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## **HABILITATION THESIS**

**HYBRID MARINE POWER SYSTEMS BASED ON  
RENEWABLE SOURCES: MODELING, CONTROL,  
AND PERFORMANCE EVALUATION**

**ABSTRACT**

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The habilitation thesis presents the main professional achievements of Assoc. Prof. PhD Eng. Florentiu Deliu. Entitled “Hybrid Marine Power Systems Based on Renewable Sources: Modeling, Control, and Performance Evaluation”, the habilitation thesis aims to highlight the multi-applicative character of the author’s research work, in which electrical engineering provides solutions to technical and scientific problems with a broader scope—problems that align with current concerns of the academic community. At the same time, the thesis outlines directions for continuing research activity from the perspective of structuring topics for future doctoral dissertations. First and foremost, it presents an integrative approach to modern hybrid energy systems, with the objective of investigating and modeling transient phenomena occurring in electrical equipment supplied from multiple sources, both renewable and conventional, under conditions of rapid power variations, operating mode switching, and external disturbances. The analysis of these phenomena focuses on quantifying the dynamic interactions among static converters, energy storage systems, and the grid; assessing electromechanical and thermal overloads; and determining transient stability conditions, with the aim of increasing the reliability and durability of electrical equipment. Additionally, the author’s contributions to the integration of photovoltaic systems with storage (PV–BESS) into marine electrical architectures may be highlighted, representing a strategic component. This topic is addressed through the development of averaged dynamic models and advanced harmonic analysis tools capable of capturing the impact of static power conversion on power quality and distribution losses. Another area of the author’s research concerns the optimization of control strategies for horizontal-axis wind turbines (HAWT) operating under high wind conditions. This approach focuses on maintaining stable operation through the development of advanced pitch angle and rotor speed control strategies aimed at limiting mechanical stresses and stabilizing the power delivered to the grid. This research direction involves the integration of aeroelastic modeling with electromechanical dynamic analysis and the implementation of adaptive control algor

The thesis is structured into five chapters and includes a list of bibliographic references at the end of each chapter, consisting of sources relevant to the topics addressed.

**The first chapter** presents the candidate’s professional career path, listing the courses and laboratory/seminar activities he has taught as course coordinator or instructor. The academic and administrative positions he has held are highlighted. It also outlines the main milestones of his scientific activity, including his involvement as a member of editorial boards of specialized journals, organizing committees of scientific events, and as a reviewer for numerous scientific publications.

**The second chapter** summarizes the author's research in the field of theorizing aspects related to the integration of renewable energy sources on board ships, which involves combining several components—typically wind turbines, photovoltaic panels, and a conventional Diesel generator—under a unified energy management system.

The issues related to the integration of hybrid renewable energy systems on board ships are addressed from theoretical, applied, and experimental perspectives, with the main objective of developing a unified framework for mathematical modeling, dynamic analysis, and performance optimization of Diesel–Wind–Solar marine power architectures. The current context of the energy transition and the regulations imposed on the maritime sector regarding the reduction of greenhouse gas emissions require the identification of sustainable solutions capable of simultaneously ensuring energy efficiency, operational reliability, and dynamic stability under variable operating conditions. Furthermore, aspects related to the integration of renewable sources into marine power systems are substantiated through the development of detailed mathematical models for the main subsystems: the marine wind turbine, the photovoltaic array, the power converter, the electrical storage system, the Diesel engine, and the synchronous generator—both in the version with direct-current excitation and in the permanent magnet configuration. The analysis is carried out in a coherent manner, starting from the mechanical and electromagnetic characteristics of each component and continuing with the study of the dynamic interactions among them within a triple-integrated marine power system.

The modeling of the Diesel engine is carried out by deriving the parabolic mechanical characteristic as a function of rotational speed and fuel flow rate, with both steady-state and transient operating regimes analyzed in correlation with variations in the ship's electrical load. It is emphasized that electromagnetic processes are significantly faster than mechanical ones, which allows for the analytical separation of electrical dynamics from mechanical dynamics in the study of transient phenomena.

In the case of the marine wind turbine, the cubic dependence of the developed power on wind speed is demonstrated, and the operating conditions corresponding to the maximum power point are determined. Mathematical relationships for the turbine torque are established, and the stability of the wind subsystem is analyzed, highlighting the existence of multiple operating points when a permanent magnet synchronous generator is used. By applying classical stability criteria and analyzing the motion equation, the stable or unstable nature of these operating points is demonstrated as a function of load resistance and the electromagnetic parameters of the generator.

An important contribution of the work consists in the analysis of the demagnetization phenomenon of permanent magnets in synchronous generators, a phenomenon that may occur at certain values of the d-axis magnetizing current. The mathematical conditions under which the magnetic flux may be significantly reduced are established, with implications for the generator's performance, efficiency, and operational safety. The stator flux may cancel the permanent magnet flux, leading to loss of excitation and the impairment of generator operation. The issue of permanent magnet sizing to achieve a unity power factor is also addressed, with overexcited and under excited operating regimes analyzed through phasor diagrams and numerical examples.

The photovoltaic subsystem is examined from the perspective of the photoelectric effect and its external characteristics, with particular attention given to the variation of the maximum power point as a function of solar irradiance. The necessity of employing DC–DC converters equipped with maximum power point tracking (MPPT) algorithms—aimed at maximizing the  $U \cdot I$  product—is demonstrated, ensuring that the solar system continuously operates at its maximum power point despite meteorological fluctuations. A comparison is made between fixed photovoltaic systems and systems equipped with solar tracking mechanisms, demonstrating the energetic superiority of mobile solutions. This aspect is particularly relevant for marine applications, where the platform itself is inherently mobile.

The DC–DC converter is modeled through equations describing the switching regime, energy storage in reactive elements, and the relationship between input and output voltage. The conditions for inductance sizing are determined, and power conservation under ideal operating conditions is analyzed, emphasizing the influence of current ripple on voltage variation and on the energetic stability of the direct current bus.

The modeling of electrical storage systems is carried out using an equivalent circuit dependent on the state of charge, temperature, and current. Chemical and polarization resistances are analyzed, as well as the behavior at high frequencies. The importance of pulsed supply is highlighted for reducing polarization resistance and optimizing charge–discharge cycles under conditions of rapid wind energy fluctuations.

Based on these models, Chapter 2 demonstrates the feasibility of integrating hybrid systems on board ships and highlights their major advantages: reduced fossil fuel consumption, increased energy autonomy, and improved supply reliability. It is shown that the use of storage systems enables the Diesel engine to operate within its maximum efficiency region, reducing sensitivity to load fluctuations and optimizing specific fuel consumption.

At the same time, the challenges associated with the implementation of these systems are critically examined, including technological complexity, the necessity of advanced control algorithms to ensure voltage and frequency stability, as well as risks related to permanent magnet demagnetization and severe marine operating conditions.

In conclusion, the work provides a rigorous theoretical and practical framework for the design and analysis of hybrid marine power systems, integrating advanced mathematical modeling, stability analysis, and the optimization of operation at maximum power points. The results obtained confirm the potential of Diesel–Wind–Solar systems to enhance energy efficiency and to support the transition toward sustainable maritime transport, grounded in solid scientific research and experimental validation.

**The third chapter** analyzes the integration of photovoltaic systems with electrochemical storage into marine power architectures, with the primary objective of dynamic modeling, evaluation of transient and harmonic performance, and stability analysis of DC–DC converters operated with global maximum power point tracking (GMPPT) strategies. The context of the study is defined by increasingly stringent requirements for reducing fuel consumption and pollutant emissions in the maritime sector, as well as by the need to enhance the resilience of onboard electrical systems. The integration of photovoltaic energy, correlated with battery storage systems, represents a viable solution for supplementing conventional Diesel generators, contributing to the stabilization of the DC bus and to increasing the share of renewable energy in the marine energy mix.

The chapter highlights that the marine environment introduces significant variability in solar irradiance, caused by atmospheric conditions and shading generated by the ship's superstructures. This leads to continuous modification of the current–voltage and power–voltage characteristics of the photovoltaic generator. Under uniform irradiance conditions, the power–voltage curve exhibits a single internal maximum corresponding to the maximum power point, determined formally by imposing the condition that the derivative of power with respect to voltage equals zero. In contrast, under partial shading conditions, multiple local maxima may occur. Classical algorithms such as Perturb and Observe or Incremental Conductance may converge to a local maximum, which justifies the adoption of a global maximum power point tracking strategy based on systematic scanning of the characteristic curve. This approach enables the identification of the global maximum with high tracking efficiency and reduced stabilized

The analyzed architecture includes a photovoltaic source, a controllable DC–DC converter, an energy storage element, and a DC bus, with the possibility of incorporating an

inverter for the AC interface. The DC–DC converter plays a key role in positioning the operating point of the photovoltaic generator within the MPP or GMPP region and in managing the bidirectional energy flow among the panel, the battery, and the load. Several topologies are examined, including classical buck and boost structures, high-gain bidirectional converters with dual PWM control, three-level and three-port configurations, as well as soft-switching architectures. It is emphasized that the choice of topology significantly influences current ripple, semiconductor device stress, transient performance, and the harmonic content of the overall system.

For system-level analysis, the author employs averaged dynamic models that eliminate switching-frequency modulation while preserving the dominant dynamics and power balance at the port level. These models enable efficient simulation of irradiance variations and control loop interactions without excessive computational costs. For the evaluation of harmonic content and steady-state performance, a switched PWM-level model is subsequently used, within a two-stage simulation workflow that separates transient analysis from harmonic analysis.

The transient study investigates the system response to a step variation in solar irradiance, demonstrating that the tracking algorithm restores operation in the vicinity of the new maximum power point, while the battery port current transitions toward the value imposed by the power balance. The evaluated performance indicators include settling time, maximum overshoot, and steady-state ripple. The results confirm the suitability of the averaged model for analyzing dominant dynamics and highlight the robustness of the GMPPT strategy under variable operating conditions.

The harmonic analysis is performed through Fourier decomposition of the current over steady-state time windows, determining indicators such as individual harmonic distortion and total harmonic distortion (THD) of both current and voltage. It is observed that the total harmonic distortion of the current increases as irradiance decreases, since the fundamental component diminishes more rapidly than the lower-order harmonics, whereas voltage distortion remains relatively constant in a stiff grid. This increase in current THD leads to higher conductor losses, as ohmic losses are proportional to the square of the total RMS current, which includes harmonic contributions.

The harmonic behavior is explicitly correlated with distribution losses, analyzing losses in transformers, conductors, and dielectric components. It is demonstrated that a moderate increase in THD results in a proportional increase in losses, thereby affecting the overall efficiency of the system. To reduce losses and improve the voltage profile, the application of

reactive power control policies dependent on active power scenarios is proposed, along with the use of advanced monitoring infrastructures for in-service validation of performance indicators.

The evaluation of stability and ride-through capability is carried out using a hybrid methodology that combines averaged modeling for preliminary analysis with electromagnetic-type simulations for fault conditions. Variations in irradiance, step changes in load, and faults at the point of common coupling are analyzed, with indicators such as the critical fault clearing time and stability margins being estimated. The influence of DC bus inductance and capacitance, control bandwidth, and the adopted MPPT strategy on overall system robustness is highlighted.

In conclusion, it is demonstrated that a photovoltaic–battery subsystem, designed on the basis of averaged dynamic modeling, equipped with a robust GMPPT strategy, and integrated within a coherent framework of harmonic analysis and reactive power optimization, can ensure efficient, stable operation compliant with power quality requirements in marine applications or grid-connected configurations. The study thus provides a comprehensive methodological framework that correlates modeling, simulation, sizing, and operational monitoring of PV–BESS systems under real dynamic conditions.

**Chapter four** presents contributions to the development of advanced adaptive and fixed-gain control strategies for constant-speed and constant-power operation of horizontal-axis wind turbines, with emphasis on the operating regime above rated wind speed. The research is motivated by the need to enhance the resilience and reliability of wind energy systems in the context of stochastic wind variability and the stringent requirements imposed by modern power grids regarding stability and delivered power quality. Within this framework, blade pitch angle control represents the primary mechanism for power regulation and mechanical load mitigation when wind speed exceeds its nominal value.

The starting point of the research is the mathematical modeling of a 2.5 MW three-bladed wind turbine, for which the mechanical power extracted from the wind is described by standard aerodynamic relationships involving air density, rotor radius, wind speed, rotor angular speed, and the power coefficient dependent on the tip-speed ratio and pitch angle. The tip-speed ratio is defined as the ratio between the blade peripheral speed and the wind speed, while the power coefficient is modeled using a parametric expression widely adopted in the specialized literature. In addition to the theoretical model, an empirical relationship identified from the experimental data of the analyzed unit is employed, enabling a continuous and realistic representation of the power surface as a function of wind speed, rotor speed, and pitch angle.

The analysis of the power surface highlights the existence of a locus of maximum power points, determined by setting the partial derivative of power with respect to rotor angular speed equal to zero. This leads to an implicit relationship showing that the optimal rotational speed is proportional to wind speed and dependent on the pitch angle through the aerodynamic power coefficient. This dependence confirms that rotor speed and pitch angle cannot be treated independently, but must be coordinated within an integrated control strategy. Increasing the pitch angle results in a reduction of the power coefficient and a shift of the maximum point of the power curve toward lower values, forming the basis of the aerodynamic limiting mechanism employed in Region 3 operation (above rated wind speed).

Within the chapter, two fundamental strategies for operation above rated wind speed are compared: maximum power point tracking under a power cap constraint and constant-speed operation with excess energy dissipated exclusively through pitch angle control. In the case of the first strategy, the simultaneous solution of the maximum power condition and the grid-imposed power limit leads to a significant increase in rotor speed as wind speed rises. This behavior generates additional mechanical stresses and potential stability risks. Numerical analysis shows that for wind speeds of 14, 16, and 18 m/s, both the pitch angle and the angular speed increase almost linearly. At higher wind speeds, the rotor speed may reach undesirable levels from the standpoint of structural integrity and dynamic stability.

In contrast, the constant-speed strategy maintains the rotor speed at its nominal value and adjusts the pitch angle so that the delivered power remains limited to the grid-imposed cap. The results show that, under this regime, the increase in wind speed is fully compensated by increasing the pitch angle, while the angular speed remains constant. The dependence of the pitch angle on wind speed is monotonically increasing and more pronounced than in the case of MPP operation under a power cap, reflecting the fact that excess energy dissipation is achieved exclusively through the reduction of the aerodynamic power coefficient. This approach reduces mechanical stresses on the shaft and gearbox and improves system robustness under turbulent wind conditions, representing the standard industrial solution.

In the dynamic control section, the work investigates the closed-loop behavior of the turbine in the presence of a sinusoidal variation in wind speed, defined around a mean value and characterized by a frequency correlated with the electromechanical time constant of the system. This choice enables excitation of the system within a frequency range relevant to the interaction between aerodynamic and electromechanical dynamics. The closed-loop model is based on the angular momentum balance equation, which correlates aerodynamic torque, generator torque, and rotor acceleration. Pitch angle control is implemented using a PID-type

structure, with the analysis focusing on the comparison between purely proportional feedback and proportional–integral (PI) regulation.

When only proportional control is employed, simulations reveal a significant overshoot of the reference speed, approximately 14.37%, indicating insufficient damping and high sensitivity to periodic disturbances. The introduction of the integral component eliminates the steady-state error and drastically reduces the overshoot, the maximum speed deviation being reduced to approximately 0.23% around the optimal value. At the same time, pitch angle variations remain within practical limits, confirming the effectiveness of the PI structure in stabilizing the system in Region 3 (above rated wind speed). The work also highlights the systemic implications of the interaction among the turbine, the power converter, and the grid, noting that variations in grid parameters may influence overall stability. The robustness observed with respect to wind oscillations supports the need for a dedicated robustness analysis under conditions of electrical uncertainty. Future research directions are outlined, including the integration of adaptive mechanisms, short-term power prediction using neural network-based methods, and the periodic re-identification of the aerodynamic surface in the context of blade degradation.

In conclusion, the chapter formulates and validates a practical control strategy for a 2.5 MW HAWT, demonstrating the superiority of the PI controller over simple proportional control and justifying the adoption of constant-speed operation with exclusive pitch-based dissipation for load limitation and constant power maintenance. The study provides a rigorous framework for optimizing wind turbine operation under highly variable high-wind conditions and lays the groundwork for integrating adaptive and predictive strategies aimed at enhancing the stability and performance of modern wind energy systems.

**The fifth chapter** highlights the main conclusions, guiding principles, and objectives of the future activity of the author of the habilitation thesis. The research themes reviewed on this occasion demonstrate significant potential for further development within doctoral dissertations and/or research grants. Teaching and scientific research activities, viewed as mutually supportive and interdependent, will be grounded in the following general principles and objectives aimed at advancing the academic career:

- Maintaining and enhancing the prestige of the department and faculty through professional activity aligned with the latest trends and developments in the international academic environment, in accordance with the strategic plans of the “Mircea cel Bătrân” Naval Academy;

- Increasing the integration of teaching and research activities by actively involving undergraduate, master's, and doctoral students in research and development projects with scientific, technical, and economic impact;
- Strengthening collaboration among members of the department and faculty, as well as with other specialists from Romania and abroad, in order to improve efficiency in both educational and research activities.

The principles and objectives mentioned above will be implemented in the educational domain through the following objectives that I intend to pursue:

- Continuous improvement of the educational process in accordance with changes in curricula, as well as with the needs of the economic environment in which the beneficiaries of this process will carry out their professional activity;
- The use of interactive teaching methods aimed at the direct involvement of undergraduate, master's, and doctoral students in the delivery of courses and related practical activities, in order to ensure intuitive and effective assimilation of the taught content;
- The introduction of evaluation methods that emphasize the acquisition of competencies rather than the mere accumulation of information;
- Guiding students and master's candidates to self-assess the competencies and knowledge acquired through the educational process;
- Delivering curricular content in a balanced manner between theory and practical applications, with the latter selected to illustrate technical requirements specific to the faculty and its study programs;
- Establishing continuous feedback mechanisms for the progressive adaptation and improvement of teaching methods and content delivery.

In concrete terms, in the short and medium term, I intend to pursue the following objectives:

- Drafting a problem collection dedicated to electrical machines, which will include a significant number of proposed problems together with their corresponding detailed solutions;
- Finalizing and publishing a monograph dedicated to renewable energy sources, which will integrate—alongside advanced theoretical developments concerning the conversion and integration of renewable energy (photovoltaic, wind, and hybrid systems)—an extensive set of illustrative applications and case studies relevant to the design, modeling, and optimization of modern energy systems. The work will have a strong didactic and formative character, addressing directly undergraduate and master's

students in electrical engineering, while also providing valuable methodological support for doctoral candidates and specialists interested in dynamic analysis, grid integration, and performance optimization of renewable sources in industrial contexts and smart infrastructures;

- Updating and expanding the course materials already published online for the subjects for which I am course coordinator, in accordance with recent developments in the specialized literature, as well as with feedback received from students, doctoral candidates, and colleagues.
- The development and implementation of interactive laboratory activities dedicated to the analysis of power flows in integrated three-phase systems, including electrical machines and renewable energy sources, operated under conditions of unbalance and harmonic distortion, with a focus on transient regimes and their influence on the dynamic performance of generators and power converters;
- Proposing bachelor's and master's thesis topics that are highly relevant and useful to graduates from the perspective of their current or desired professional positions.

The principles and objectives outlined above will be materialized through the following activities:

- Proposing research topics within internal competitions initiated by the Ministry of National Defence and UEFISCDI, as well as by other governmental bodies or entities from the industrial and business sectors; external competitions, such as those launched by agencies of the European Union, will also be considered;
- Selecting research themes with tangible impact on the economic environment, aimed at developing new industrial products or improving the performance of existing ones;
- Involving undergraduate, master's, and doctoral students—according to their skills and interests—in high-value research and innovation activities, with outcomes suitable for publication in leading journals or major international conferences;
- Establishing collaborations with national and international partners capable of contributing innovative elements to both theoretical and applied research.

The pursuit of these objectives will materialize through the further development of the main research directions detailed in this habilitation thesis, which may be synthesized as follows:

- The development of multi-physical electromagnetic models for electrical machines used in wind and hybrid applications, capable of simultaneously capturing electromagnetic field effects, thermal phenomena, and mechanical stresses;

- Deepening the analysis of the interaction between electrical machines (permanent magnet synchronous generators and induction generators) and power converters within photovoltaic, wind, and hybrid architectures;
- The study of methods for improving power quality, taking into account emerging phenomena that affect modern electrical networks;
- The development of new modeling and analysis methods for adaptive and predictive control strategies applied to wind generators;
- The development of methods for optimizing the overall efficiency of the conversion–storage–distribution chain;
- Participation in highly prestigious scientific events in the country and abroad, as well as involvement as a member of scientific and organizing committees of such events, enabling direct engagement with current research topics and emerging scientific directions;
- Undertaking documentation visits or exchange programs at academic institutions and industrial organizations to enhance professional expertise;
- Continuing activity as a reviewer for specialized publications and scientific events both nationally and internationally.

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