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On fault diagnosis, fault resilient control, and smart energy management for renewables-based microgrid optimal operation

Elhoussin Elbouchikhi

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HABILITATION A DIRIGER DES RECHERCHES DE

L'UNIVERSITE
DE BRETAGNE OCCIDENTALE

COMUE UNIVERSITE BRETAGNE LOIRE

Par

Elhoussin ELBOUCHIKHI

**On fault diagnosis, fault resilient control, and smart energy management
for renewables-based microgrid optimal operation**

HdR présentée et soutenue à Brest, le 08 juillet 2020

Unité de recherche : ISEN Yncréa Ouest, IRDL, UMR CNRS 6027

Rapporteurs avant soutenance :

Corinne ALONSO

Professeur des Universités, Université de Toulouse III
Paul Sabatier/LAAS

Demba DIALLO

Professeur des Universités, Université Paris-
Saclay/GeePs

Xavier ROBOAM

Directeur de Recherche CNRS, LAPLACE, Toulouse

Composition du Jury :

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Franche-Comté/FEMTO-ST, directeur du FCLAB

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Ali KHENCHAF, Professeur des Universités, UBO /ENSTA, LabSTICC,
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Ayman AL FALOU, Professeur ISEN Yncréa Ouest, ISEN Yncréa
Ouest, Brest

Mohamed BENBOUZID, Professeur des Universités, Université de
Bretagne Occidentale, Brest

Abstract

This HdR manuscript summarizes my teaching activities, main research contributions and publications, PhD students supervising, and scientific services and responsibilities. These teaching and research activities have been carried out since 2013 and have been performed as associate professor at ISEN Yncréa Ouest, Brest campus and a research scientist at IRDL (Institut de Recherche Dupuy de Lôme), UMR CNRS 6027, Brest since 2016.

This manuscript is organized as follows. Part I presents my Curriculum Vitae, teaching and research activities, national and international services, and main experimental platforms with education and research capabilities. Part II focuses on main research topics synthesis. Three research contributions have been highlighted: faults diagnosis and fault tolerant control of electric machines and drives and energy management system for microgrids with high rate of renewable resources. Part III describes perspectives and some directions for future research works.

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General introduction

This HDR (Habilitation à Diriger des Recherches) manuscript summarizes my research and teaching activities as an associate professor at ISEN Yncréa Ouest, Brest and a scientist researcher at Institut de Recherche Dupuy de Lôme, IRDL UMR CNRS 6027 since I defended my PhD thesis in November 2013. During my PhD, my research activities focused on condition-based maintenance implementation based on motor current signature analysis (MCSA) for induction motors monitoring. The developed approaches allow faults detection and characterization based on maximum likelihood estimation and a generalized likelihood ratio test for decision making. My PhD thesis manuscript is entitled: “On parametric spectral estimation for faults detection in induction machine for stationary and non-stationary environments”. After my PhD, I joined ISEN Yncréa Ouest, first as a postdoctoral researcher and then as an associate professor since 2014. I was also a member of LBMS laboratory (Laboratoire Brétois de Mécanique et des Systèmes) EA 4325 from 2014 to 2016 and currently a member of IRDL laboratory since 2016.

My research activities after the PhD are focused on renewable energy generation systems and their applications. More precisely, the focus has been made on marine renewable energy sources (specifically, marine currents turbine) modeling, control, and resilience improvement and DC/AC microgrids energy management. These research works can be summarized in three themes:

- **Faults diagnosis of electrical machines and drives:**

The focus has been made on induction motors faults detection and diagnosis based on stator currents analysis. High resolution techniques and parametric spectral estimation techniques have been investigated for faults feature extraction. Moreover, generalized likelihood ratio test has been proposed for decision making.

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An experimental setup has been developed, which allows to prove the effectiveness of the developed approaches on bearing faults and both stator and rotor faults.

– **Fault-tolerant control of electric machines and drives: application to marine renewable energy converters:**

In this research theme, research activities have been conducted in order to improve marine current turbine (MCT) resilience. Fault-tolerant control strategies have been proposed and performance demonstrated for both power converters and permanent magnets synchronous generator faults. Specifically, second-order sliding mode control has been implemented to improve MCT resilience to permanent magnets demagnetization, which may be due to harsh environment, high torque, and speed variations.

– **Energy management system of hybrid power generation systems with high rate of renewables:**

This research area has focused on microgrid energy management systems development. Both DC and AC microgrids has been investigated. More precisely, an islanded marine microgrid has been proposed to supply Ouessant island in Brittany region in France. In fact, a microgrid composed of MCT, photovoltaic panels, battery energy storage system, and small-scale diesel generator has been proposed and an energy management system developed, which allows better energy scheduling while reducing CO_2 emissions and fulfilling technical constraints (network constraints, voltage bounds, power balance, etc.).

The present HDR manuscript is organized as follows:

- **Part I** presents my research and teaching activities, including my Curriculum Vitae, scientific publications, co-advised PhD thesis, local, national, and international scientific responsibilities, research projects and funding and industrial collaborations. This part also describes the developed experimental platforms, which can serve for both research and teaching activities.
- **Part II** is dedicated to the synthesis of my research activities since my PhD, in which:

- **Chapter 1** presents the interest of condition-monitoring of electrical machines in energy production and many other industrial applications. This chapter mainly focuses on induction machine faults detection and diagnosis based on motor current signature analysis (MCSA). Specifically, maximum likelihood estimation and generalized likelihood ratio test are demonstrated to be efficient for eccentricity faults, bearings faults, broken rotor bars defects, and unbalanced stator fault detection and diagnosis.
- **Chapter 2** deals with fault-tolerant control of electrical machines in tidal turbine context. This chapter presents marine currents turbine modeling and main failures including power converters and permanent magnets synchronous generator faults. Permanent magnets demagnetization fault has been simulated based on magnetic equivalent circuit method. Then, the limitations of PI controllers have been highlighted while applied for PMSG control under magnets failure. Followed by the development of a fault-tolerant control strategy using second order sliding mode control approach.
- **Chapter 3** deals with marine renewable energy resources based microgrid. The focus is made on microgrid energy management system development taking into account load profile, available renewable resources and conventional energy generation (diesel generator), grid constraints, energy storage system ageing and degradation, and consumers incentives.
- **Part III** presents a general conclusion and summarizes main research contributions. Several research perspectives are described at last for my future research directions.

INTRODUCTION



PART

Summary of research, scientific,
and teaching activities

Curriculum Vitae

Elhoussin ELBOUCHIKHI

Address : ISEN Yncréa Ouest, 20, Rue Cuirassé Bretagne, 29200 Brest, France
Birthday : Junuarry 1st 1987, Messaghra, Sfassif, Morocco
Nationality : French/Moroccan
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1.1 Current situation

Since 2014 Associate Professor at ISEN Yncréa Ouest, L@ISEN, SEANERGY team,
Department of Energy and Electromechanical systems

- Qualification for the functions of lecturer awarded by the National Council of Universities (CNU), France in 2014 and 2019.
- In charge of first year Master students,
- In charge of project building for financial support application at Brest Métropole and Finistère County Council

Since 2016 Research scientist at Institut de Recherche Dupuy de Lôme (IRDL, UMR CNRS 6027), PTR4 (Pôle Thématique de Recherche): Energy Systems & Thermal Processes

- In charge of diagnosis research team at PT4.

1. CURRICULUM VITAE

1.2 Professional career

Since 2014	Associate Professor at ISEN Yncréa Ouest, Department of Energy and Electromechanical systems Qualification to “Fonctions de Maître de Conférences” by CNU.
Since 2016	Research Scientist at Institut de Recherche Dupuy de Lôme (IRDL, UMR CNRS 6027), PTR4 (Pôle Thématique de Recherche): Energy Systems & Thermal Processes
2013 – 2014	Assistant Professor at ISEN Yncréa Ouest, Brest, LBMS Laboratory EA 4325
2010 – 2013	Contractual PhD Student at University of Brest, IUT of Brest, GEII department (PhD Thesis & 64 hours annual courses)
March to Sept. 2010	Engineer graduation project at Continental Automotive in Toulouse, France. "Switched mode power supply digital control based on FPGA board."
2007-2010	Training periods both at AIRBUS, Laplace Laboratory, and LAAS Laboratory, Toulouse, France.

1.3 Academic education

2010 – 2013	PhD thesis on electrical engineering at University of Brest. Manuscript Title: On parametric spectral estimation for induction machine faults detection in stationary and non stationary environments (Available online - Archives ouvertes) Thesis jury members: <ul style="list-style-type: none">– Prof. MIRAOUI Abdellatif, President of the University of Marrakech, MARRAKECH, MOROCCO– Prof. AUGER François, University of Nantes - NANTES, FRANCE– Prof. MAUSSION Pascal, University of Toulouse - TOULOUSE, FRANCE
-------------	--

1.3 Academic education

- Prof. ANTONINO-DAVIU Jose Alfonso, Polytechnic University of Valencia - VALENCIA, SPAIN
 - Prof. BELOUCHRANI Adel, Professeur, National Polytechnic School of Algiers - ALGER, ALGERIA
 - Prof. Burel Gilles, University of Brest - BREST, FRANCE
 - Dr-HdR. CHARPENTIER Jean-Frédéric, French Naval Academy –LANVEOC POULMIC, FRANCE
 - Prof. BENBOUZID Mohamed, University of Brest - BREST, FRANCE
 - Dr. Choqueuse Vincent, University of Brest - BREST, FRANCE
- 2007 – 2010 Engineer Diploma (Master’s degree) at ENSEEIHT-INPT, Toulouse, France. Department of Electrical and Control engineering
- 2005 – 2007 Preparatory classes for engineering schools, Moulay Youssef high school, Rabat, Morocco.
- 2004 – 2005 Bachelor’s degree, Moussa Ben Nouçair high school, Khémisset, Morocco.

1. CURRICULUM VITAE

Research activities

After my PhD defence, I was hired as a postdoctoral fellow at ISEN (engineering school) in Brest and joined the LBMS EA4325 laboratory (Mechanics and Systems Laboratory of Brest) and more particularly the team “Energy and Electromechanical Systems” whose main research interests are control and diagnosis of complex electromechanical systems.

Since September 2014, I am an associate professor at ISEN Brest, Yncréa Ouest and research scientist at the Dupuy de Lôme Research Institute (IRDL UMR CNRS 6027). I am a member of the PT4 (Pôle Thématique de Recherche): "Energy Systems and Thermal Processes ". Within this team, I am in charge of the diagnostic research topic. My current research interests are focusing on:

- Diagnosis and faults detection of rotating electrical machines (both electrical and mechanical defects) through electrical signals analysis and more precisely the stator currents,
- Fault-tolerant control in marine renewable energy systems context (Marine Currents Turbine),
- Design, optimization, and energy management of hybrid power generation systems with high rate of renewable energies.

2.1 Summary of research activities

2.1.1 Faults detection and diagnosis of electrical machines

The objective of the research activities in this topic is to propose reliable and efficient techniques to detect and characterize electromechanical systems defects at an early stage and thus take actions before the system catastrophic shutdown. The main application

2. RESEARCH ACTIVITIES

of these research activities is marine renewable energies (MREs) such as offshore wind turbines and tidal turbines. The most effective way to minimize maintenance costs and decrease the failure rates of MREs and their subsystems is to build more robust and reliable systems. Moreover, the focus should be made on the design of real-time monitoring systems and promote condition-based maintenance. The interest of diagnosis and real-time monitoring of these systems is to improve their availability, reliability, and robustness and value preventive maintenance compared to corrective maintenance. This should contribute to make MREs systems more competitive than conventional energy sources, mainly nuclear power and fossil fuels.

This research topic focuses on the use of electrical signals measurement, mainly stator currents, to detect mechanical and/or electrical faults. Advanced signal processing techniques are used to extract the frequencies, signature of the faults, based on the stator currents measurement. These signatures allow to characterize the fault in terms of failing component (each faulty component is characterized by the rise of the amplitude of specific frequency components in currents spectrum) and in terms of fault severity. Furthermore, techniques based on detection theory, particularly the generalized likelihood ratio test, have been proposed in order to perform an automatic fault detection and diagnosis.

This research topic has been carried out during the PhD thesis of **Mr. Youness Trachi**. He has particularly focused on the detection and diagnosis of failures by stator current analysis in asynchronous machine drives. Based on previous works, a signal model in the presence of a fault is presented. To estimate the model parameters, a statistical technique based on the Maximum Likelihood and an approach based on the signal/noise subspaces (MUSIC / ESPRIT) were studied. In order to achieve the automatic decision-making step, the detection problem was formulated as an hypothesis test and was solved based on the Generalized Likelihood Ratio Test. These techniques have been developed to analyse the stator currents in stationary and non-stationary environments to detect both bearing faults and broken-rotor bars. This work has been published in 2 international referred journals [4, 5] and 3 international refereed conferences [6, 7, 8].

2.1.2 Fault-tolerant control in marine currents turbine context

My research activities in this field are interested in marine energy conversion systems fault-tolerant control. Even if the potential for electricity generation from marine currents

is estimated at 100 GW worldwide, the tidal energy conversion systems are still emerging technologies and have not yet experienced much integration as distributed generators. Moreover, these systems are subject to severe operating modes and environmental constraints. These constraints inevitably increase the performance degradation of system functional blocks and consequently accelerate their ageing process. This leads to the appearance of mechanical and/or electrical defects. Consequently, the implementation of fault-tolerant control techniques can help improving the reliability, performance, and reduce the operation and maintenance costs.

This topic has been dealt with during the PhD thesis of **Mme. Sana Toumi**. She focused on modeling and simulation of a variable-speed marine currents turbine in both healthy and faulty cases (Permanent Magnets Synchronous Generator (PMSG) with permanent magnets defects (demagnetization fault) and power converters (Power switches (IGBT) open-circuit). This PhD thesis work led to 4 publications in peer-reviewed international journals [9, 10, 11, 12] and 4 international refereed conferences [13, 14, 15, 16].

2.1.3 Energy management system for microgrid with high rate of renewables

The current power grid is facing a number of challenges mainly related to growing energy demand, environmental issues, high reliability requirements and planning restrictions. Energy production systems-based on renewable resources (wind turbines, tidal turbines, photovoltaic systems, etc.) are currently being deployed at a large scale to meet the growing energy demand, mitigate the impact of pollutants of fossil fuels on the environment and guarantee socio-economic benefits for sustainable development. The integration of these distributed energy resources in the distribution and transmission network, the emergence of new consumption modes (electric vehicles (EVs), for example), the use of storage devices, and the activation of smart energy concept in industry and residential buildings pave the way for smart grids. Smart grids constitute a solution to take advantage of the new power economy priorities, which aims promoting a bidirectional management of power and information flow and thus introduces the notion of “prosumers”.

The intermittent nature of renewable energy resources requires the implementation of new resources allowing this intermittency balancing at energy systems level. Energy

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storage makes it possible to meet this requirement. Nowadays, energy storage technologies are mainly limited to pumped storage plants, whose technological advancement have recently allowed a more fast and precise control. The recent advancement in battery technologies has significantly improved their lifetime and cost, leading to development of new usage of grid-connected batteries, either directly at grid substations or at renewable resources farms level or large power consumption plants. These decentralized production and storage systems must be integrated into the central controller.

This research topic is developed within the framework of the PhD thesis of **Mr. Muhammad Fahad Zia**. The focus is made on energy management system design for hybrid energy production system with high rate of renewables and storage devices to power islanded site (Ouessant island for example). This research work has led to 3 publications in peer-reviewed international journals [17, 18, 19] and a 2 international conferences [20, 21].

Moreover, the integration electric vehicles (EV) to power grid inevitably leads to the problem of optimal management of energy flow between these potential means of distributed storage, local consumers and finally renewable energy producers. The research activities in this field are focusing on "vehicle-to-grid" (V2G) or "vehicle-to-home" (V2H) concept, smart buildings, distributed generator system services. This research should deal with several aspects related to power electronics and various embedded energy storage technologies, advanced and fault-tolerant control algorithms for a wide range of applications, better reliability and availability and optimal energy management in a micro-grid consisting of conventional and renewable resources, distributed energy storage-based on EVs and controllable loads. These storage facilities, renewable resources and loads must participate to grid ancillary services: voltage regulation (local ancillary service) and frequency regulation (global ancillary service).

This research work is performed as part of the PhD thesis of **Mme. Khadija El Harouri** (in collaboration with ENSET Rabat, Morocco) who is interested in fast charging stations for electric vehicles with the possibility of a bidirectional power flow. This research work has been published in a peer-reviewed international journal [22].

2.2 PhD thesis, postdoc, and research masters co-advising

2.2.1 Defended PhD thesis

1. PhD thesis of **Mr. Youness TRACHI**: 2014 – 2017

- Co-supervisor rate: 30%
- Date of PhD oral defence: November 22nd 2017
- PhD supervisor and other co-supervisor:
 - Prof. Mohamed BENBOUZID, University of Brest, IRDL UMR CNRS 6027
 - Dr. Vincent CHOQUEUSE, ENIB of Brest, Lab-STICC UMR CNRS 6285
- Manuscript title: “On induction machine faults detection using advanced parametric signal processing techniques”
- PhD thesis jury members:
 - Dr-HdR. Claude DELPHA, University of Paris-Sud
 - Prof. Demba DIALLO, University of Paris-Sud
 - Prof. Mohamed ELBADAoui, University of Saint Etienne
 - Dr. Emmanuel SCHAEFFER, University of Nantes
 - Prof. Tianzhen WANG, Shanghai Maritime University, China
 - Dr. Elhoussin ELBOUCHIKHI, ISEN Yncréa Ouest, Brest
 - Prof. Mohamed BENBOUZID, University of Brest
- Joint publications with the PhD student:
 - [1] Y. Trachi, **E. Elbouchikhi**, V. Choqueuse, M. Benbouzid, and T. Wang, “A novel induction machine faults detector based on hypothesis testing,” *IEEE Transactions on Industry Applications*, vol. 53, no. 3, pp. 3039 – 3048, May-June 2017
 - [2] Y. Trachi, **E. Elbouchikhi**, V. Choqueuse, and M. Benbouzid, “Induction machines fault detection based on subspace spectral estimation,” *IEEE Transactions on Industrial Electronics*, vol. 63, no. 9, pp. 5641–5651, September 2016

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- [3] Y. Trachi, **E. Elbouchikhi**, V. Choqueuse, T. Wang, and M. Benbouzid, “Induction machine faults detection based on a constant false alarm rate detector,” in *proceedings of the 2016 IEEE IECON*. Florence, Italia: IEEE, October 2016, pp. 6359–6363
 - [4] Y. Trachi, **E. Elbouchikhi**, V. Choqueuse, and M. Benbouzid, “Stator current analysis by subspace methods for fault detection in induction machines,” in *proceedings of the 2015 IEEE IECON*. Yokohama, Japan: IEEE, November 2015, pp. 3479–3484
 - [5] **E. Elbouchikhi**, V. Choqueuse, Y. Trachi, and M. Benbouzid, “Induction machine bearing faults detection based on hilbert-huang transform,” in *proceedings of the 2015 IEEE ISIE*. Búzios, Rio de Janeiro, Brazil: IEEE, June 2015, pp. 843–848
- Current professional position: Research engineer

2. PhD thesis of **Mme. Sana TOUMI**: 2014 – 2017

- Co-supervisor rate: 30%
- Date of PhD oral defence: December 09th 2017
- PhD supervisors and other co-supervisor:
 - Prof. Mohamed BENBOUZID, University of Brest, IRDL UMR CNRS 6027
 - Prof. Mohamed Faouzi MIMOUNI, ENISO Sfax, Tunisie
 - Dr. Yassine AMIRAT, ISEN Yncréa Ouest, Brest, France
- Manuscript title: “Contribution à la commande résiliente aux défaillances des convertisseurs statiques et à la démagnétisation de la génératrice synchrone à aimants permanents d’une hydrolienne”
- PhD thesis jury members:
 - Prof. Jaleleddine BEN HADJ SLAMA, ENI Sousse, Tunisia
 - Dr-Hdr. Jean Frédéric CHARPENTIER, French Naval Academy
 - Prof. Maria PIETRZAK-DAVID, INP ENSEIHT Toulouse
 - Prof. Ilhem SLAMA-BELKHODJA, ENI Tunis, Tunisia
 - Dr. Yassine AMIRAT, ISEN Yncréa Ouest, Brest

2.2 PhD thesis, postdoc, and research masters co-advicing

- Dr. Elshoussin ELBOUCHIKHI, ISEN Yncréa Ouest, Brest
 - Dr. Mohamed TRABELSI, ENI Sousse, Tunisia
 - Prof. Mohamed Faouzi MIMOUNI, ENI Monastir, Tunisia
 - Prof. Mohamed BENBOUZID, University of Brest
- Joint publications with the PhD student:
- [1] S. Toumi, **E. Elbouchikhi**, Y. Amirat, M. Benbouzid, and G. Feld, “Magnet failure-resilient control of a direct-drive tidal turbine,” *Ocean Engineering*, vol. 187, September 2019
 - [2] S. Toumi, **E. Elbouchikhi**, Y. Amirat, M. Benbouzid, and M. Faouzi Mimouni, “Marine current turbine system post-fault behavior under an open circuit fault,” *Advances in Electrical and Electronic Engineering*, July 2018
 - [3] S. Toumi, Y. Amirat, **E. Elbouchikhi**, M. Trabelsi, M. Benbouzid, and M. F. Mimouni, “A comparison of fault-tolerant control strategies for a pmsg-based marine current turbine system under generatorside converter faulty conditions.” *Journal of Electrical Systems*, vol. 13, no. 3, September 2017
 - [4] S. Toumi, S. Benelghali, M. Trabelsi, **E. Elbouchikhi**, Y. Amirat, M. Benbouzid, and M. F. Mimouni, “Modeling and simulation of a pmsg-based marine current turbine system under faulty rectifier conditions,” *Electric Power Components and Systems*, vol. 45, no. 7, pp. 715–725, November 2016
 - [5] S. Toumi, Y. Amirat, M. Trabelsi, **E. Elbouchikhi**, M. F. Mimouni, and M. Benbouzid, “Backstepping control of a pmsg-based marine current turbine system under faulty conditions,” in *proceedings of the 2018 IEEE IREC*. Hammamet, Tunisia: IEEE, March 2018, pp. 1–6
 - [6] S. Toumi, Y. Amirat, **E. Elbouchikhi**, M. Trabelsi, M. Mimouni, and M. Benbouzid, “Second-order sliding mode for marine current turbine fault-tolerant control,” in *proceedings of the 2016 IEEE CEIT*. Hammamet, Tunisia: IEEE, December 2016, pp. 1–6
 - [7] S. Toumi, Y. Amirat, **E. Elbouchikhi**, M. Trabelsi, M. Benbouzid, and M. Mimouni, “A simplified mathematical approach for magnet defects

2. RESEARCH ACTIVITIES

modeling in a pmsg used for marine current turbine,” in *proceedings of the 2016 IEEE STA*. Sousse, Tunisia: IEEE, 2016, pp. 552–557

- [8] S. Toumi, S. B. Elghali, M. Trabelsi, **E. Elbouchikhi**, M. Benbouzid, and M. F. Mimouni, “Robustness analysis and evaluation of a pmsg-based marine current turbine system under faulty conditions,” in *proceedings of the 2014 IEEE STA*. Hammamet, Tunisia: IEEE, December 2014, pp. 631–636

- Current professional position: Associate professor at “l’Ecole Pluridisciplinaire Internationale” EPI Educational Group of sousse, Tunisia

2.2.2 PhD thesis undergoing

1. PhD thesis of **Mr. Fahad Muhammad ZIA**: 2017 – 2020

- Co-supervisor rate: 50%
- PhD supervisor:
 - Prof. Mohamed BENBOUZID, University of Brest, IRDL UMR CNRS 6027
- PhD topic: “Optimization of hybrid power generation systems with high rate of renewables: from microgrids to grid-connected systems”
- Joint publications with the PhD student:

- [1] M. F. Zia, M. Nasir, **E. Elbouchikhi**, M. Benbouzid, J. C. Vasquez, and J. M. Guerrero, “Energy management system for a hybrid pv-wind-tidal-battery based islanded dc microgrid: Modeling and experimental validation,” *IEEE transactions on Smart Grid*, vol. PP, 2020
- [2] M. F. Zia, M. Benbouzid, **E. Elbouchikhi**, S. M. Muyeen, K. Techato, and J. M. Guerrero, “Microgrid transactive energy: Review, architectures, distributed ledger technologies, and market analysis,” *IEEE Access*, vol. 8, pp. 19 410 – 19 432, January 2020
- [3] M. F. Zia, **E. Elbouchikhi**, M. Benbouzid, and J. M. Guerrero, “Energy management system for an islanded microgrid with convex relaxation,” *IEEE Transactions on Industry Applications*, vol. PP, Mai 2019

2.2 PhD thesis, postdoc, and research masters co-advising

- [4] M. F. Zia, **E. Elbouchikhi**, and M. Benbouzid, “Optimal operational planning of scalable dc microgrid with demand response, islanding, and battery degradation cost considerations,” *Applied Energy*, vol. 237, pp. 695–707, March 2019
- [5] —, “Microgrids energy management systems: A critical review on methods, solutions, and prospects,” *Applied Energy*, vol. 222, pp. 1033–1055, July 2018
- [6] M. F. Zia, M. Nasir, **Elhoussin Elbouchikhi**, M. Benbouzid, J. C. Vasquez, and J. M. Guerrero, “Energy management system for an islanded renewables-based dc microgrid,” in *proceedings of the 2019 IEEE ICSPRES*, Bangkok (Thailand), June 2020, pp. 1–6
- [7] —, “An energy management system for hybrid energy sources-based stand-alone marine microgrid,” in *proceedings of the 2019 IEEE ICSPRES*. Melbourne, Australia: IEEE, April 2019, pp. 1–6
- [8] M. F. Zia, **Elhoussin Elbouchikhi**, M. Benbouzid, and J. M. Guerrero, “Microgrid transactive energy systems: A perspective on design, technologies, and energy markets,” in *Proceedings of the 2019 IEEE IECON*, Lisbon (Portugal), Oct. 2019, pp. 1–6

2. PhD thesis of **Mme. Khadija EL HAROURI**: 2019 – 2022

- Co-supervisor rate: 50%
- PhD supervisors:
 - Prof. Mohamed BENBOUZID, University of Brest, IRDL UMR CNRS 6027
 - Prof. Soumia EL HANI, University Mohamed V, ENSET RABAT, Morocco
- PhD topic: “Optimal scheduling, management and control of charging/discharging of electric vehicles”
- Joint publications with the PhD student:

2. RESEARCH ACTIVITIES

- [1] K. E. Harouri, S. El Hani, **E. Elbouchikhi**, M. Benbouzid, and H. Mediouni, “Grid-connected plug-in electric vehicles charging stations energy management and control,” *International Journal on Energy Conversion (IRECON)*, vol. 1, pp. 1–9, March 2019

2.2.3 Postdoc

- Postdoctorate position of **Dr. Pierre MASSONNAT**
 - Post-Doc duration : July 2015 to February 2017
 - Partners : French Naval Academy, IRENAV EA 3634
 - Project funding: Stratégie d’Attractivité Durable (SAD) of Bretagne region
 - Postdoctorate topic : Modeling, control and diagnosis of permanent magnets synchronous generators (PMSG) in marine currents turbine context
 - Current professional position: Research engineer.

2.2.4 Research master students

- Research Master of **Mme. Fatemah HOURZADEHGHARABOLAGH**
 - Start date of the research master training period: Mai 15th, 2019
 - Funding source: ISEN Yncréa Ouest.
 - Training period topic: “Real-time monitoring of swimmers: Application to La Baule beach”.
 - Current professional position: Second year of research master Robotique, Assistance et Mobilité at the university of Versailles-Saint-Quentin-en-Yvelines.
- Research Master of **Mme. Camille DI RUZZA**
 - Date of training period oral defence: July 13rd, 2017
 - Funding source: SAD project
 - Training period topic: “Real-time implementation of faults detection in induction machines-based on stator currents analysis (MCSA)”.

2.3 Research funding and projects

- Current professional position: Engineer at “l’armée, Centre d’Expertise des Techniques de l’Infrastructure de la Défense, Département d’Expertise des Techniques Bâtimentaires et Opérationnelles, Pôle Ingénierie Electrique et Electrotechnique, Chargée d’Etudes.
- Research Master of **Mr. Nabil FEKI**
 - Date of training period oral defence: July, 2014
 - Funding source: Campus France, Tunisia
 - Training period topic: Asynchronous machine-based wind turbines faults detection and diagnosis: FAST toolbox integration.
 - Current professional position: Electrical engineering engineer, Tunisia.

2.3 Research funding and projects

A summary of contract activities and research projects is presented in this section. Tables below present the following research projects and industrial collaborations:

- “Fonds de Concours au développement de la recherche” funded by the city of Brest and Bretagne Regional Council,
- SAD project funded by Regional Council of Bretagne,
- SEEDS project funded by GdR SEEDS,
- Industrial collaborations with Cap’tronic, Guinard Energies, and SABELLA,
- ANR/European Martera Project.

2. RESEARCH ACTIVITIES

Year	2019-2020
Project	Equipment grant application : Artificial intelligence and multi-modal imaging for human behaviour monitoring and maritime and agricultural environments study
Partners	– ISEN Yncrea OUEST, Brest, France
Funding source	City of Brest/ Bretagne Council
Total amount	42.8 k€
Role	Author of the draft

Table 2.1: FCR project

Year	2015-2017
Project	<ul style="list-style-type: none"> – Project title: “Modeling, diagnosis and faults detection in permanent magnets synchronous generators-based marine currents turbines” – Main topic: Marine science and technologies – Attractive regional priority theme: D3A Blue growth for the marine activities – Marine Renewable Energies
Partners	<ul style="list-style-type: none"> – ISEN Brest, Yncrea OUEST, France – University of Brest, Institut de recherche Dupuy de Lôme (UMR CNRS 6027 IRDL) France – French Naval Academy, IRENav EA 3634, France
Funding source	Regional Council of Bretagne - CG 29
Total amount	80 k€
Role	Project coordinator

Table 2.2: SAD project

2.3 Research funding and projects

Year	2015-2016
Project	Diagnosis and faults detection in marine renewable energy resources based on stator currents monitoring
Partners	<ul style="list-style-type: none">– ISEN Brest, Yncrea OUEST, France– University of Brest, Institut de recherche Dupuy de Lôme (UMR CNRS 6027 IRDL) France– University of Nantes, IREENA, EA 4642, France
Funding source	GdR CNRS SEEDS
Total amount	10 k€
Role	Project coordinator

Table 2.3: SEEDS project

2. RESEARCH ACTIVITIES

Year	2020
Project	Marine current turbine configurations (IG/PMSG) investigation with both embedded and onshore power electronics
Industrial partner	SABELLA
Total amount	10 k€
Role	Project collaborator
Project deliverables	Report on comparative study of 4 MCT configurations and simulation study
Year	2019
Project	Technical and economic studies of a residential solar power plant for Africa
Industrial partner	Cap'tronic
Total amount	4 k€
Role	Project coordinator
Project deliverables	Architecture and sizing of the solar power plant, and components suppliers
Year	2018
Project	Simulation and prototype implementation for a small-scale marine current turbine for powering stand-alone equipments
Industrial partner	Guinard Energies
Total amount	12 k€
Role	Project collaborator
Project deliverables	Study report of 100 pages

Table 2.4: Expertise and industrial contracts

2.3 Research funding and projects

Year	2018-2020
Project	Integrated Technologies Longterm Deployment of Robotic Underwater Platforms
Partners	<ul style="list-style-type: none"> – ISEN Brest, Yncrea OUEST, France – University of Brest, Institut de recherche Dupuy de Lôme (UMR CNRS 6027 IRDL) France – INESC TEC-CRAS, Portugal – NTNU-Biological Sciences Aalesund Norvège – Runde Environmental Centre, Environmental Monitoring, Norvège – INEGI – Institute of Science and Innovation in Mechanical and Industrial engineering, Portugal
Funding source	ANR : MARTERA
Total amount	210 k€
Role	In charge of a Work Package

Table 2.5: ANR/ADEME/European Project

2. RESEARCH ACTIVITIES

International scientific services and responsibilities

3.1 Scientific awards and recognition

Since 2019	Senior Member of IEEE (Institute of Electrical and Electronics Engineers)
2016 and 2019	IEEE TRANSACTIONS ON ENERGY CONVERSION journal Star Reviewer award
2014 – 2015 & 2017 – 2018	Certificate of appreciation from the IEEE PES (Power & Energy Society) and the Editorial Board of Transactions on Energy Conversion
2012	Best paper award at international conference IEEE IECON'12 at Montréal (Canada)

3.2 Editorial responsibilities in international journals

Since Mai 2020	Associate Editor in the area of Generation for IET Generation, Transmission & Distribution
Since March 2020	Member of the Editorial Board of MDPI Energies
Since January 2020	Topic editor for MDPI Energies
2020	Guest editor of MDPI Energies Special Issue: “Special Issue: “Advances in the Fault Tolerance and Resilience of Wind and Tidal Energy Conversion Systems”
2019	Guest editor of MDPI Energies Special Issue: “Marine Tidal and Wave Energy Converters : Technologies, Conversions, Grid Interface, Fault Detection, and Fault-Tolerant Control”

3. INTERNATIONAL SCIENTIFIC SERVICES AND RESPONSIBILITIES

3.3 Organization of international conferences

3.3.1 Member of international conference organizing/technical committee

- | | |
|------|--|
| 2020 | 4 th International conference on electrical and information technologies, ICEIT'20, Rabat-Salé, Morocco |
| 2014 | 3 rd International conference on Industrial Engineering and Manufacturing, ICIEM'14, University of Batna, Algeria |

3.3.2 Technical track chair and tutorials of international conference

- | | |
|------|---|
| 2020 | - Tutorial at the international conference IEEE ICEIT 2020, Rabat, Morocco: “Digital control based on dSPACE/DSP: Application to wind energy conversion and energy storage systems” |
| 2020 | SS01 - Special session chair at IEEE SPIES 2020, Bangkok, Thailand, entitled: “Microgrids/Nanogrids Implementation, Planning, and Operation” |
| 2019 | SS20 - Special session at IEEE IECON 2019, Lisbon, Portugal, entitled: “Microgrids/Nanogrids Implementation, Planning, and Operation” |
| 2017 | Tutorial at the international conference IEEE IECON 2017, Beijing, China: “Advanced Signal Processing Techniques for Electromechanical Systems Fault Detection and Diagnosis” |

3.3.3 Special session chair of international conference

- | | |
|------|---|
| 2020 | SSVII - Session chair at IEEE ICEIT 2020, Rabat, Morocco, entitled: “Control Systems and Robotics” |
| 2019 | SS20 - Special session chair at IEEE IECON 2019, Lisbon, Portugal, entitled: “Microgrids/Nanogrids Implementation, Planning, and Operation” |
| 2017 | SS20 - Special session chair at IEEE IECON 2017, Beijing, China, entitled: “Advances in Fault Tolerance and Resilience in Power Conversion Systems” |

3.4 Technical reviewer services

3.4.1 Frequent technical paper reviewer for the following international journals

- IEEE Transactions on Energy Conversion

3.5 Integration of research networks/teams

- IEEE Transactions on Power Electronics
- IEEE Transactions on Industrial Electronics
- IEEE Transactions on Industry Applications
- Elsevier Mechanical Systems and Signal Processing
- Elsevier ISA Transactions
- MDPI Energies
- MDPI Sensors
- MDPI Applied Sciences
- International Review of Electrical Engineering (IREE)
- International Journal on Energy Conversion (IRECON)

3.4.2 Frequent technical paper reviewer for the following international conferences

- IEEE International Conference on Electrical and Information Technologies (ICEIT)
- IEEE Annual Conference of IEEE Industrial Electronics (IECON)
- International Symposium on Industrial Electronics (ISIE)
- IEEE International Conference on Green Energy (ICGE)
- IEEE International Electric Machines & Drives Conference (IEMDC)

3.5 Integration of research networks/teams

3.5.1 At international level

- 2016 and 2019: Invited professor at University of Marrakech and ENSET Engineering School in Rabat.
- Since 2011 : IEEE Member.

3. INTERNATIONAL SCIENTIFIC SERVICES AND RESPONSIBILITIES

3.5.2 At French national level

- Since 2014: Member of French national research group SEEDS

3.5.3 Invited professors

- Dr. Yazid KAIKAA, Frères Mentouri University, Constantine, Algéria
- Dr. Lotfi SAIDI, Sousse University, Tunisia
- Prof. Tianzhen WANG, Shanghai Maritime University (SMU), Shanghai, China

3.6 Collaboration with other electrical engineering laboratories

3.6.1 At international level

- Control and Power Electronics Laboratory, Shanghai maritime University (SMU), China
- Electrical Engineering Laboratory of Marrakech, University of Marrakech, Morocco
- Research Centre for Engineering Sciences and Health Technologies, University of Rabat, ENSET, Morocco

3.6.2 At French national level

- IRENAV Laboratory EA 3634, French Naval Academy, Brest
- IREENA Laboratory EA 4642, Saint Nazaire

Scientific publications

4.1 Summary

Main scientific publications are summarized by table 4.1.

International journal papers	29 + 4 (Ongoing)
National (French) journal papers	3 + 1 (Ongoing)
Book chapters	2 + 1 Ongoing
Edited Books	1 MDPI Energies
2 tutorials on international conferences	- 1 IEEE ICEIT 2020, Rabat, Morocco - 2 IEEE IECON 2017, Beijing, China
2 special sessions on international conferences	- 1 IEEE SPIES 2020, Bangkok, Thailand - 2 IECON 2019, Lisbon, Portugal
International conference papers	30
National (French) conference papers	3
Total impact factors	105.65
Journal papers first author position	13
Joint publications with PhD student (Journal papers)	13
Google scholar h-index	14 - 875 citations

Table 4.1: Scientific publications and main metrics.

4. SCIENTIFIC PUBLICATIONS

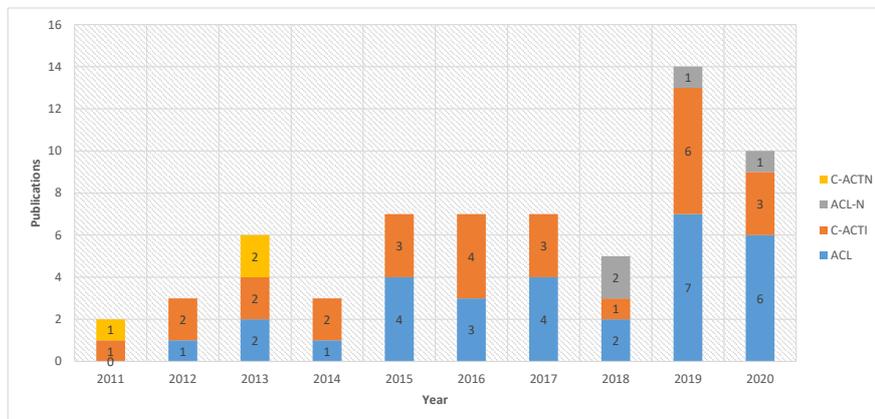


Figure 4.1: Total publications by year since 2011.

Figure 4.1 gives total publications including journal papers and national and international conference papers by year. Journal papers impact factor is depicted by Fig. 4.2 and Google Scholar and Web Of Science metrics are presented in Fig. 4.3.

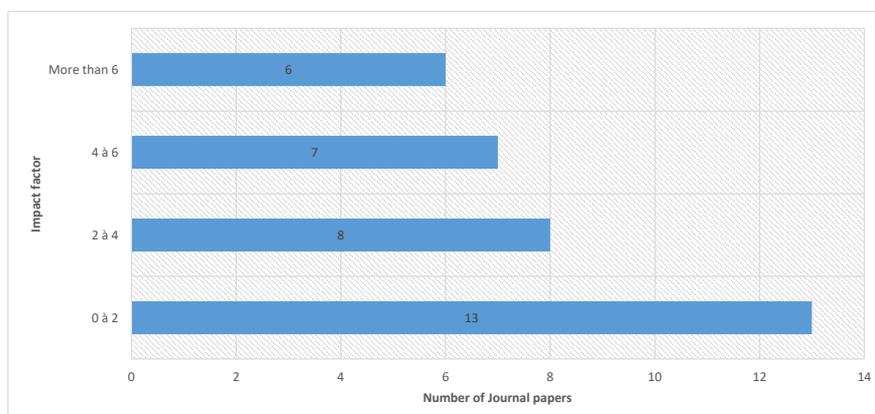


Figure 4.2: Journal papers impact factors.

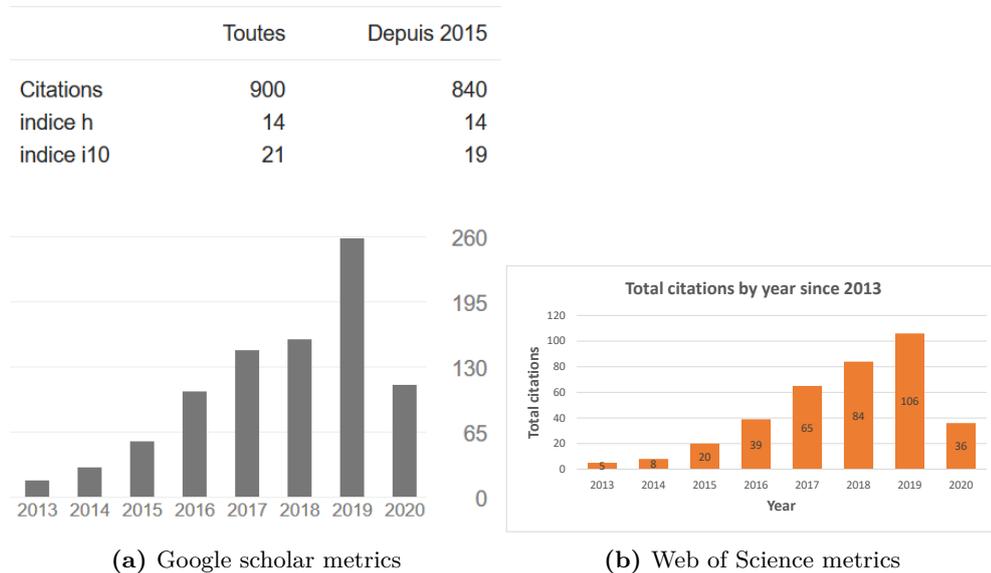


Figure 4.3: Metrics

4.2 Edited books

- [1] M. Benbouzid, Y. Amirat, and **Elhoussin ELBOUCHIKHI**, *Marine Tidal and Wave Energy Converters: Technologies, Conversions, Grid Interface, Fault Detection, and Fault-Tolerant Control*. MDPI Energies, 2020, vol. PP

4.3 Book chapters

- [1] Y. Amirat, **Elhoussin ELBOUCHIKHI**, C. Delpha, M. Benbouzid, and D. Diallo, *Modal Decomposition for Bearing Fault Detection*. ISTE Science Publishing LTD, 2020, vol. PP
- [2] C. Delpha, D. Diallo, J. Harmouche, Y. Amirat, M. Benbouzid, and **Elhoussin ELBOUCHIKHI**, *Bearing Fault Diagnosis in Rotating Machines*. ISTE Science Publishing LTD, 2020, vol. PP
- [3] **Elhoussin ELBOUCHIKHI** and M. Benbouzid, *The parametric signal processing approach*. IET, 2020, vol. PP

4. SCIENTIFIC PUBLICATIONS

4.4 National (French) journal papers

- [1] **E. Elbouchikhi** , G. Feld, Y. Amirat, M. Benbouzid, and F. Le Gall, “Mise en oeuvre expérimentale d’une plateforme de conversion d’énergie éolienne à base de génératrice asynchrone double alimentation,” *3EI*, April 2020
- [2] Y. Amirat, G. Feld, **E. Elbouchikhi**, M. Benbouzid, and N. Ruiz, “Emulateur d’une hydrolienne,” *3EI*, January 2019
- [3] **E. Elbouchikhi** , Y. Amirat, G. Feld, F. Le Gall, and M. Benbouzid, “Diagnostic et détection des défauts dans les machines asynchrones par des méthodes avancées de traitement du signal,” *3EI*, January 2018
- [4] Y. Amirat, G. Feld, **E. Elbouchikhi**, F. Le Gall, and M. Benbouzid, “Batterie alternative,” *3EI*, January 2018

4.5 International journal papers

- [1] M. F. Zia, M. Benbouzid, **E. Elbouchikhi**, S. M. Muyeen, K. Techato, and J. M. Guerrero, “Microgrid transactive energy: Review, architectures, distributed ledger technologies, and market analysis,” *IEEE Access*, vol. 8, pp. 19 410 – 19 432, January 2020
- [2] **E. Elbouchikhi**, Y. Amirat, G. Feld, M. E. H. Benbouzid, and Z. Zhou, “A lab-scale flywheel energy storage system: Control strategy and domestic applications,” *MDPI Energies*, vol. 13, no. 3, p. 653, February 2020
- [3] **E. Elbouchikhi**, G. Feld, Y. Amirat, M. E. H. Benbouzid, and F. Le Gall, “Design and experimental implementation of a wind energy conversion platform with education and research capabilities,” *Computers and Electrical Engineering*, vol. PP, 2020
- [4] M. F. Zia, M. Nasir, **E. Elbouchikhi**, M. Benbouzid, J. C. Vasquez, and J. M. Guerrero, “Energy management system for a hybrid pv-wind-tidal-battery based islanded dc microgrid: Modeling and experimental validation,” *IEEE transactions on Smart Grid*, vol. PP, 2020

- [5] Z. Zhou, S. B. Elghali, M. Benbouzid, Y. Amirat, **E. Elbouchikhi**, and G. Feld, “Tidal stream turbine control: An active disturbance rejection control approach,” *Ocean engineering*, vol. 202, April 2020
- [6] H. Ahmed, M. L. Pay, M. Benbouzid, Y. Amirat, and **E. Elbouchikhi**, “Gain normalized adaptive observer for three-phase system,” *Electrical Power and Energy Systems*, vol. 118, June 2020
- [7] M. Krichen, **E. Elbouchikhi**, N. Benhadj, M. Chaieb, M. Benbouzid, and R. Neji, “Motor current signature analysis-based pmsm demagnetization characterization and diagnosis,” *Machines*, vol. PP, 2020
- [8] H. Ahmed, S. Biricik, **E. Elbouchikhi**, and M. Benbouzid, “Adaptive filtering-based pseudo open-loop three-phase grid-synchronization technique,” *Energies*, vol. PP, 2020
- [9] L. Saidi, M. Benbouzid, D. Diallo, Y. Amirat, **E. Elbouchikhi**, and T. Wang, “Higher-order spectra analysis-based diagnosis method of blades biofouling in a pmsg driven tidal stream turbine,” *Energies*, vol. PP, 2020
- [10] M. Krichen, M. Chaieb, **E. Elbouchikhi**, N. B. Hadj, M. Benbouzid, and R. Neji, “Eccentricity faults diagnosis in permanent magnet synchronous motors: a finite element-based approach,” *International Journal on Energy Conversion*, vol. 7, no. 6, November 2019
- [11] H. Ahmed, M. L. Pay, M. Benbouzid, Y. Amirat, and **E. Elbouchikhi**, “Hybrid estimator-based harmonic robust grid synchronization technique,” *Electric Power Systems Research*, vol. 177, December 2019
- [12] S. Toumi, **E. Elbouchikhi**, Y. Amirat, M. Benbouzid, and G. Feld, “Magnet failure-resilient control of a direct-drive tidal turbine,” *Ocean Engineering*, vol. 187, September 2019
- [13] **E. Elbouchikhi**, Y. Amirat, G. Feld, and M. E. H. Benbouzid, “Generalized likelihood ratio test-based approach for stator faults detection in a pwm inverter-fed induction motor drive,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 8, pp. 6343 – 6353, August 2019

4. SCIENTIFIC PUBLICATIONS

- [14] M. F. Zia, **E. Elbouchikhi**, M. Benbouzid, and J. M. Guerrero, “Energy management system for an islanded microgrid with convex relaxation,” *IEEE Transactions on Industry Applications*, vol. PP, Mai 2019
- [15] M. F. Zia, **E. Elbouchikhi**, and M. Benbouzid, “Optimal operational planning of scalable dc microgrid with demand response, islanding, and battery degradation cost considerations,” *Applied Energy*, vol. 237, pp. 695–707, March 2019
- [16] K. E. Harouri, S. El Hani, **E. Elbouchikhi**, M. Benbouzid, and H. Mediouni, “Grid-connected plug-in electric vehicles charging stations energy management and control,” *International Journal on Energy Conversion (IRECON)*, vol. 1, pp. 1–9, March 2019
- [17] —, “Microgrids energy management systems: A critical review on methods, solutions, and prospects,” *Applied Energy*, vol. 222, pp. 1033–1055, July 2018
- [18] S. Toumi, **E. Elbouchikhi**, Y. Amirat, M. Benbouzid, and M. Faouzi Mimouni, “Marine current turbine system post-fault behavior under an open circuit fault,” *Advances in Electrical and Electronic Engineering*, July 2018
- [19] **E. Elbouchikhi**, V. Choqueuse, F. Auger, and M. E. H. Benbouzid, “Motor current signal analysis based on a matched subspace detector,” *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 12, pp. 3260–3270, December 2017
- [20] **E. Elbouchikhi**, V. Choqueuse, Y. Amirat, M. Benbouzid, and T. Wang, “An efficient hilbert-huang transform for bearing faults detection in induction machine,” *IEEE Transactions on Energy Conversion*, vol. 32, no. 2, pp. 401–413, January 2017
- [21] S. Toumi, Y. Amirat, **E. Elbouchikhi**, M. Trabelsi, M. Benbouzid, and M. F. Mimouni, “A comparison of fault-tolerant control strategies for a pmsg-based marine current turbine system under generatorside converter faulty conditions.” *Journal of Electrical Systems*, vol. 13, no. 3, September 2017
- [22] Y. Trachi, **E. Elbouchikhi**, V. Choqueuse, M. Benbouzid, and T. Wang, “A novel induction machine faults detector based on hypothesis testing,” *IEEE Transactions on Industry Applications*, vol. 53, no. 3, pp. 3039 – 3048, May-June 2017

- [23] S. Toumi, S. Benelghali, M. Trabelsi, **E. Elbouchikhi**, Y. Amirat, M. Benbouzid, and M. F. Mimouni, “Modeling and simulation of a pmsg-based marine current turbine system under faulty rectifier conditions,” *Electric Power Components and Systems*, vol. 45, no. 7, pp. 715–725, November 2016
- [24] Y. Trachi, **E. Elbouchikhi**, V. Choqueuse, and M. Benbouzid, “Induction machines fault detection based on subspace spectral estimation,” *IEEE Transactions on Industrial Electronics*, vol. 63, no. 9, pp. 5641–5651, September 2016
- [25] **E. Elbouchikhi**, V. Choqueuse, and M. Benbouzid, “Induction machine bearing faults detection based on a multi-dimensional music algorithm and maximum likelihood estimation,” *ISA transactions*, vol. 63, pp. 413–424, July 2016
- [26] —, “Induction machine faults detection using stator current parametric spectral estimation,” *Mechanical Systems and Signal Processing*, vol. 52-53, pp. 447–464, February 2015
- [27] T. Wang, H. Xu, J. Han, **E. Elbouchikhi**, and M. E. H. Benbouzid, “Cascaded h-bridge multilevel inverter system fault diagnosis using a pca and multiclass relevance vector machine approach,” *IEEE Transactions on Power Electronics*, vol. 30, no. 12, pp. 7006–7018, December 2015
- [28] **E. Elbouchikhi**, V. Choqueuse, and M. Benbouzid, “Induction machine diagnosis using stator current advanced signal processing,” *International Journal on Energy Conversion*, vol. 3, no. 3, pp. 76–87, May 2015
- [29] —, “Condition monitoring of induction motors based on stator currents demodulation,” *International Review of Electrical Engineering*, vol. 10, no. 6, pp. 704–715, December 2015
- [30] V. Choqueuse, A. Belouchrani, **E. Elbouchikhi**, and M. E. H. Benbouzid, “Estimation of amplitude, phase and unbalance parameters in three-phase systems: analytical solutions, efficient implementation and performance analysis,” *IEEE Transactions on Signal Processing*, vol. 62, no. 16, pp. 4064–4076, August 2014
- [31] M. Becherif, **E. Elbouchikhi**, and M. Benbouzid, “On impedance spectroscopy contribution to failure diagnosis in wind turbine generators,” *International Journal on Energy Conversion*, vol. 1, no. 3, pp. 147–153, 2013

4. SCIENTIFIC PUBLICATIONS

- [32] **E. Elbouchikhi**, V. Choqueuse, and M. E. H. Benbouzid, “Current frequency spectral subtraction and its contribution to induction machines’ bearings condition monitoring,” *IEEE Transactions on Energy Conversion*, vol. 28, no. 1, pp. 135–144, March 2013
- [33] **E. Elbouchikhi**, V. Choqueuse, M. Benbouzid, and F. C. Jean, “Etude comparative des techniques de traitement du signal non-stationnaires dédiées au diagnostic des génératrices asynchrones dans les eoliennes offshores et les hydroliennes,” *European Journal of Electrical Engineering*, 2012

4.6 International conference papers

- [1] M. F. Zia, M. Nasir, **Elhoussin Elbouchikhi**, M. Benbouzid, J. C. Vasquez, and J. M. Guerrero, “Energy management system for an islanded renewables-based dc microgrid,” in *proceedings of the 2019 IEEE ICSPRES*, Bangkok (Thailand), June 2020, pp. 1–6
- [2] **Elhoussin Elbouchikhi**, G. Feld, Y. Amirat, and M. Benbouzid, “A flywheel-based distributed control strategy for grid congestion at domestic level,” in *proceedings of the 2010 IEEE ICEIT*, Rabat (Morocco), March 2020, pp. 1–6
- [3] A. Hezzi, S. B. Elghali, **Elhoussin Elbouchikhi**, and M. Benbouzid, “Linear adrc for speed control of 5-phase pmsm-based electric vehicles,” in *proceedings of the 2010 IEEE ICEIT*, Rabat (Morocco), March 2020, pp. 1–6
- [4] M. F. Zia, **Elhoussin Elbouchikhi**, M. Benbouzid, and J. M. Guerrero, “Micro-grid transactive energy systems: A perspective on design, technologies, and energy markets,” in *Proceedings of the 2019 IEEE IECON*, Lisbon (Portugal), Oct. 2019, pp. 1–6
- [5] Y. Amirat, **Elhoussin Elbouchikhi**, Z. Zhou, M. Benbouzid, and G. Feld, “Variational mode decomposition-based notch filter for bearing fault detection,” in *Proceedings of the 2019 IEEE IECON*, Lisbon (Portugal), Oct. 2019, pp. 1–6
- [6] Z. Zhou, S. B. Elghali, M. Benbouzid, Y. Amirat, **Elhoussin Elbouchikhi**, and G. Feld, “Control strategies for tidal stream turbine systems - a comparative study

- of adrc, pi, and high-order sliding mode controls,” in *Proceedings of the 2019 IEEE IECON*, Lisbon (Portugal), Oct. 2019, pp. 1–6
- [7] L. Saidi, M. Benbouzid, D. Diallo, Y. Amirat, **Elhoussin Elbouchikhi**, and T. Wang, “Pmsg-based tidal current turbine biofouling diagnosis using stator current bispectrum analysis,” in *Proceedings of the 2019 IEEE IECON*, Lisbon (Portugal), Oct. 2019, pp. 1–6
- [8] A. Aghmadi, S. El Hani, **Elhoussin Elbouchikhi**, N. Naseri *et al.*, “Prediction global solar radiation using ann model based on meteorological data in morocco,” in *proceedings of the 2019 IEEE ICPSE*. Dublin, Ireland: IEEE, December 2019, pp. 50–54
- [9] —, “An energy management system for hybrid energy sources-based stand-alone marine microgrid,” in *proceedings of the 2019 IEEE ICSPRES*. Melbourne, Australia: IEEE, April 2019, pp. 1–6
- [10] S. Toumi, Y. Amirat, M. Trabelsi, **E. Elbouchikhi**, M. F. Mimouni, and M. Benbouzid, “Backstepping control of a pmsg-based marine current turbine system under faulty conditions,” in *proceedings of the 2018 IEEE IREC*. Hammamet, Tunisia: IEEE, March 2018, pp. 1–6
- [11] **E. Elbouchikhi**, V. Choqueuse, G. Feld, Y. Amirat, and M. Benbouzid, “A symmetrical components-based load oscillation detection method for closed-loop controlled induction motors,” in *proceedings of the 2017 IEEE IECON*. Beijing, China: IEEE, October 2017, pp. 8047–8052
- [12] V. Choqueuse, **E. Elbouchikhi**, Z. Oubrahim, and M. Benbouzid, “On the use of phase diversity for spectral estimation in current signature analysis,” in *proceedings of the 2017 IEEE IECON*. Beijing, China: IEEE, October 2017, pp. 8093–8098
- [13] Y. Amirat, G. Feld, **E. Elbouchikhi**, M. Benbouzid, H. Kermarrec, N. Ruiz, and C. Leloup, “Design and applications of a tidal turbine emulator based on a pmsg for remote load,” in *proceedings of the 2017 IEEE IECON*. Beijing, China: IEEE, October 2017, pp. 2437–2441

4. SCIENTIFIC PUBLICATIONS

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4. SCIENTIFIC PUBLICATIONS

des génératrices asynchrones dans les éoliennes offshore et les hydroliennes,” in *proceedings of the 2011 Elctrotechnique du Futur*, December 2011, pp. 1–10

Teaching activities

5.1 Summary of teaching hours since 2011

- Teaching modules: Electrical engineering, Energy conversion, analog and power electronics, and control engineering.
- In charge of the following modules since 2014:
 - Analog Electronics,
 - Power Electronics,
 - Control Engineering.
- Master student projects supervisor (some projects are listed in the following).
- Member of the oral defence committee of student projects and training periods.
- Training periods academic supervisor of engineering school students.

5.2 Teaching and educational responsibilities

2014-2017	In charge of Analog Electronics courses content and modules
2014-2019	Involved in the preparation of the accreditation application of the French Commission du Titre d'Ingénieur (CTI)
	Involved in financial support application from « CG29 », BMO, and ITII Bretagne, for power electronics research equipment acquisition

5.3 Teaching modules

The pedagogical contents of the teaching modules are as follows:

5. TEACHING ACTIVITIES

- Electrical engineering: Electromagnetism, magnetic circuits, magnetic material, transformers, DC motor, synchronous machine, diode-based rectifiers.

- Energy conversion: Energy and power, production, renewable resources, energy storage systems, power electronics, DC/DC converters, DC/AC converters, Electrical machines (DC motor, Synchronous motors, Asynchronous motors).

- Analog electronics: Basic electronic circuitry analysis, operational amplifiers, oscillators, diodes, transistors, stabilized DC power supply, switched mode power supply, practical works on analog circuitry.

- Power electronics: DC/DC and DC/AC power converters architecture and control strategies, converters modelling and simulation both on PSIM and Matlab/Simulink, advanced closed-loop control of power converters, practical works on power electronics and electrical machines fed by power electronics and controlled by dSPACE.

- Control engineering: Continuous linear systems modelling and controller design, open-loop and closed-loop (feedback) control, sampled-data control systems, state space control.

A summary of the teaching activities is given by table 5.1.

Year Position	Institution	Module	Graduate degree	Course	Tutorials	Practical works
2017 – 2020 Associate professor	– ISEN Yncréa Ouest – Yncréa Morocco	– Analog Electronics	BAC+3	60	42	29
		– Power Electronics – Energy Conversion – Control Engineering	BAC+4 BAC+3/+4 BAC+4	30 – 12	– 36 18	15 – –
		Annual summary		102	96	44
2016 – 2017 Associate professor	– ISEN Yncréa Ouest	– Analog Electronics	BAC+3	128	13.5	22
		– Power Electronics – Energy Conversion	BAC+4 BAC+3	12 –	– 24	20 –
		Annual summary		140	37.5	42
2015 – 2016 Associate professor	– ISEN Yncréa Ouest	– Analog Electronics	BAC+3	126	51	22
		– Power Electronics	BAC+4	12	–	40
		Annual summary		138	51	62
2014 – 2015 Associate professor	– ISEN Yncréa Ouest	– Analog Electronics	BAC+3	159	27	15
		– Power Electronics	BAC+4	–	–	36
		Annual summary		159	27	51
2013 – 2014 Vacation	– ISEN Yncréa Ouest – DUT GEIL, IUT of Brest	– Analog Electronics	BAC+3	126	27	67
		– Power Electronics	BAC+2	26	–	–
		Annual summary		152	27	67
2012 – 2013 Doctoral contract	– ISEN Yncréa Ouest – DUT GEIL, IUT of Brest	– Analog Electronics	BAC+3	–	40.5	31
		– Electrical Engineering	BAC+1	–	40	24
		Annual summary		–	80.5	55
2011 – 2012 Doctoral contract	– ISEN Yncréa Ouest – DUT GEIL, IUT of Brest	– Analog Electronics	BAC+3	–	9	31
		– Electrical Engineering	BAC+1	–	40	24
		Annual summary		–	49	55
2010 – 2011 Contractual teacher	– ISEN Yncréa Ouest	– Analog Electronics	BAC+3	–	–	16
		Annual summary		–	–	16

Table 5.1: Teaching modules.

5. TEACHING ACTIVITIES

5.4 Student projects

- 2019-2020
 - “Web application development for the design and economic analysis of a photovoltaic system for domestic application”
 - “Electrically assisted cycles: Battery sizing, converter design, and digital control based on Raspberry Pi3+”
- 2018-2019
 - “Test bench development for electrical characterization of solar cells” in collaboration with EcoSolar Breizh
 - “Induction motor diagnosis based on motor current signature analysis: Application to electric vehicle”
 - “Electrically assisted cycles: buck converter design “36V-24V/250W””
- 2017-2018
 - “Electrically assisted cycles: power electronics design and control implementation based on Raspberry PI3+”
 - “LED solar street lights design and implementation”
 - “Test bench development for electrical characterization of solar cells” in collaboration with EcoSolar Breizh
- 2016-2017
 - “Digital control of induction motor based on Texas Instrument microcontroller (F28335)”
 - “Digital control of an inverter connected to the grid for active filtering application”
- 2015-2016
 - “Implementation of a boost converter connected to the grid with power factor correction capability”
- 2014-2015
 - “Design and experimental validation of a Forward switched mode power supply “40V-5V/20W”

Experimental platforms with research and education capabilities

6.1 DFIG-based wind turbine platform

Pitch-controlled variable-speed wind turbines are the most installed wind energy conversion systems (WECs). These systems use mainly two type of generators, which are permanent magnets synchronous generator (PMSG) and doubly fed induction generator (DFIG). DFIG-based WECs offer several advantages such as reduced-capacity converters, possibility to implement MPPT algorithm for better energy extraction, and active and reactive power flow control in order to meet wind farm grid code requirements. The implemented experimental platform could be used for education and research dealing with the timely topic of wind energy. DFIG-based WECs system configuration is given by Fig. 6.1.

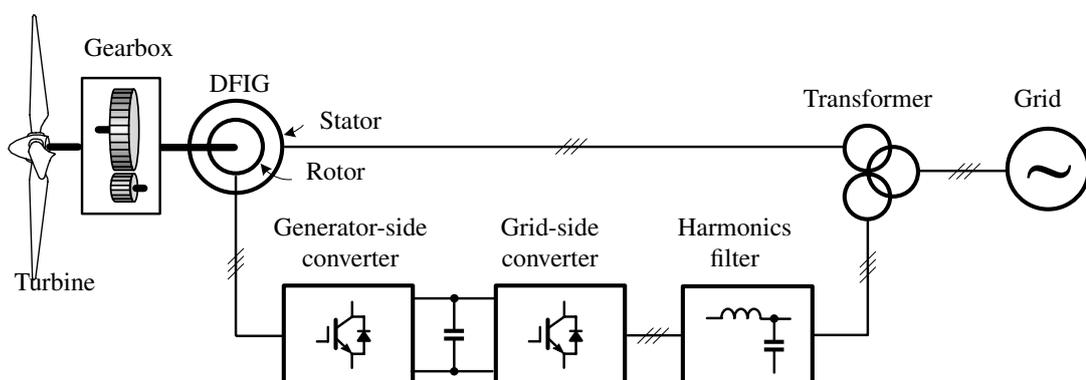


Figure 6.1: DFIG-based WECs: system configuration.

6. EXPERIMENTAL PLATFORMS WITH RESEARCH AND EDUCATION CAPABILITIES

6.1.1 Modeling framework

As for airplanes, the aerodynamic shape of the blade changes speed of wind on top and bottom of the blades. The difference in speed produces difference in pressure, hence a lifting force is generated, which creates a torque on the horizontal axe of the turbine. Consequently, a mechanical power is captured by the blades and transmitted to the drive train, which is given by

$$P_T = \frac{1}{2} \rho A C_p(\lambda, \beta) v_w^3 \quad (6.1)$$

- ρ air density in kg/m^3 (at sea level and $20^\circ C$: $\rho \approx 1.225 kg/m^3$),
- $A = \pi R_T^2$ swept area by the blades (wind turbine rotor normally disposed to the wind speed) in m^2 , with R_T turbine radius,
- $C_p(\lambda, \beta)$ power coefficient of the blade, which depends on tip speed ratio $\lambda = \frac{R_T \Omega_T}{v_w}$ and pitch angle β , which is generally used as aerodynamic brake,
- v_w wind speed in m/sec ,
- Ω_T wind turbine speed in rad/sec .

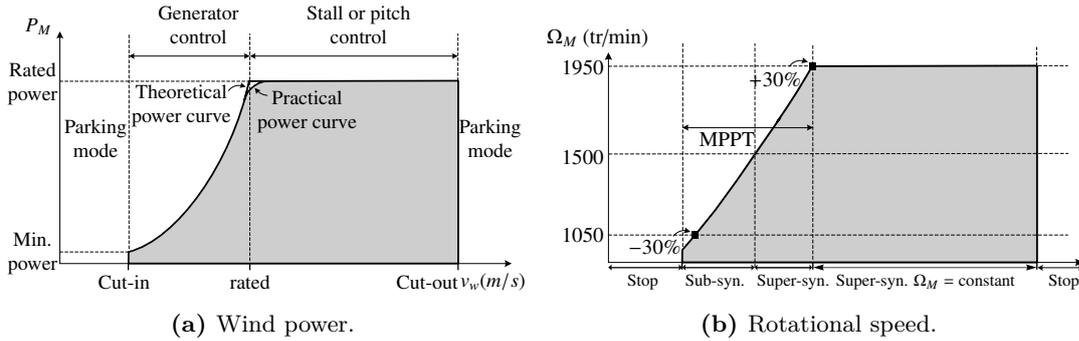


Figure 6.2: Operating regions in variable speed WECS.

Figure 6.2a gives the operating regions of DFIG-based wind turbine system. We can distinguish mainly three operating regions:

- Parking mode for which brake is on (wind speed is too low to produce energy or too high and dangerous for the blades),

- Generator control where the speed is controlled to capture maximum power (maximum power point tracking),
- Stall/pitch control for which blades are used to limit the extracted power from the wind (excess power could harm the turbine and power converters).

In generator control zone two operating modes are possible as it can be seen from Fig. 6.2b:

- Sub-synchronous operation mode: $\Omega_M < \Omega_s$, with Ω_s corresponds to synchronous speed ($\Omega_{M_{min}} = 70\%\Omega_s$).
- Super-synchronous operation mode: $\Omega_M > \Omega_s$ ($\Omega_{M_{max}} = 130\%\Omega_s$).

A gearbox is typically used in a wind turbine to increase rotational speed from a low-speed rotor to a higher speed electrical generator. The rotational speed of the turbine (low speed shaft) and the rotational speed of the DFIG (high speed shaft) are linked by the following expression:

$$\Omega_M = G_r \Omega_T \quad (6.2)$$

where, G_r denotes the gearbox ratio. Therefore, the tip speed ratio can be expressed as follows:

$$\lambda = \frac{\Omega_M R_T}{G_r v_w} \quad (6.3)$$

6.1.2 Experimental platform

A system study is carried out in a small-scale wind turbine. The base wind speed for the wind turbine is 13 m/s, the cut-in speed of wind turbine is 5 m/s and the cutoff speed of wind turbine is 25 m/s, and the base rotational speed at the base wind speed is 204 rad/s. Figure 6.3 gives the considered C_p curve. The extractable power P_T and output torque Γ_T with respect to rotational speed Ω_M and wind speed v_w are depicted by Fig. 6.4. For the sake of simplicity, the pitch angle β is set to zero and no pitch control is implemented in this study.

The experimental platform has been designed using a 1.5 kW test rig composed of DFIG connected to the utility grid through a back-to-back converter and a transformer

6. EXPERIMENTAL PLATFORMS WITH RESEARCH AND EDUCATION CAPABILITIES

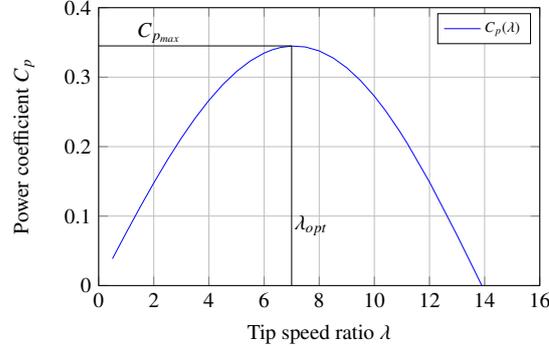


Figure 6.3: Power coefficient $C_p(\lambda)$.

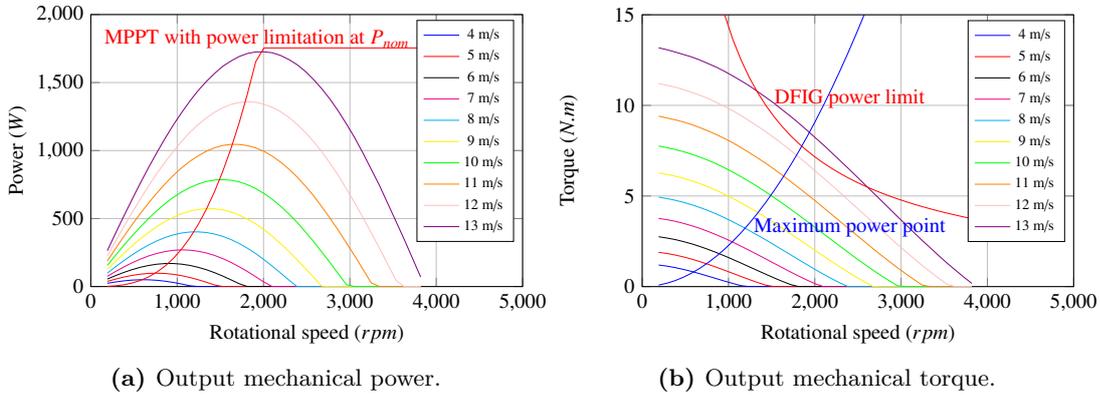


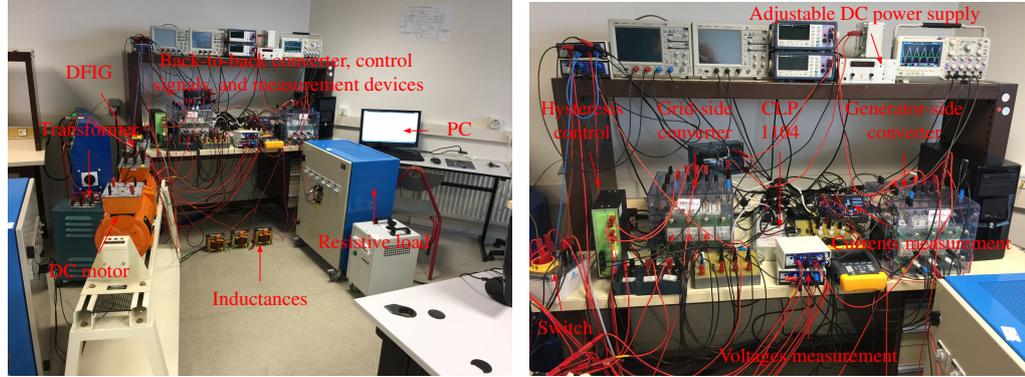
Figure 6.4: Wind turbine characteristics.

and driven by a DC motor (see Fig. 6.5). The DC motor is used for emulating the turbine. The achieved emulator enables accurate dynamic reproduction behavior of real WEC under deterministic and realistic conditions. The back-to-back converter is controlled based on DS1104 controller board from dSPACE and real time parameters tuning is performed based on ControlDesk application (Fig. 6.6).

6.2 Flywheel energy storage system platform

Flywheel is a promising energy storage system for domestic application, uninterruptible power supply, traction application (tramways), electric vehicle charging stations and even for smart grids. In fact, recent developments in materials, electrical machines, power electronics, magnetic bearings, and microprocessors offer the possibility

6.2 Flywheel energy storage system platform



(a) Experimental platform.

(b) Back-to-back converter control devices.

Figure 6.5: DFIG-based WEC: Experimental platform.

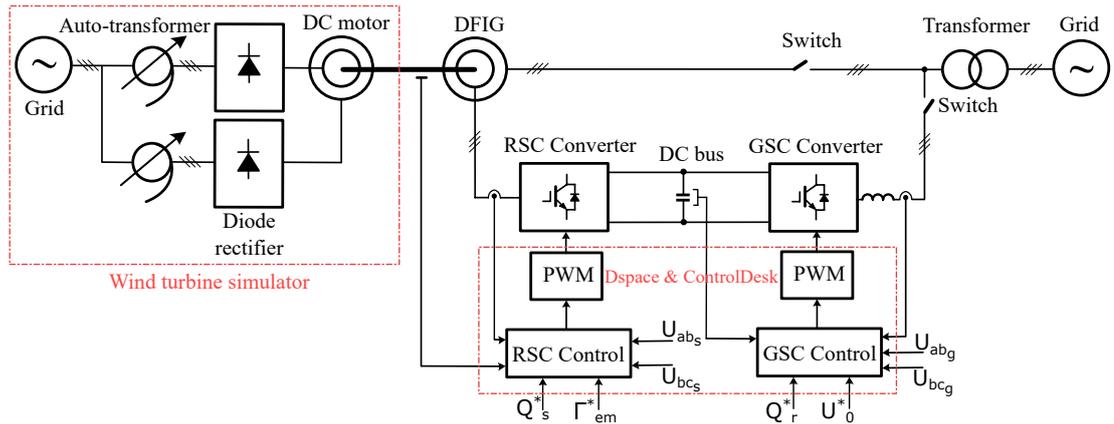


Figure 6.6: DFIG-based WEC: Experimental setup scheme.

to consider flywheels as a competitive option for electric energy storage. A FESS-based domestic energy storage can be useful for power peak shaving and power backup, which can be of great interest for domestic fast charging station (FCS) for electric vehicle in the near future for example. A lab-scale prototype has been built to demonstrate the possibilities offered by such energy storage system for both power backup and power peak shaving for congestion prevention in the distribution grid. This experimental platform could be used for education, research, and industry projects dealing with the timely topic of energy storage technologies for smart grids.

6. EXPERIMENTAL PLATFORMS WITH RESEARCH AND EDUCATION CAPABILITIES

6.2.1 Modeling framework

Flywheels store energy in kinetic form. The energy is stored in a rotating mass. The stored energy is function of the moment of inertia and angular velocity as given by equation 6.4

$$E_c = \frac{1}{2}J\Omega^2 \quad (6.4)$$

where, J is the moment of inertia of the rotating mass and Ω is the angular velocity.

Basically, a modern flywheel energy storage system (FESS) consists of five key components as depicted by Fig. 6.7; 1) flywheel rotor, 2) bearings, 3) electrical machine (operated in both motor and generator modes), 4) power electronic interface, and 5) housing. It should be pointed out here that the FESS capacity is limited by the mechanical properties (Shape, strength of material, mass density, and angular velocity) of the actual flywheel and the limit for power rating is set by the electrical machine and power electronics.

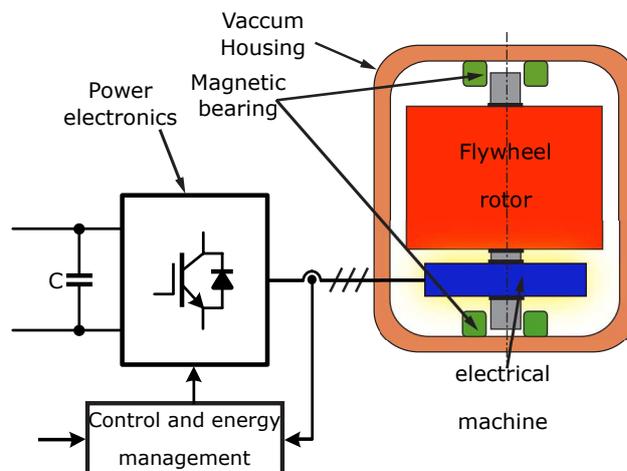
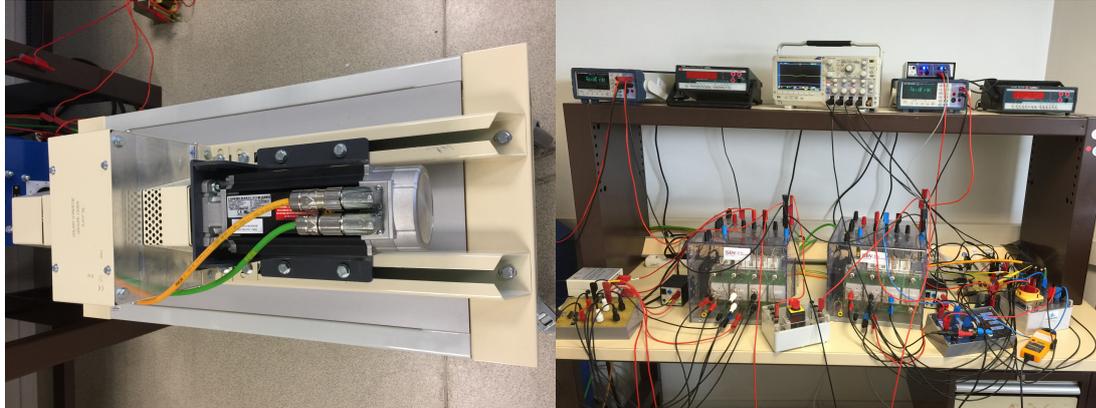


Figure 6.7: Conceptual overview of FESS.

6.2.2 Experimental platform

Flywheel general scheme is given by Fig. 6.8. This figure allows to distinguish flywheel energy storage system main subsystems, which are: 1) Flywheel rotor, 2) Permanent magnet synchronous machine, 3) Back-to-back converter, 4) LC filter for currents and voltages harmonics filtering, 5) Control and energy management devices.

6. EXPERIMENTAL PLATFORMS WITH RESEARCH AND EDUCATION CAPABILITIES



(a) Flywheel coupled to PMSM.

(b) Back-to-back converter.

Figure 6.10: Flywheel and associated power electronics.

6.3 PMSG-based wind and marine currents turbine platform

France holds a unique position in tidal energy potential since it has the second largest tidal energy deposit in Europe, just behind the United Kingdom. This energy resource, estimated between 3 to 5 Gigawatts (GW), represents a production capacity greater than that of two EPR nuclear reactors.

Two sites are particularly promising in France (Fig 6.11): Raz Blanchard site (west of Pointe du Cotentin, Manche), and the passage du Fromveur site (near Ouessant island, Finistère). The two sites account for 80% of marine currents energy potential in France. The exploitation of this huge potential can benefit from large industrial ports near the areas of interest (Cherbourg and Brest) and industrial partners with recognized skills.

6.3.1 Modeling framework

Marine currents, linked to the tides, have the particularity to be predictable and characterized by high energy density (Sea water is more than 830 times denser than air). Nevertheless, two main types of marine currents fluctuations can lead to the reduction of power quality injected to main grid:

6.3 PMSG-based wind and marine currents turbine platform

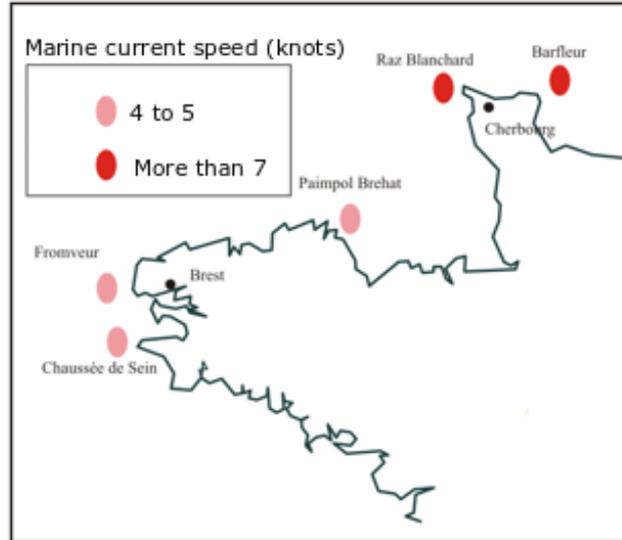


Figure 6.11: Potential tidal turbine sites.

- Marine current variation related to tide phenomenon of about 6 hours period.
- Marine current variation due to swell effect with few seconds period.

Since the produced power is proportional to the cube of the currents speed, these fluctuations will cause power variations, which will affect the power quality fed to the grid (Fig. 6.13a). Consequently, these short-term and long-term variations in marine current speed related to swell effect and disturbances related to turbulence and tides cause many technical issues that have to be addressed in order to make this technology practically and economically reliable.

The main goal of the developed experimental platform is to demonstrate the effectiveness of the use of energy storage systems, namely batteries and supercapacitors, for MCT generated power smoothing. The scheme of the energy conversion system is given by Fig. 6.12. It is composed of the marine current turbine and associated energy storage systems. These energy storage systems, used for power smoothing, are chosen based on power and energy density and are given by Ragone diagram given by Fig. 6.13b.

- Rapid power fluctuations will be compensated using supercapacitors (Fig. 6.14b),
- Slow power fluctuations will be compensated by using batteries (Fig. 6.14c).

6. EXPERIMENTAL PLATFORMS WITH RESEARCH AND EDUCATION CAPABILITIES

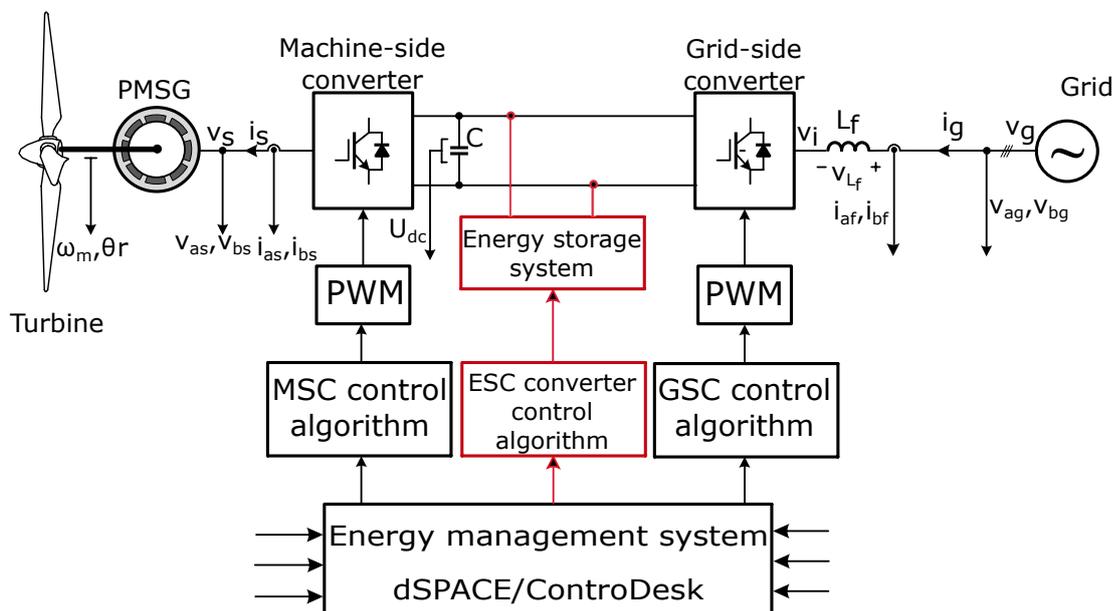


Figure 6.12: Energy conversion system (Black: existing system - Red: to be developed).

DC/DC converters (Fig 6.14a) are used to control energy storage systems power flow and for energy management. The overall scheme of the energy storage system composed of DC/DC converters, batteries and supercapacitors are given by Fig 6.15.

6.3.2 Experimental platform

The developed experimental setup is depicted by Fig. 6.16 and the corresponding scheme is depicted in Fig 6.17. It is composed of induction motor (11kW- Fig 6.16a) fed by a programmable industrial converter (ALTIVAR), which allows emulating the turbine behavior and a permanent magnets synchronous generator (16kW), which is connected to the grid through a back-to-back converter (Fig. 6.16a), LC filter, and a transformer. The generated power should be similar to the one provided by a real marine current turbine for a given marine current speed and possibly any fluctuation. The back to back converter is controlled based on dSPACE 1202 board (Fig. 6.16c).

6.3 PMSG-based wind and marine currents turbine platform

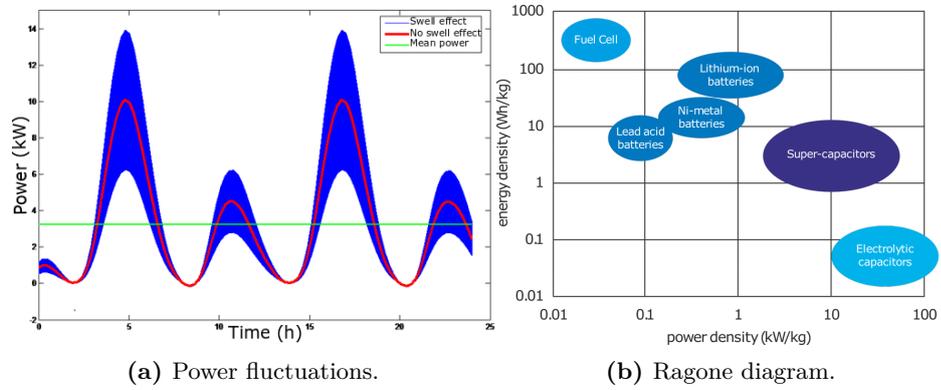


Figure 6.13: Marine energy fluctuations due to tides and swell effects.

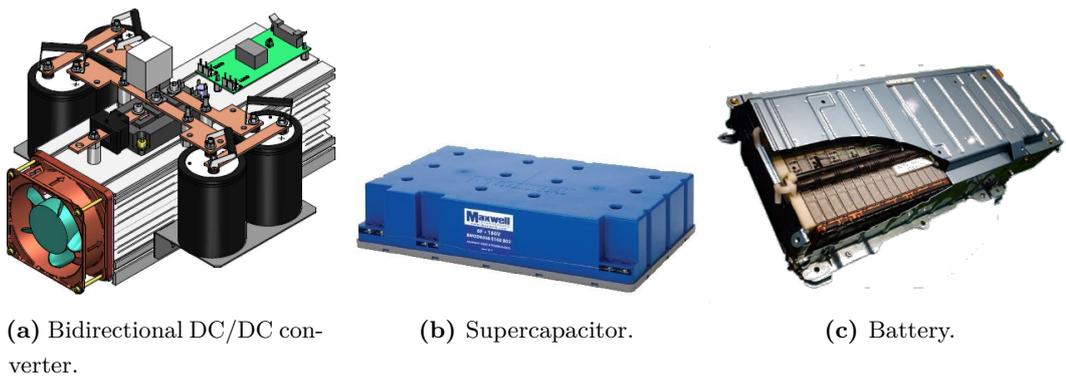


Figure 6.14: Experimental equipment.

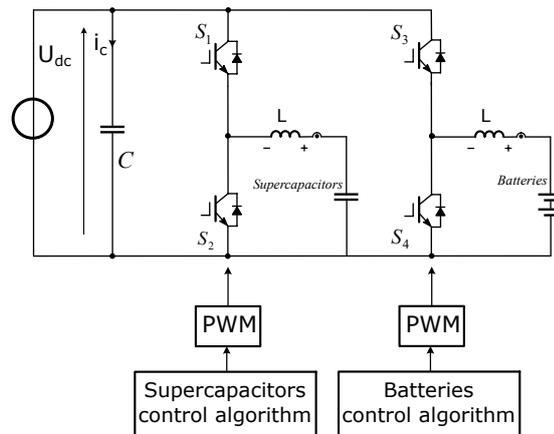


Figure 6.15: Energy storage system with power converters.

6. EXPERIMENTAL PLATFORMS WITH RESEARCH AND EDUCATION CAPABILITIES

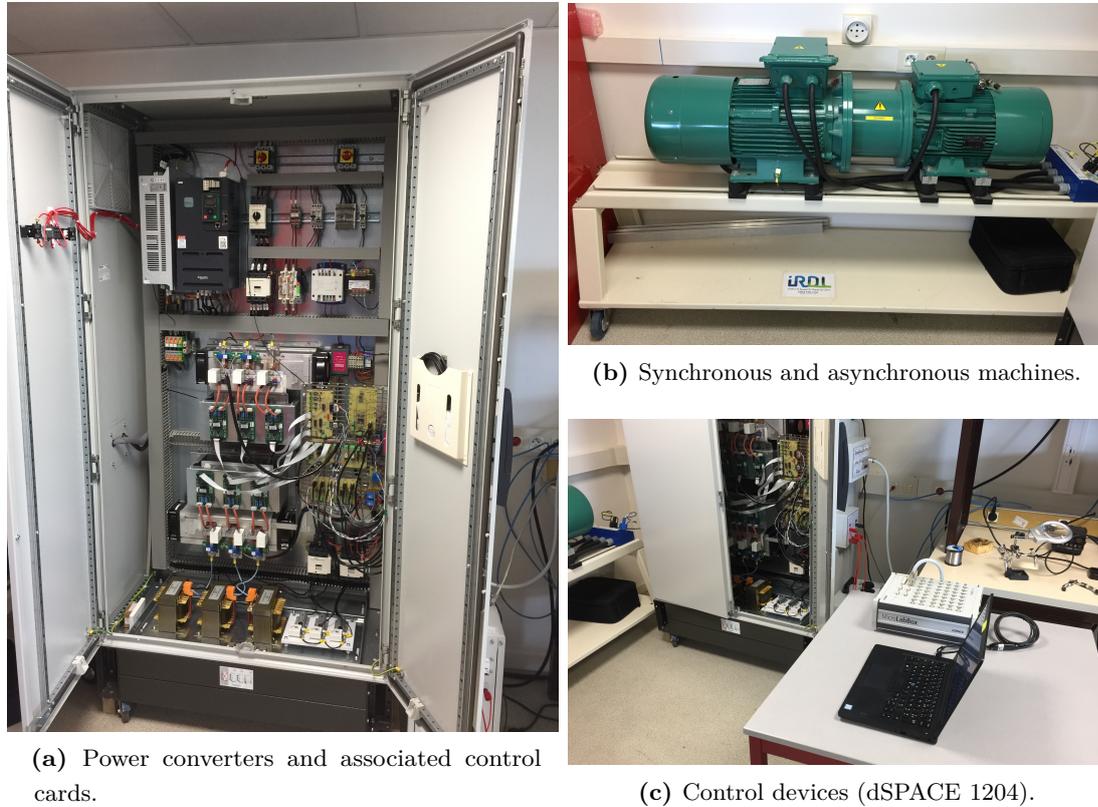


Figure 6.16: 15kW marine currents turbine emulator.

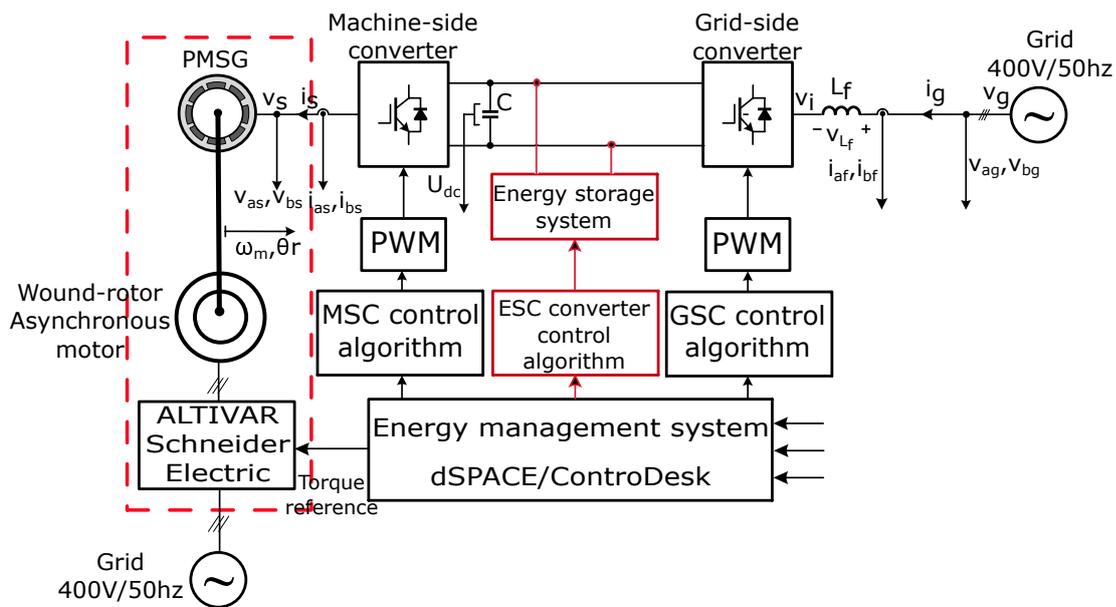


Figure 6.17: Scheme of the MCT emulator and associated storage systems.

PART

Synthesis of main research
contributions

Condition monitoring of electric machines and drives

1.1 Introduction

In the field of energy production and many other industrial applications, the electrical drives are subject to various failures, possibly combined ; failure of power supply devices, failure of electrical machines (broken bars, short-circuits, demagnetization for PMSM, etc.), failure of mechanical load (wear or breakage of all or part of the bearings, shafts, gears, etc.), failure of control devices, and failure of cables, connections, protective devices, etc.

Safety, reliability, efficiency, and performance are major concerns that direct the research activities in the field of electrical machines. Although, the use of switching power converters has improved the performance of electrical machines and drives and has extended its use to adjustable speed drives, their lifetime has been reduced. This fact has increased the range of applications where the need of condition monitoring is crucial. Consequently, researchers in academia and industry are mainly focusing on early stage failures detection and diagnosis in order to prevent breakdowns. Induction machines are widely used in industrial applications such as traction, wind generation, medical equipment, and aircraft systems. Hence, in this chapter, the emphasis is made on electrical machines condition monitoring techniques with special reference to induction machines faults detection. In particular, focus is made on condition monitoring techniques based on stator currents processing (motor current signature analysis - MCSA), which is already measured on the drive system for other purposes such as control and protection.

1. CONDITION MONITORING OF ELECTRIC MACHINES AND DRIVES

Fault-tolerant control of electric machines and drives

2.1 Introduction

Tidal stream energy is highly predictable renewable energy resource and is considered as a promising technology to lower greenhouse gas emissions for sustainable development [75]. Unfortunately, tidal stream turbines are still in development stages with few industrial project deployments. Even though, technological similarities exist between wind and tidal turbines, tidal turbines are not as mature as wind turbines technology and several design and operation differences require more investigation such as biofouling and marine current turbulence [76]. Moreover, tidal turbines are submerged systems so they have to withstand high loading and harsh submarine conditions, which make this technology suffering from higher failures rate. Horizontal-axis tidal turbines typically harness this kind of renewable energy (Fig. 2.2) [77]. Two main drivetrain technologies have been implemented in industry, which are geared and direct-drive systems [77, 78].

Tidal energy systems are unfortunately not yet massively deployed as they are facing reliability and availability challenges mainly due to the harsh immersion conditions [79]. In fact, load variability and rotor speed variations in tidal turbines lead to higher failure rate of major tidal turbines components as shown by Fig. 2.1 [80]. Evidences of these failures highlight the need for specific condition monitoring scheme. Moreover, the control algorithm and energy management systems should be upgraded in order to be fault-tolerant, which may enhance system availability.

2. FAULT-TOLERANT CONTROL OF ELECTRIC MACHINES AND DRIVES

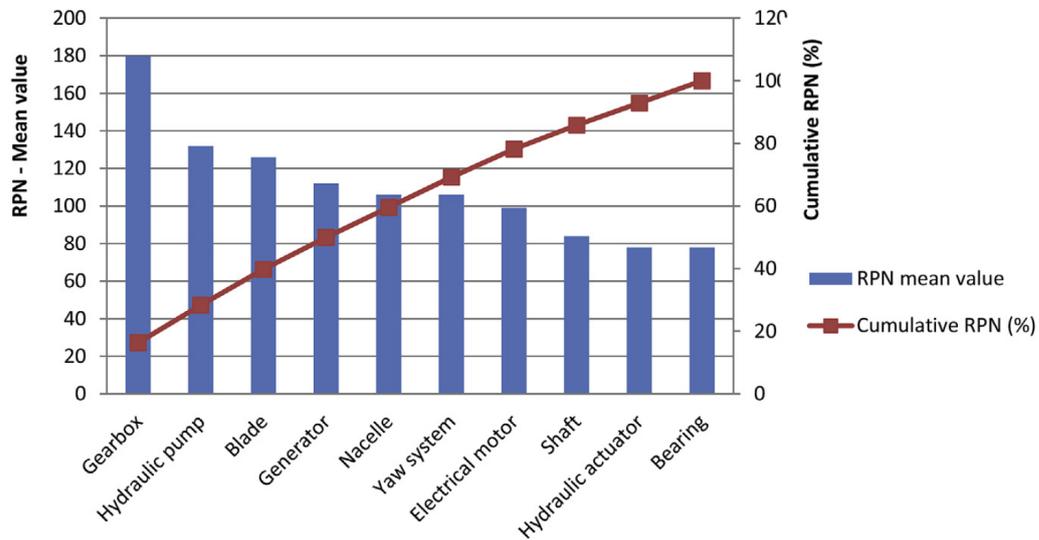


Figure 2.1: Tidal turbine components criticality (RPN stands for Risk Priority Number, which is the multiplication of occurrence, severity, and difficulty of detection values).



(a) SeaGen tidal turbine (Simec Atlantis energy).



(b) Guinard Energies shrouded tidal turbine.

Figure 2.2: Typical industrial tidal turbine systems.

Energy management system of hybrid power generation systems with high rate of renewables

3.1 Introduction

The exponential increase in global energy demand is the main cause of rapid depletion of fossil fuels and increased greenhouse gas emissions of conventional generators (CGs). To overcome these problems, the world has taken initiatives to deploy renewable energy resources (RERs) on a large scale, in order of GW, since a decade [81, 82]. The RERs, such as solar, wind, biomass, hydro, and tidal power are one of the most important sources in providing clean energy and mitigating greenhouse gas (GHG) emissions for sustainable development [83]. United Nations Sustainable Development and Paris Climate Agreement goals also promote installation of RERs. In 2016, the global deployment of RERs, excluding hydro power, reached 921 GW due to the increased awareness of climate change, with China being at the top spot in deployment of RERs followed by the USA, and Germany, as shown in Figure 3.1.

RERs, micro CGs, and energy storage systems (ESSs) are often described as distributed energy resources (DERs) in the literature [84]. DERs are on-site generation sources in distribution system. Hence, no transmission equipment is required for power transfer to load ends. In DERs, the RERs, particularly solar and wind energy, are volatile and intermittent energy sources. Therefore, ESSs and micro CGs are needed to overcome these uncertainties. The integration of DERs into distribution network requires the optimal sizing, control, and scheduling of these energy resources. A micro-grid (MG) embodies these issues by integrating DERs into power grid, together with an ability to operate in an islanded mode during main grid failure [85]. Hence, It helps in achieving objectives of efficient transformation of the passive network into an active one, bidirectional and controlled power flow management, reliable and continuous supply, power quality enhancement, and clean environment.

3. ENERGY MANAGEMENT SYSTEM OF HYBRID POWER GENERATION SYSTEMS WITH HIGH RATE OF RENEWABLES

Renewable Power Capacities in World, BRICS, EU-28 and Top 6 Countries, 2016

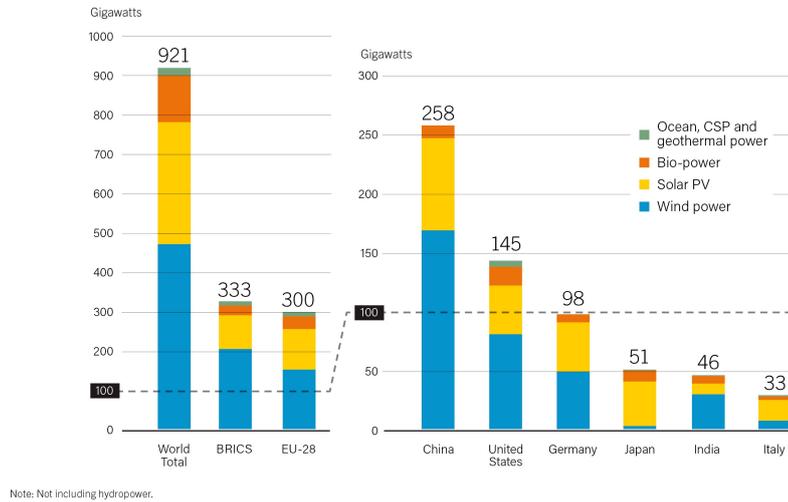


Figure 3.1: Global deployment of RERs [1].

MG is defined as a low-voltage distribution network of interconnected DERs, controllable loads, and critical loads. It can operate in either grid-connected or islanded mode subject to operational characteristics of the main grid [86, 87]. To have a flexible operation of MG, power electronic interfaces (PEIs) and controls are integrated with DERs for power quality monitoring, continuous, and reliable power supply [88].

MGs offer several advantages such as reduction in GHG emissions, reactive power support for voltage profile improvement, decentralization of energy supply, heat load integration for cogeneration, ancillary services and demand response (DR) [88]. It also reduces line losses and outages in transmission and distribution system. The MG deployment market status, all over the world, is presented in Figure 3.2. Autonomous basic MGs are defined as microgrids that cannot meet the load demand for 24 hours a day. However, autonomous full MGs have provisions for supplying energy to load end for all the day. Autonomous basic MGs are already deployed in all over the world except in Middle East, while autonomous full and interconnected community-based MGs are still in emerging and piloting phases of deployment.

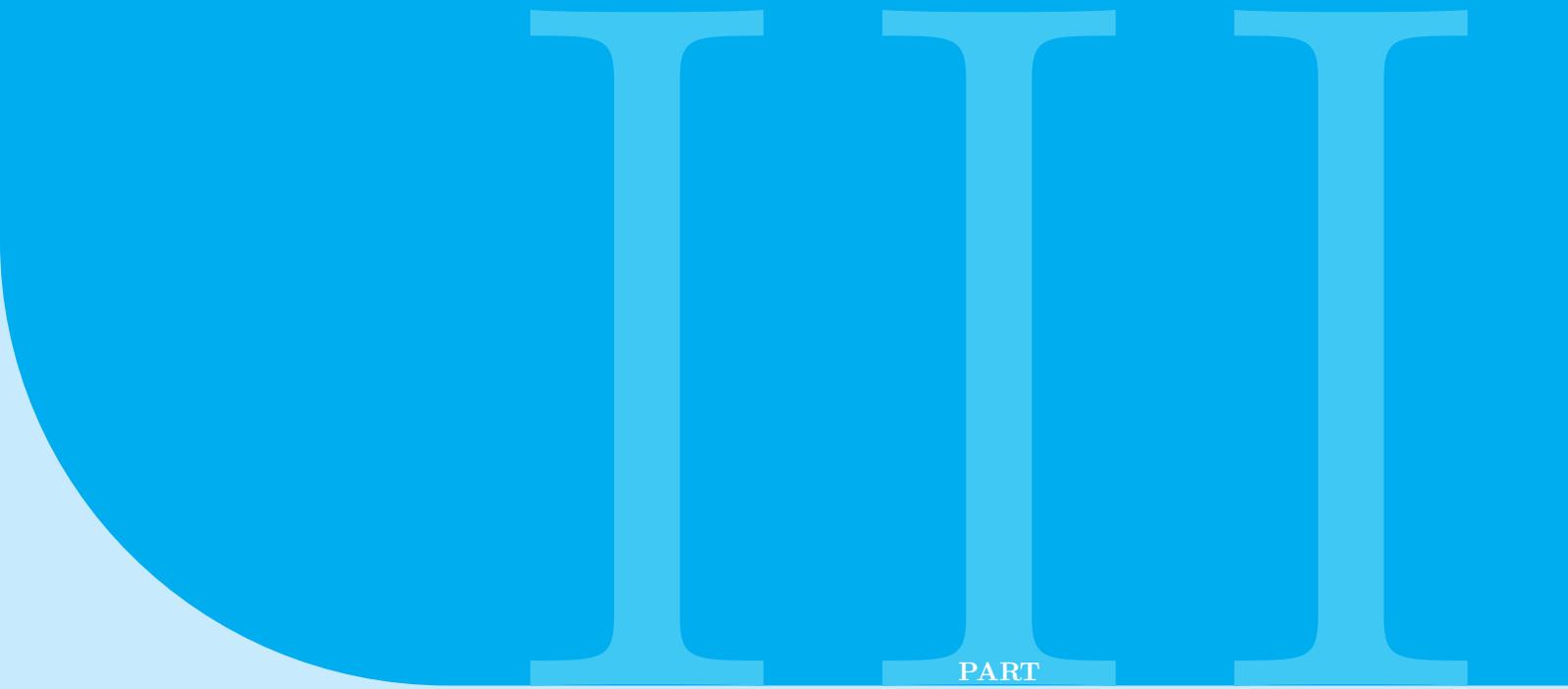
MGs have some limitations such as high investment cost of RERs, optimal use of energy sources, control issues and lack of system protection and regulatory standards, and customer privacy. Due to high deployment of inherently intermittent RERs and

	Region	Autonomous Basic	Autonomous Full	Interconnected Community
■ Limited	Central America and the Caribbean	■	■	■
□ Pilots	South America	■	■	■
■ Emerging	Northern Africa	■	■	■
■ Mature	Sub-Saharan Africa	■ ■	■	■
	Central and North Asia	□ ■	■	■
	East and South Asia	■	□ ■ ■	■
	Middle East	■	□	■
	Oceania	■	■ ■	□

Figure 3.2: MG market status [1].

increased integration of probabilistic controllable loads into MGs, researchers have focused on solving its energy management problems. Energy management system (EMS) of an MG encompasses both supply and demand side management, while satisfying system constraints, to realize an economical, sustainable, and reliable operation of MG [89].

3. ENERGY MANAGEMENT SYSTEM OF HYBRID POWER GENERATION SYSTEMS WITH HIGH RATE OF RENEWABLES



PART

Perspectives and research project

Perspectives and research project

1.1 Introduction

This research synthesis manuscript has summarized my main research contributions since 2013. During the last six years, my research activities were focusing on modeling, fault diagnosis, fault tolerant control of electric machines and drives, with special focus on marine energy converters application and energy management of hybrid microgrids with high rate of renewable resources. Specifically, three main research topics have been investigated:

- Faults detection and diagnosis of induction machines based on motor current signature analysis (MCSA) with special focus on spectrum analysis, demodulation techniques, time-frequency and time-scale analysis, and empirical mode decomposition.
- Modeling and sliding mode-based control for fault-tolerant control of marine current turbines. Both permanent magnet failure and converters open-circuit failure have been investigated in marine context.
- Modeling and energy management system for islanded or utility grid-connected microgrid with large-scale renewable energy resources.

1.2 Perspectives

Based on the previously discussed research topics and contributions, my future work should be focusing on the following two specific areas of research:

- Diagnosis, prognosis and fault-tolerant control of electric machines and power electronics for renewable energy generation systems and electric vehicles.

1. PERSPECTIVES AND RESEARCH PROJECT

- Microgrids and smartgrids: Optimal sizing, energy management, and control of hybrid microgrid with high rate of renewable resources and distributed energy storage systems and power quality monitoring based on signal processing techniques.

1.2.1 Diagnosis, prognosis and fault-tolerant control of electric machines and power electronics

The main issue hindering the development of marine renewable energy converters (MREC) such as offshore wind turbines, tidal turbines, and wave energy systems is their economic competitiveness. Indeed, the exploitation of MREC remains more expensive than the exploitation of fossil and nuclear energies, nowadays. This high cost can be partly explained by a relatively low equipment availability rate and maintenance operations cost. Indeed, to take advantage of certain energy sources, energy conversion systems are generally installed in geographic locations that are difficult to access (offshore, submerged, etc.) and are subject to extreme environmental conditions. Although efforts are being made to increase the robustness of these equipments, failures can never be totally ruled out. The reliability requirements of MREC require the design of energy conversion systems with low intrinsic level of failure and high fault tolerance. In addition, operating and maintenance costs reduction of MREC requires smart monitoring of its critical subsystems (generators, power converters, bearings and gearboxes, etc.). In this case, condition monitoring aims to collect data from sensors or provided by operators, which will then be processed and analyzed to monitor system operating conditions over time. More specifically, continuous monitoring of equipments health state allows detecting failures at an early stage (incipient faults) and thus schedule preventive maintenance before system shutdown.

This work can be viewed as part of “Prognostics and Health Management (PHM)”. PHM aims the development of methods and algorithms for systems monitoring, failures detection, diagnosis and prognosis as well as automatic decision-making as shown by Fig. 1.1. The implementation of PHM allows increasing smart maintenance rate; conditional maintenance and predictive maintenance and reducing traditional maintenance; corrective maintenance and scheduled preventive maintenance. Consequently, PHM allows increasing the availability, reliability and safe operation of these systems while reducing operating costs.

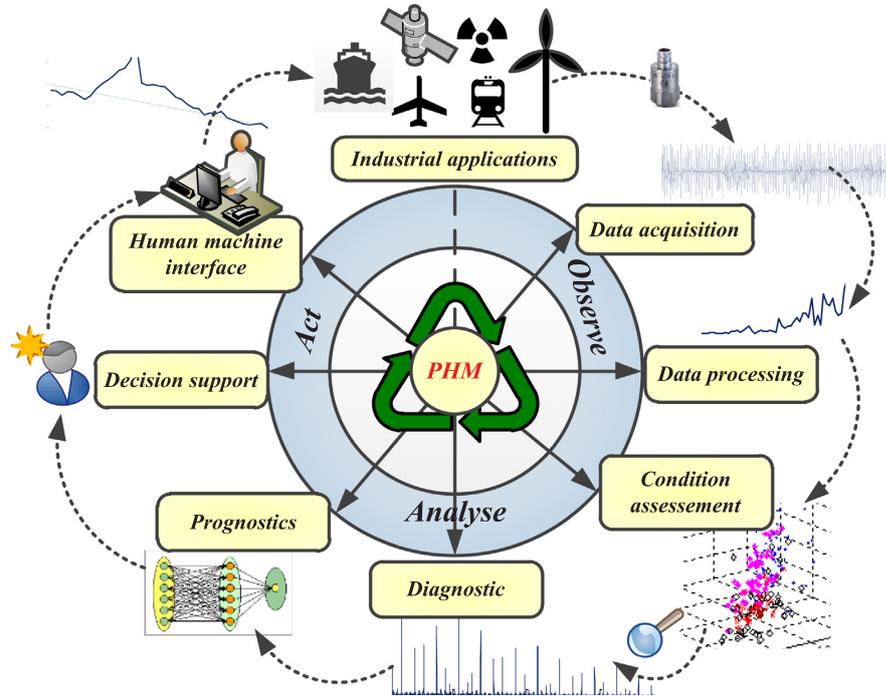


Figure 1.1: PHM cycle [2].

In this study, we will focus on fault detection of generators, bearings and power electronics based on the analysis of hybrid signals issued from currents sensors and vibration sensors. This analysis will ultimately enable online faults detection during operation or maintenance operations of MREC systems. The study will be carried out on a test bench at ISEN Yncréa Ouest in Brest and will be structured in three actions:

- **Action 1:** It will address failures detection based on electrical and vibration signals analysis and the definition of health parameters and indicators that will allow tracking health degradation of electrical machines, bearings and power converters (Fig. 1.2). It will investigate different detection methods to highlight the limits of each method and to propose a reliable and efficient fault detection approaches. Although most of the existing works focus on signals analysis approaches, it seems mandatory to deal with detection and decision-making stage. This stage should allow automatically detecting and characterising energy conversion chain faults. In this context, several algorithms can be investigated: hypothesis testing (Neyman-Pearson approach), artificial neural networks, support vector machines, deep learning, etc.

1. PERSPECTIVES AND RESEARCH PROJECT

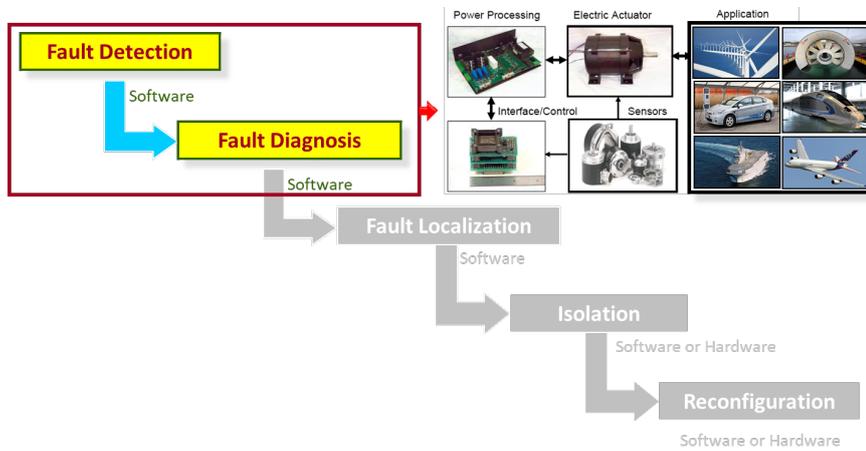


Figure 1.2: Faults diagnostic.

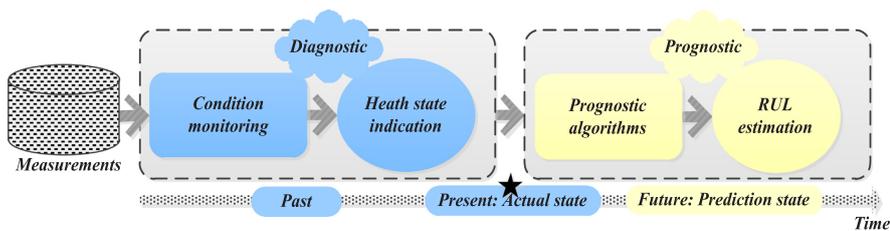


Figure 1.3: From diagnostic to prognostic [2].

- **Action 2:** It will concern failure prognosis method development (prediction of residual useful life) based on the use of condition monitoring indicators developed during previous action as shown by Fig. 1.3.
- **Action 3:** It will concern the design of reconfigurable fault-tolerant control systems for availability improvement (Fig. 1.4). Indeed, for off-shore and submerged / semi-submerged (tidal or wave) energy conversion chains, monitoring for preventive maintenance implementation is a key feature for massive deployment. However, it must be associated with fault-tolerant control and modular multilevel converter with redundant power modules for noninterruptible energy transfer. In the last few years, we are witnessing the fault diagnosis and condition monitoring moving toward the design and fault-tolerant drives. Hence, more sophisticated control techniques should be developed to ensure the continuity of production under faulty conditions. Moreover, the use of machine intrinsically robust toward failures, like multiphase machines are investigated and seems to be attractive solutions for

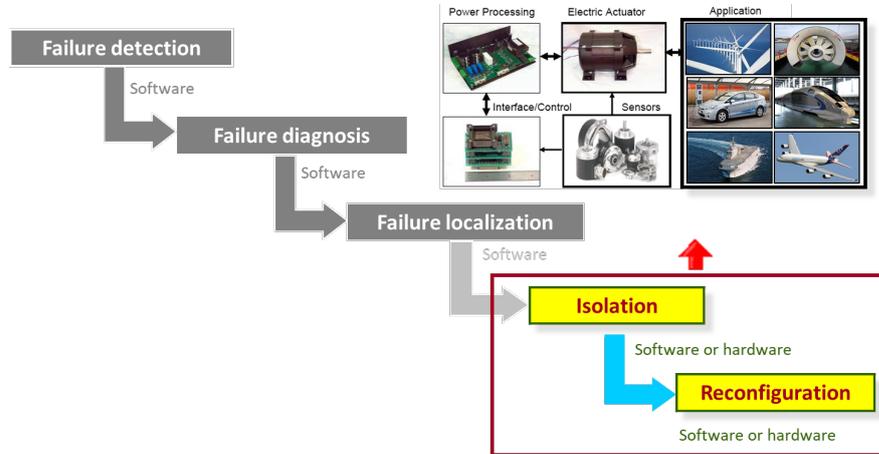


Figure 1.4: Fault tolerance and control reconfiguration.

more reliable and safe electromechanical systems.

1.2.2 Optimal sizing, control, and energy management of hybrid microgrid/smartgrid with high rate of renewable resources

Renewable resources-based energy production systems (wind turbines, tidal turbines, photovoltaic systems, etc.) are currently being deployed on a large scale to meet the needs of a growing energy demand, mitigate the impact of pollutants in fossil fuels and guarantee socio-economic benefits for sustainable development. Besides, in order to manage the intermittent nature of renewable energy resources and satisfy the load at all times, it is mandatory to develop energy storage systems such as pumped hydro, compressed air energy storage, batteries (Sodium-Sulfur, Lead-Acid, Nickel-Cadmium, Lithium-Ion, Redox-Flow), superconducting magnetic energy storage (SMES), supercapacitors, and flywheels. The integration of these distributed energy resources and storage devices into the distribution and transmission grid pave the way for microgrids. The concept of micro-grids has been introduced to have an autonomous power system that can effectively integrate various renewable energy sources, distributed energy resources, energy storage systems, controllable loads, and measurement and control devices that can operate in island mode during grid outages. In microgrids, an energy management system, which is a control and supervising unit, is mandatory for optimal use of these distributed energy resources in a smart, secure, reliable and

1. PERSPECTIVES AND RESEARCH PROJECT

coordinated way. It is therefore of great interest to develop decision-making strategies and methods for optimization problems solving for hybrid energy management systems in microgrids.

In a microgrid, distributed energy resources, energy storage systems, loads, and the main grid connection point are controlled by local controllers. These different local controllers communicate with the central controller who decides on the strategy to adopt for each local controller to ensure optimal operation (minimizing operation and maintenance costs, for instance). Therefore, a comparative analysis of communication technologies must be carried out for a cost-effective implementation of microgrid energy management systems. Moreover, the increasing deployment of electric vehicles has paved the way for battery-based electrical energy storage technologies enhancement both in terms of lifespan and cost. This leads to consider new usages for batteries connected to utility grid, either directly in the substations, at renewable plants level or at large consumption centers. These highly distributed energy storage systems must be integrated into central controller. Finally, information on prospects, future directions and possible industrial applications of microgrids and smartgrids need to be highlighted.

The objective types of MG EMS depend on its operation mode, its centralized or decentralized operation, economical aspects, and the intermittent and volatile nature of renewable energy sources. They also consider environmental issues of conventional generators, health status of batteries, active DR integration, system losses and reliability, and customer privacy. Many research studies have been conducted on some of these objective types. However, extensive investigations are still required to manage the customer privacy issues, develop secure and reliable communication system cost management, particularly for decentralized operation. Furthermore, microgrid systems reliability analysis is not studied in detail for islanding and remote applications. These potential areas need to be addressed in detail to achieve optimal energy efficient operation of microgrids.

In this context, the proposed project is a program for long-term anticipation of electrical systems including large-scale of renewable energy resources, battery-based distributed energy storage systems, flywheel energy storage system and electrical vehicles. By focusing on the system components, this project will provide an overview of new electrical architectures and their operation. Moreover, the connection of various energy storage systems to the utility grid as well as the integration of high rate of renewables,

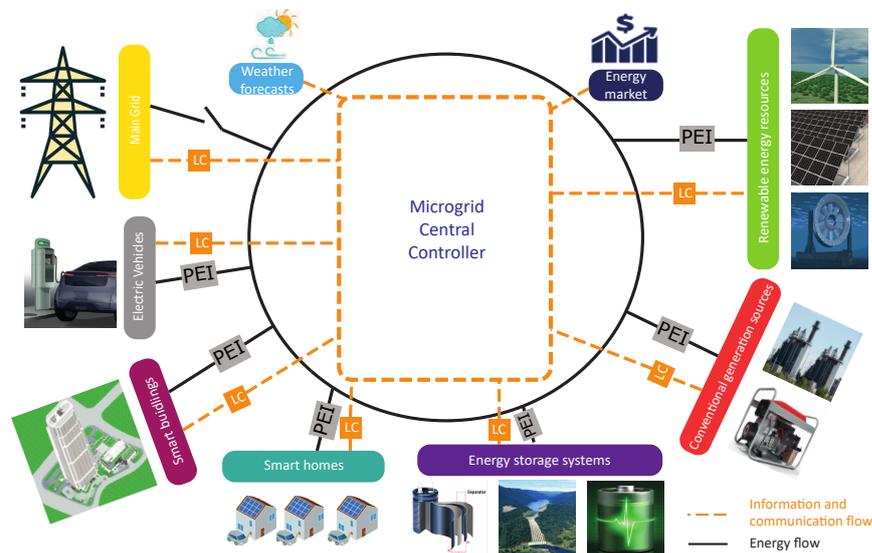


Figure 1.5: Microgrid control architecture.

inevitably raises the issue of optimal management of power flow between these potential means of distributed energy storage, local consumers and finally producers based on renewable energy. We are therefore talking about smartgrid, smart building, internet of energy (upgrading and automating of electricity infrastructures for energy producers), and distributed generators ancillary services.

This research topic should be investigated according to the following actions:

- **Action 1:** It will focus on microgrids design and optimal sizing that can effectively integrate various sources of distributed generation, especially renewable energy sources (RES), and can supply emergency power, changing between island and connected modes. The control architecture of a microgrid is depicted by Fig. 1.5
- **Action 2:** It will concern techniques for microgrid modeling and optimization of energy management system in a hybrid energy production system with the introduction of the concept of prosumers (bi-directional flow of power and information). This microgrid will consist of conventional and renewable resources, energy storage systems based on electric vehicles, batteries and flywheels and controllable loads. Microgrids can be interconnected in a cluster as shown by Fig. 1.6, in islanded mode or connected to distribution or transmission grid.

1. PERSPECTIVES AND RESEARCH PROJECT

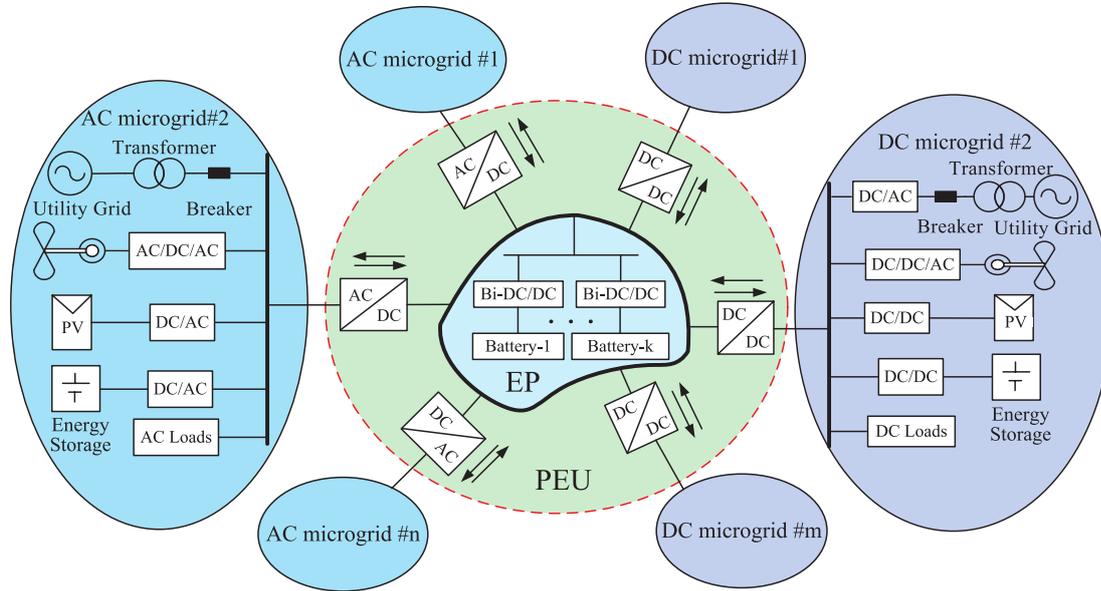


Figure 1.6: Microgrids clustering [3].

- **Action 3:** It will focus on the study of the integration of renewable energy resources to utility grid and their contribution to auxiliary services: frequency regulation and voltage regulation.

1.3 Conclusion

The discussed future works can be implemented during PhD thesis project or projects in collaboration with national and international laboratories. Moreover, more efforts should be made to build projects following a Call for proposals for research funding (ANR, European projects, etc.). In addition of the above detailed research perspectives, further actions should be undertaken to develop:

- National and international collaborations,
- Industrial collaborations,
- Experimental platforms with research and teaching capabilities.

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Titre : Amélioration de la qualité de l'énergie d'un micro-réseau à base de ressources renouvelables : diagnostic, commande en mode dégradé et gestion optimale de l'énergie

Mots clés : Micro-réseau, énergie renouvelable, gestion optimale de l'énergie, diagnostic, commande en mode dégradé.

Résumé : Ce manuscrit de HdR résume mes activités d'enseignement, mes principales contributions scientifiques, ainsi que mes services et responsabilités scientifiques. La première partie de ce document présente mon curriculum vitae, mes activités d'enseignement et de recherche, les services et responsabilités nationaux et internationaux et les principales plateformes expérimentales réalisées qui peuvent servir dans les activités d'enseignement et de recherche. La deuxième partie est dédiée à la synthèse des principales activités de recherche et d'encadrement.

Les contributions scientifiques majeures ont été présentées : diagnostic des défaillances dans les machines électriques tournantes et contrôle tolérant aux défauts des machines et entraînements électriques dans un contexte lié aux énergies marines renouvelables et développement des systèmes de gestion optimale de l'énergie des microréseaux à fort taux d'intégration des ressources renouvelables avec application à l'île Ouessant en Bretagne. La troisième partie décrit les perspectives et les orientations possibles des futurs travaux de recherche.

Title : On fault diagnosis, fault-resilient control, and smart energy management for renewables-based microgrid optimal operation

Keywords : Microgrid, renewable energy, energy management systems, diagnosis, fault-tolerant control.

Abstract : This HdR manuscript summarizes my teaching activities, main research contributions and publications, PhD students supervising, and scientific services and responsibilities. These teaching and research activities have been carried out since 2013 and have been performed as associate professor at ISEN Yncréa Ouest, Brest campus and a research scientist at IRDL (Institut de Recherche Dupuy de Lôme), UMR CNRS 6027, Brest since 2016. This manuscript is organized as follows.

Part I presents my Curriculum Vitae, teaching and research activities, national and international services, and main experimental platforms with education and research capabilities. Part II focuses on main research topics synthesis. Three research contributions have been highlighted: faults diagnosis and fault tolerant control of electric machines and drives and energy management system for microgrids with high rate of renewable resources. Part III describes perspectives and some directions for future research works.

