RESEARCH ON THE MODELING, IDENTIFICATION AND OPERATION OF RENEWABLE ENERGY CONVERSION SYSTEMS

Doctoral thesis - Summary

for obtaining the scientific title of doctor at
Politehnica University of Timisoara
in the doctoral field of Systems Engineering

author eng. Cezara-Liliana Raț
scientific director Prof.univ.dr.ing. Octavian Proștean

month March year 2022

Chapter 1, INTRODUCTION, presents the main objectives and the structure of the paper depending on the concerns it addresses. Environmental pollution and the desire to fight this aspect of today's world are at the heart of the author's motivation for choosing this subject. The opportunity to research it arose due to the increased use of renewable energy sources for the production of *eco-friendly* electricity, resulting in the reduction of environmental pollution. However, the expansion of these types of energy sources is hampered by the costs involved and the lower performance of these sources compared to established energy sources. Thus, it becomes extremely necessary to develop new solutions to increase their competitiveness.

The main objectives proposed in this paper are:

- Forming a critical analysis of renewable energies to electricity conversion systems.
- Identifying the mathematical models of the main components found in these energy conversion systems in order to develop control structures for them.
- Forming a critical analysis on the control of renewable energy conversion systems.
- Developing control structures aimed at maximizing the power produced by these sources (PV, wind turbines, hydro turbines).
- Analyzing the means of integrating renewable energy conversion systems in the energy grid through microgrid systems.

The thesis is a synthesis of the author's achievements during her doctoral research program. Some of her accomplishments have already been published: 10 papers published in ISI indexed conference volumes and 7 papers published in non-indexed international conference volumes.

The paper was structured in 7 chapters, 208 pages, comprising 145 figures, 35 tables, and having as inspiration 200 bibliographical references.

Chapter 2, STATE OF THE ART OF RENEWABLE ENERGY CONVERSION SYSTEMS AND THEIR INTEGRATION INTO THE MAIN GRID, begins with a bibliographic study on the use of unconventional energy sources, such as wind energy, hydro energy and solar energy. Wind energy conversion requires wind turbines, their features being presented in detail in this chapter. Hydro energy conversion has also been discussed highlighting hydrokinetic turbines, a type of hydro turbine that have gained popularity recently. Solar energy conversion is done mainly through either photovoltaic panels or concentrators, PV panels being the overall preference due to the fact that they convert solar energy directly into electricity.

The chapter continues with an overview of the primary means of integrating renewable energy conversion systems as well as microgrids into the main grid. It presents an analysis of the state of the art in renewable energy conversion systems based on source type (wind, sun, water).

A description of the advancements in microgrid architecture and functionality highlighting features such as adaptability, flexibility, scalability and efficiency is also provided.

Chapter 3, MODELING THE COMPONENTS OF RENEWABLE ENERGY CONVERSION SYSTEMS, deals with issues regarding the modeling of the main components of renewable energy conversion systems, namely turbines (wind turbines and hydrokinetic turbines), generators (synchronous generators and permanent magnets) and PV panels, models being developed for each of the aforementioned components.

The turbine behavior is expressed by the aerodynamic model and the mechanical model, both of which are necessary to describe the static and dynamic regimes of the process of converting wind / water energy into rotational energy. The aerodynamic model is more complex requiring a larger volume of calculations that cannot be completed in the time required to implement real-time control algorithms. Therefore, it is necessary to find equivalent relationships that involve as few calculations as possible, which are easier to implement on DSP or microcontroller control systems. Relationships in the form of polynomial regressions have been developed to approximate the torque or power coefficient. The relationships with the best quality indicators were chosen.

The PMSG behavior is also described through a dynamic and a mechanical model. The mechanical model is similar to that of turbines, the difference being the inclusion of the friction factor, which is neglected in the case of turbines. The dynamic model is attained by using the Park transformation from the abc reference system to the dq0 reference system, with the purpose of deriving a model with a simpler form.

In the case of the PV panels, an extended variant of the one-diode model is used, namely the five-parameter model, a model with good performance, acceptable accuracy and relatively low complexity. Relationships have also been developed to approximate the values of specific panel parameters, relationships that can be used directly in the synthesis of control strategies.

The simulations were performed using MATLAB / Simulink and LabVIEW. The LabVIEW simulation was used to design the software part of a real-time Hardware-In-the-Loop (HIL) emulator based on NI equipment, which is described in detail in Chapter 6.

The results obtained in this chapter also serve as a basis for the implementation and testing of control strategies for renewable energy conversion systems.

Chapter 4, MODELING AND SIMULATION OF DC-DC CONVERTERS, deals with issues regarding the modeling and identification of DC-DC converters, namely Buck, Boost and Buck-Boost converters. Different models have been developed for all three converters. The most informative models regarding converter characteristics are those resulting from classical state-space modeling, but these models (MM-ISI-SISO and MM-ISI-MIMO) may be nonlinear (both types of models in the case of Boost converters and Buck-Boost are nonlinear), and require linearization. In order to simplify the procedure of obtaining a linear model, the author has contrived a method which involves analyzing the configuration in which the converter is used (source-side converter - SSC and load-side converter - LSC) in order to obtain simplified linear models. Another option would be to model the load-connected converter by an equivalent resistor, but this model no longer preserves the essential dynamics of the system, it being more suited for estimating the current delivered by the generator. The proposed simplified models (MM-ISI-SSC and MM-ISI-LSC) have the advantage of retaining the essential features of the system dynamics. These models are directly usable in implementing and testing control strategies, as demonstrated in Chapter 5.

Another problem that may arise is the insufficient knowledge of the parameters of the converter components (for example, the resistance value of the coil R_L or the capacitor R_C are not usually provided by the manufacturers). The solution is to experimentally identify them. Two methods of identifying the Buck converter model were tested, these being the graphic-analytic method and an original regression method, based on the analytical expression of the step input response using MATLAB's CFtool. The original method was validated by laboratory tests performed on a Buck converter and by comparison with the graphic-analytic method.

Both methods can only be used if resistance R_C is negligible. Otherwise, the analytical model of the converter is too complex to be identified by either method, but the hypothesis that is generally accepted in the literature is that the value of R_C is small enough to be neglected. The method chosen to identify the models was the regression method because it proved to be more accurate and more efficient. However, the parameters of the identified models (transfer functions) depend on the value of the load resistance. In order to obtain a general model that can be used regardless of the value of the load, the dependencies of the previously identified parameters α and ω on the value of the load were determined through the use of regression methods. In order that the resulting models be more suitable to be used in control algorithms, only regression functions with a lower degree of complexity, such as power and exponential functions with one or two terms and polynomial functions with orders less than or equal to 5, were sought. In these conditions, the results obtained for the regression function $\omega(R_S)$ were not satisfactory, however, since the transfer function can be rewritten according to parameters ξ and ω_n, an attempt was made to determine the dependencies between these parameters and R_S. The quality indicator values obtained for $\xi(R_S)$ and $\omega_n(R_S)$ were satisfactory.

Chapter 5, CONTROL OF RENEWABLE ENERGY CONVERSION SYSTEMS, consists of designing, implementing and validating control structures based on maximum power point tracking (MPPT). The main objective pursued in MPPT control strategies is to obtain maximum power in any mode of operation. This increases the efficiency of the renewable energy conversion system while maintaining electricity quality.

Control strategies aimed at extracting maximum power generally involve a two-level control structure: at the inferior level, basic converter currents and voltages are regulated (output voltage, output current or input current), and at the superior level, the MPPT algorithm operates, providing references for the lower level control structure (voltage or current reference). There are exceptions to this rule: MPPT algorithms that do not require the existence of a lower level regulator, the algorithms themselves providing the value of the duty cycle for the converter. These algorithms are generally based on classical online methods such as: perturb and observe, incremental conductance etc.

The first part of this chapter is dedicated to converter control. Designing the control algorithms of Buck and Boost converters was significantly simplified through the use of the simplified models based on the configuration in which the converter is used (SSC - 4.3.52 și LSC – 4.3.67, 4.3.78), developed by the author in Chapter 4. There are huge differences between the required control structures when the configuration is changed: in the case of the load-side converter (LSC) - state control is used, and in the case of the source-side converter (SSC) - output regulation is used. These control strategies were selected based on information obtained from the simplified converter models. The resulting control systems were used as a basis for implementing MPPT control strategies.

The second part of this chapter is dedicated to MPPT control of PV panels and turbines (wind and hydrokinetic).

Three original MPPT algorithms were developed for PV panels: one based on a search table (L), one P&O algorithm with variable perturbation based on fuzzy logic (FL) and one based on polynomial regression (R). The L algorithm is based on a classic offline method, the FL algorithm is based on a hybrid P&O-Fuzzy Logic method, and the R algorithm is based on an optimization method. The algorithms were implemented in a photovoltaic energy conversion system consisting of a PV panel, a Buck-Boost converter and a resistive load. The performances of the three algorithms were analyzed by comparison with a classical P&O algorithm with constant perturbation. These methods were chosen because they present affordable implementation costs.

In the light of the results obtained from the comparison, the performances of hybrid MPPT methods compared to the classical methods were analyzed:

• hybrid methods have the potential to find the right MPP voltage in a shorter time than online methods, but in a longer time than offline methods;

• hybrid methods can provide better accuracy than offline methods, but cannot eliminate oscillations around MPP;

• hybrid methods have higher implementation costs than individual methods.

Hybrid methods combine the characteristics of both online and offline methods, but their widespread use is hindered by high implementation costs.

Regarding the turbines, MPPT algorithms can be classified according to the operating region into three categories:

• Algorithms that operate in region 2, also called the partial load region, where the wind speed is below the nominal value, the objective being to maximize the turbine output power.

• Algorithms operating in region 3, where the wind speed is higher than the nominal value, so the captured power must be limited to ensure the safe operation of the turbine.

• Hybrid algorithms, which use a combination of the above techniques.

An MPPT algorithm used to adjust the angle of attack of the blades of a hydrokinetic turbine using fuzzy logic has been developed. This algorithm works in region 3, where the control structure is basically an overspeed protection and requires the simultaneous existence of a region 2 control structure.

Chapter 6, INTEGRATION OF RENEWABLE ENERGY SOURCES INTO ENERGY SYSTEMS, deals with the issue of connecting renewable energy conversion systems to the main grid. Solutions were implemented on experimental stands within a microgrid laboratory (at UPT).

In order to emulate the operation of a wind turbine in laboratory conditions, an experimental stand, which is the HIL simulator, was created. The use of a HIL simulator as a turbine is a satisfactory solution, its advantages being:

- flexibility: a multitude of wind turbines can be tested without investment in wind tunnels and real turbines, leading to the possibility of rapid prototyping for WECS systems;

- universality: the possibility of testing different control systems, power converters, energy storage elements, electrical charges, etc.;

- generality: the use of the simulator structure can be extended to other energy conversion systems (hydro, sea currents, sea waves, etc.).

The limitations of the HIL simulator are related to the limitations of the physical equipment, namely the simulator can be used for turbines of different powers, but it is necessary to adapt to the power of the drive motor. Another problem would be the relatively low efficiency of the conversion system. This is due to the MPPT algorithm built into the inverter which is not customized for the turbine model with which it operates. Therefore, in order to be able to test various turbines in optimal operating conditions, it is necessary to update the MPPT algorithm each time the turbine model is changed, a time-consuming and resource-intensive process. This simulator is the author's contribution to the microgrid laboratory in which it is incorporated.

The microgrid reconfigurable laboratory incorporates two types of renewable energy sources (PV panels and the HIL emulator for wind turbines), a storage system consisting of supercapacitors and batteries, two DC buses, as well as a connection to the national energy network. The composition, architecture, functionality and control of the implemented DC microgrid are presented in detail.

Chapter 7, FINAL CONCLUSIONS AND CONTRIBUTIONS. DEVELOPMENT PERSPECTIVES, highlights the conclusions of the thesis, the original contributions of the author and possible future research directions. The results of this thesis consist of the following original contributions:

- Carrying out a comparative analyzes between the simulation results of the wind turbine, the hydrokinetic turbine and the PMSG generator in Matlab / Simulink and LabVIEW respectively;
- Determining the power coefficient of the HKT hydrokinetic turbine by using regression methods;
- Developing a PV panel model;
- Determining a MPP voltage estimating relationship at as a function of temperature at constant irradiation;
- Determining a MPP voltage estimating relationship as a function of irradiation at constant temperature;
- Determining a maximum power estimating relationship as a function of irradiation at constant temperature;
- Elaborating a critical analysis of the switching converters models (Buck, Boost and Buck-Boost) existent in the literature, with highlighting their essential particularities;
- Classifying converters according to the configuration in which they can be used in a microgrid;
- Developing of simplified linear models (1st order) for Boost and Buck-Boost converters, directly usable in designing control strategies.
- Developing of an original method for identifying an ET-PT2 based on approximating the experimentally determined step input response through a regression function and applying of the method to the identification of the Buck converter model;
- Performing a comparative analysis between the proposed regression method and the graphic-analytic method;
- Determining the dependencies between the identified parameters of the model (α, ω, ξ and ω_n) and the value of the load, as well as a parameterized converter model as a function of the load;
- Developing and testing of control structures for Buck and Boost converters depending on the configuration in which the converters are used in a microgrid;
- Developing and testing MPPT control algorithms for PV panels using regression methods, fuzzy logic and lookup tables;
- Performing a comparative analysis between the proposed MPPT algorithms and a standard P&O algorithm;
- Performing a critical comparative analysis of MPPT methods for WECS;
- Developing and testing of a blade angle control algorithm for HKT;
- Implementing the software part of a Hardware-in-the-Loop emulator;
- Gathering experimental data on the operation of a microgrid with two renewable sources (wind turbine and PV) with decentralized control;
- Implementing a data acquisition application in the LabVIEW programming environment for WECS1 based on the MVC technique;
- Implementing two remote WECS1 monitoring applications using different technologies (Remote Panels and RFC);
- Use ActiveX technology for remote video monitoring.

The problems presented, as well as the results obtained after solving them, give this paper a character of practical applicability, opening new perspectives in the research in the field of renewable energy conversion.

Selective references

1. [Bha 2020] - Bhattacharyya, S., Samanta, S., & Mishra, S. (2020). Steady Output and Fast Tracking MPPT (SOFT-MPPT) for P&O and InC Algorithms. IEEE Transactions on Sustainable Energy, 12(1), 293-302.
2. [Bol 2020] - Bollipo, R. B., Mikkili, S., & Bonthagorla, P. K. (2020). Hybrid, optimal, intelligent and classical PV MPPT techniques: A review. CSEE Journal of Power and Energy Systems, 7(1), 9-33.
3. [Chi 2019] - Chinnappan, R., Logamani, P., & Ramasubbu, R. (2019). Fixed frequency integral sliding-mode current-controlled MPPT boost converter for two-stage PV generation system. IET Circuits, Devices & Systems, 13(6), 793-805.
4. [Fil 2018] - Filip, I., Dragan, F., Szeidert, I., & **Rat, C.** (2018, September). Design of an extended self-tuning adaptive controller. In International Workshop Soft Computing Applications (pp. 392-402). Springer, Cham.
5. [Fir 2020] - Firdaus, A. A., Yunardi, R. T., Agustin, E. I., Nahdliyah, S. D., & Nugroho, T. A. (2020). An improved control for MPPT based on FL-PSo to minimize oscillation in photovoltaic system. International Journal of Power Electronics and Drive Systems, 11(2), 1082.
6. [Pan 2015] - Panoiu, M., **Rat, C. L.,** & Panoiu, C. (2015, May). Video streaming technologies using ActiveX and LabVIEW. In IOP Conference Series: Materials Science and Engineering (Vol. 85, No. 1, p. 012023). IOP Publishing.
7. [Pat 2017] - C. Patrascu, **C. Rat**, D. Hulea, D. Vitan and N. Muntean, "Mixed PV-wind small power microgrid," 2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP), 2017, pp. 699-704, doi: 10.1109/OPTIM.2017.7975050.
8. [**Rat 2018a**] **- Rat, C. L.**, Prostean, O., Filip, I., & Vasar, C. (2018, September). Remote Wind Energy Conversion System. In International Workshop Soft Computing Applications (pp. 273-282). Springer, Cham.
9. [**Rat 2018b**] – **Rat C. L.** (2018), Design of a SCADA system for a Traffic Turbine, ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering, Tome XVI [2018], Fascicule 4 [November].
10. [**Rat 2018c**] **- Rat, C. L.,** & Panoiu, M. (2018, January). Wind turbine remote control using Android devices. In IOP Conference Series: Materials Science and Engineering (Vol. 294, No. 1, p. 012070). IOP Publishing.
11. [**Rat 2018d**] **- Rat, C. L.**, Prostean, O., Filip, I., & Vasar, C. (2018, June). The Modeling and Simulation of an Archimedes Spiral Turbine for Use in a Hydrokinetic Energy Conversion System. In 2018 IEEE 22nd International Conference on Intelligent Engineering Systems (INES) (pp. 000245-000248). IEEE.
12. [**Rat 2018e**] **- Rat, C.**, Vasar, C., Gana, O., & Prostean, O. (2018). Microgrid supply management. Procedia-Social and Behavioral Sciences, 238, 46-52.
13. [**Rat 2018f**] **- Rat, C. L.**, Prostean, O., & Filip, I. (2018). Hardware-in-the-Loop emulator for a hydrokinetic turbine. In IOP Conference Series: Materials Science and Engineering (Vol. 294, No. 1, p. 012071). IOP Publishing.
14. [**Rat 2019**] **- C. Rat**, O. Prostean and I. Filip, "Power Control of a Variable-Pitch Hydrokinetic Turbine," 2019 IEEE 13th International Symposium on Applied Computational Intelligence and Informatics (SACI), 2019, pp. 167-172, doi: 10.1109/SACI46893.2019.9111515.

15. [**Rat 2021a**] - **Rat C.**, Prostean O., " The Impact Of Communication Network On Grid Management", 37th IBIMA International Conference, Cordoba, Spain, 2021, ISBN: 978-0-9998551-6-4.
16. [**Rat 2021b**] - **Rat C.**, " WECS Simulator for A Virtual Microgrid Laboratory", 37th IBIMA International Conference, Cordoba, Spain, 2021, ISBN: 978-0-9998551-6-4.
17. [**Rat 2021c**] - **Raţ, C.L.**, Ichim-Burlacu, C.I., Panoiu, C. Modeling the synchronous permanent magnet generator with RLC load, INTERNATIONAL CONFERENCE ON APPLIED SCIENCES (ICAS2021), May 12-14, 2021, Hunedoara, Romania.
18. [**Rat 2021d**] - **Raţ, C.L.**, Ichim-Burlacu, C.I., Panoiu, M. The impact of communication on microgrid control, INTERNATIONAL CONFERENCE ON APPLIED SCIENCES (ICAS2021), May 12-14, 2021, Hunedoara, Romania.
19. [Reh 2019] - Rehmani, M. H., Davy, A., Jennings, B., & Assi, C. (2019). Software Defined Networks-Based Smart Grid Communication: A Comprehensive Survey. IEEE Communications Surveys & Tutorials, 21(3), 2637-2670.
20. [Tch 2020] - Tchouani Njomo, A. F., Kenne, G., Douanla, R. M., & Sonfack, L. L. (2020). A Modified ESC Algorithm for MPPT Applied to a Photovoltaic System under Varying Environmental Conditions. International Journal of Photoenergy, 2020.
21. [Tha 2019] - Thakur, R. N., & Pandey, U. S. (2019). The Role of Model-View Controller in Object Oriented Software Development. Nepal Journal of Multidisciplinary Research, 2(2), 1-6.
22. [Vas 2018] - Vasar, C., **Rat, C. L.**, & Prostean, O. (2018). Experimental model of a wind energy conversion system. In IOP Conference Series: Materials Science and Engineering (Vol. 294, No. 1, p. 012081). IOP Publishing.