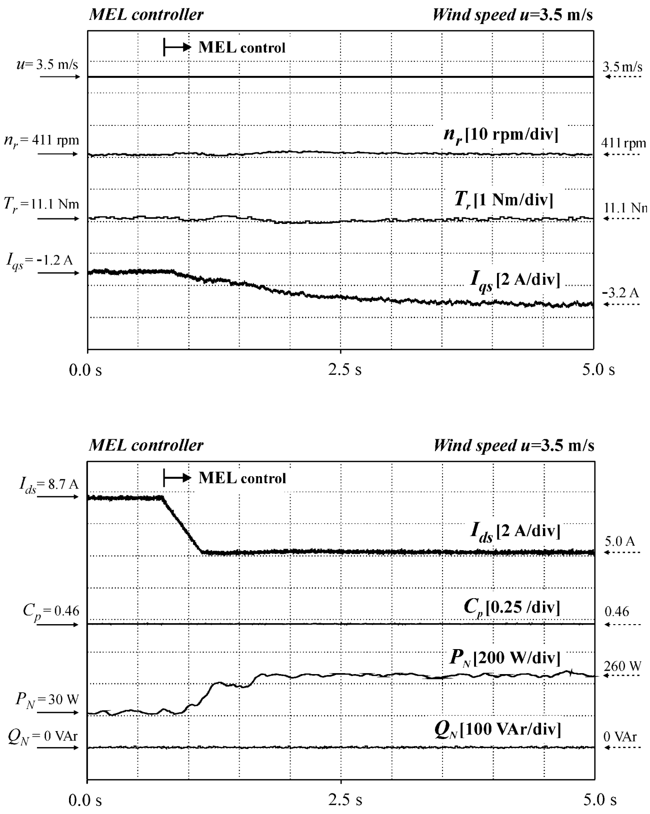

Fig. 8 Response of a 10kW WECS-BSS when the MEL controller is activated at 1.2s.

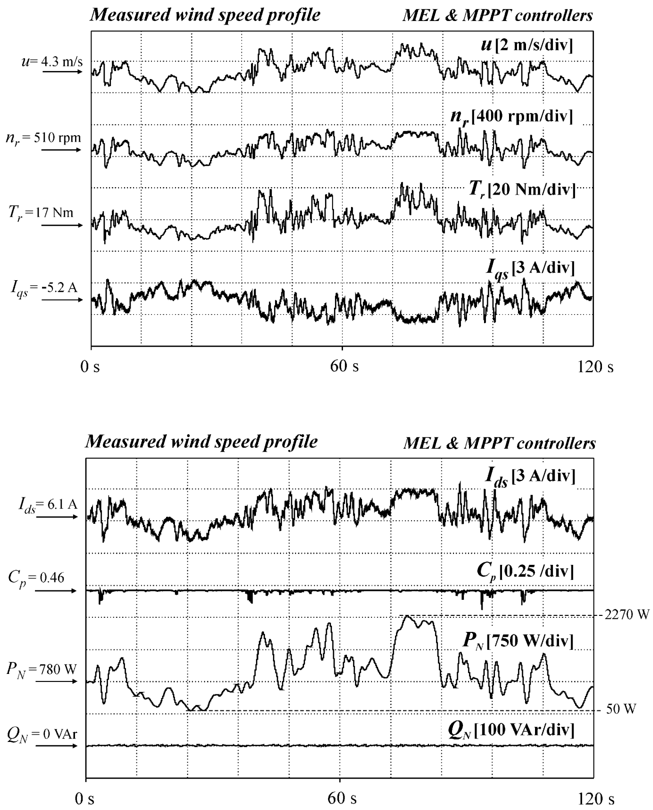

Fig. 9 Performance of a 10kW WECS-BSS when both MEL and MPPT controllers are active.

6 Simulation analysis

The MATLAB/Simulink program has been used to validate the effectiveness of the proposed integrated WECS with SCIG and BSS. The technical characteristics of the WECS-SCIG and the parameters of the optimal controllers are provided in Table 1. The gear-box ratio is 5.2.

The existence of the optimal d- and q-axis stator currents that through them can be attained maximum efficiency of the WECS are shown in Fig. 6. As can be seen, there is a specific value of the I_d and I_q for each wind speed that can provide minimum electric losses of the SCIG as well as MPPT for the wind turbine, respectively. These values are that determined by the optimal conditions (6) and (7) of the MEL and MPPT controllers, respectively.

The improvement of the WECS efficiency is verified in Fig. 7 which compares the variation of the electrical output power of the WECS with the proposed control scheme against that of the conventional control system where the SCIG operates with rated flux-linkage and the wind turbine with MPPT. As can be seen, higher power increase is attained with the proposed system at low wind speeds, since for this wind speed region higher loss reduction can be achieved. Also, the cut-in wind speed has been reduced with the proposed system and therefore, the WECS can start to supply electric energy to the ship's microgrid at lower wind speed (less than 3.0m/s for the proposed system against the cut-in wind speed of 3.5m/s for the conventional system). Therefore, the efficiency improvement is attained from both reduction of the electric loss and increase of the wind speed operating range towards the region of lower wind speeds.

The response of the tested 10kW WECS with BSS when the MEL control is activated at 1.2s is presented in Fig. 8. Specifically, at wind speed 3.5m/s (which is close to the cut-in speed), the wind turbine initially operates with MPPT and when the MEL controller is activated at 1.2s, it finds very quickly (less than 0.5s) the optimal value of the d-axis current. Thus, the generated power by the WECS P_N is increased from 30W to 260W. The aerodynamic coefficient C_p remains constant at the optimal value of 0.46 as well as the rotor speed at 411 rpm, since maximum power harvesting of the wind is attained through the MPPT controller.

The performance of the whole WECS-BSS scheme in a real wind speed profile that has been obtained by measurements is shown in Fig. 9. The wind speed fluctuates between 3.0÷6.6 m/s and the generated electric power by the WECS ranges 50 to 2270 W. The combined

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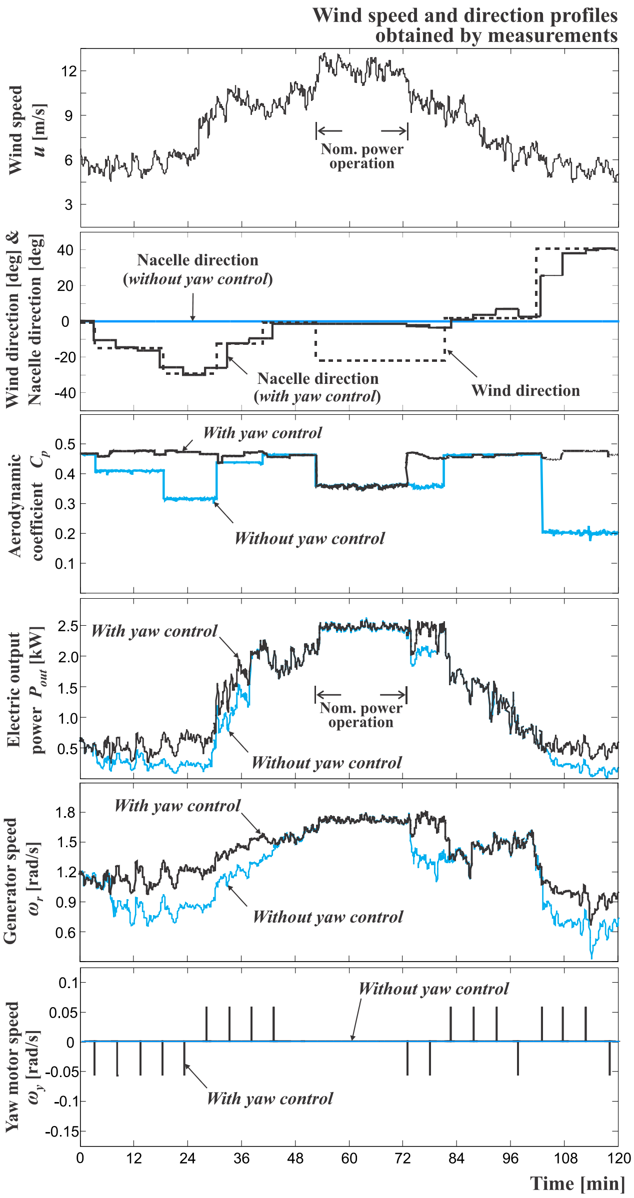

Fig. 9 Comparison of the WECS-SCIG performance with the proposed yaw control system and without yaw control. The wind speed and direction profiles have been obtained by measurements.

scheme of MEL and MPPT optimal controllers satisfactorily follow the wind speed variations by simultaneously providing the optimal d- and q-axis currents as that determined by the (6) and (7) optimal conditions to provide maximum efficiency in the WECS.

The satisfactory operation of the yaw control system is validated in Fig. 10 that compares the performance of the proposed yaw system with that of without yaw control. As you can see, the proposed yaw control system satisfactorily cooperates with the optimal efficiency system of the WECS-SCIG and correctly aligns the nacelle to the wind direction for any wind speed value in the range of greater than cut-in and lower than the nominal wind speed. The nacelle direction of the cases of with and without yaw control is shown in the 2nd diagram of Fig. 10 and the yaw motor speed controlled by the proposed yaw system is given in the 6th diagram

The aerodynamic coefficient is close to the optimal value of 0.46, except for the case of high wind speed (greater than the nominal value), where the yaw control method is inactive because the rotor speed does not operate with MPPT. In the 5th diagram of Fig. 10, it is depicted the misleading of the MPPT control for the case of without yaw control against the correct MPPT control with the proposed yaw system. Thus, due to the yaw control and the combined scheme of MEL and MPPT, the generated electric energy is higher than that of without yaw control (4th diagram of Fig. 10).

It is worth noting that the proposed yaw control is realized without requiring direct measurement of the wind direction, but indirectly through the rotor speed. Thus, there is no need for additional hardware and consequently, the cost of the wind system has not been increased. This means that the suggested yaw control system can be applied even to low cost WECS and therefore to small ships.

7 Conclusions

This paper examined the advantages of adopting environmentally friendly energy sources to power the electric microgrid system of a ship. Specifically, the case of using wind energy for ship propulsion was studied. A combined scheme of a wind energy conversion system (WECS) with a squirrel cage electric generator and a battery storage system (BSS) has been utilized. The proposed control system can enhance the efficiency of the WECS by minimizing the electric loss of the generator and attaining maximum energy harvesting by the wind. This can be accomplished by the MEL and MPPT controllers that regulate the d- and q-axis stator current of the electrical generator, respectively

Moreover, a yaw control system has been proposed that can cooperate with the MEL and MPPT controllers to correctly align the wind turbine to the wind direction. For the implementation of both MEL and MPPT as well as yaw controllers, no additional hardware is required and thus, the proposed control scheme can be effectively applied even to low cost WECS.

The BSS consists of Li-ion batteries properly controlled by an energy management system so that maximum utilization of the generated energy by the wind is accomplished and also, smooth power and energy performance of the ship's electric microgrid is ensured by absorbing any potential fluctuations of electric energy generated by the wind turbine and electric loads on board. The effectiveness of the suggested combined scheme of WECS-BSS with yaw control for ship applications has been validated through simulations in MATLAB/Simulink environment and selective simulation results are provided to demonstrate the attained operating improvements.

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