Gerasimos G. Rigatos

Intelligent Renewable Energy Systems

Modelling and Control

Springer

To Elektra

Foreword

Renewable energy systems become progressively a significant part of the electric power network, worldwide. During the last years there has been a raise in the use of renewable energy sources, in the form of hydroelectric systems, wind power systems, photovoltaic units, marine power systems, fuel cells, biomass systems etc. It is necessary renewable energy sources to become more reliable and more profitable. This will allow countries to reduce their dependence on energy coming from fossil fuels or natural gas. while it will also contribute to the elimination of the negative environmental effects of thermal power stations.

To deploy the exploitation of renewable energy sources, technologies of the smart grid have gained particular importance. At a first stage one has to solve in an efficient and intelligent manner problems associated with the connection of renewable energy sources to the electricity grid, as for instance perturbations in the quality of electric power or synchronisation and stability issues of distributed power generators. Thanks to information technology one can better integrate renewable energy sources into the electricity grid.

The monograph focuses on the modelling and control of renewable energy sources and on technologies which allow for the more efficient integration of such sources in the electricity grid. The monograph presents recent results and methods which assure that the production of electric power coming from renewable energy systems, will be free of interruptions, that power losses will be minimised while also the generators functioning will be robust to adverse operating conditions (for example to faults of the electricity grid). The monograph analyses advanced technologies for renewable energy systems, as for example:

(i) intelligent control for power generators (synchronous and asynchronous) finding application in the exploitation of renewable energy sources (control of the rotors speed of power generators, control of the magnetic flux and control of the produced active and reactive power).

(ii) intelligent control of power electronics which are used for the connection of renewable energy sources to the electricity grid (control of AC to DC converters, control of inverters, control of distortions in voltage harmonics with the use of active filters, and control of high voltage transmission lines of the HVDC type).

(iii) optimisation methods for the synchronisation and stabilisation of distributed power generators (interconnected generators of the PMSG or DFIG type, DC electric power units such as photovoltaics, optimal planning and management of electric power production coming from renewable energy sources).

(v) Computational intelligence techniques for the financial exploitation of the electric power that is produced by renewable energy sources, in the framework of open and interconnected electricity markets.

The monograph contains new results and findings on control and estimation problems for renewable energy sources within a smart grid context. Actually it presents new nonlinear control and estimation methods, which are based on the exact linearization of the dynamics of renewable power sources. Such methods make use of differential flatness theory. Such methods are shown to have specific advantages in terms of accuracy of estimation and computation speed comparing to other control and filtering methods. Moreover, the monograph analyzes approximate linearization methods for renewable energy sources based on H-infinity control theory. Such methods succeed solution of control and estimation problems for the electric machines and the power electronics constituting the renewable energy systems, without the need for computing linearizing transformations. The latter methods, yet being computationally and conceptually simple succeed robustness for the control and estimation schemes of renewable energy sources. Finally, the monograph analyzes methods for control of renewable energy systems which are based on the definition and minimization of suitable Lyapunov functions. Such methods can be completely model-free, and the lack of knowledge about the dynamics of the renewable energy systems can be compensated by adaptive-learning schemes of proven convergence and stability.

The content of the monograph can be used for teaching undergraduate or postgraduate courses in renewable energy systems. Therefore it can be used by both academic tutors and students as a reference book for such a course. The monograph's methods and findings on renewable energy systems can be also of interest for the engineering community. The nonlinear control and estimation methods analyzed in the monograph can be a powerful tool and useful companion for engineers working on practical problems of renewable energy systems.

Athens, June 2016 *Gerasimos Rigatos*

Preface

The use of renewable energy systems, such as wind power, hydro-power, tidal power, solar power, geothermal power and biomass burn is growing. Research in electric power generation from renewable sources is continuously expanding and stands for an area of high technological and financial importance. The implementation of new technologies for the functioning and management of renewable energy systems will help to further develop the renewable energy sector. The application of advanced scientific methods (for the modelling,, identification and control of the dynamics of renewable energy systems and for the management of the electric power that is generated by them) can improve the reliability and efficiency of renewable power generation units. To this end, the present monograph analyses newer methods in the design of renewable energy systems based on intelligent information processing.

The monograph gives emphasis to the following key topics and technologies for renewable energy systems: (i) intelligent control of power generators (sybchronous or asynchronous) used in renewable energy systems (control of rotational motion, electromagnetic field, as well as control of active and reactive power), (ii) intelligent control of the power electronics that connect renewable power generation units to the grid (control of AC to DC voltage source converters, control of inverters, AC lines control through active power filters, control of HVDC lines), (iii) synchronization and stability of distributed power generation units (interconnected PMSGs or DFIGs), as well as power planning and management in distributed renewable energy sources, (iv) fault diagnosis for power generators and power electronics used for producing power from renewable sources, as well as condition monitoring of the associated transmission and distribution grid.

The monograph comprises 10 chapters.

Chapter 1 overviews the basic components of renewable energy systems, such as (i) power generators (PMSG, DFIG, multi-phase machines, and Doubly-Fed Reluctance machines), (ii) power electronics for connecting generators to the grid (DC to

AC inverters, AC to DC and DC to DC converters, active power filters, power transformers. First, doubly-fed induction generators (DFIGs) are analyzed. The concept of field orientation is explained and the complete 6-th order model of the asynchronous machine is introduced. Next, the model of synchronous generators is analyzed. Additionally, More elaborated schemes for power generation from renewable sources arise in the case of using power generators of multi-phases (windings) at the stator. Thus,the model of multi-phase synchronous generators and doubly-fed reluctance generators is introduced. Next, the dynamics of power electronics used for connecting renewable energy sources to the grid is explained. To this end the model of three-phase AC to DC converters, of inverters (DC to AC converters), of DC to DC converters and of HVDC transmission lines is given. Moreover, the dynamic model of electrochemical power generation devices, such as fuel cells, is explained. Additionally, the distributed parameters (PDE) model of power storage devices, such as Li-ion batteries is explained.

Chapter 2 analyzes nonlinear control for Doubly-fed induction generators, through different approaches: (i) flatness-based control in cascading loops, (ii) flatness-based control through transformation to the canonical form, (iii) differential geometry-based control, (iv) nonlinear H-infinity control, (v) flatness-based adaptive control (vi) field orientation and backstepping control.

First, the chapter proposes a solution to the problem of sensorless control of doubly-fed induction generators, which is based on differential flatness-theory and which is implemented in successive loops. Next, the chapter studies differential flatness properties and an input-output linearization procedure for control doubly-fed induction generators. Additonally, the chapter introduces a new method for feedback control of asynchronous electrical machines, which consists of a repetitive solution of an H-infinity control problem for the DFIG. The method makes use of a locally linearized model of the generator and is based on the solution of an algebraic Riccati equation at each iteration of the control algorithm. Finally, the chapter proposes an adaptive control approach, being based on differential flatness theory, that is capable of compensating for model uncertainty and parametric changes of the DFIG, as well as for lack of measurements for the DFIG's state vector elements. The stability of the adaptive control method is proven through Lyapunov analysis.

Chapter 3 analyzes different approaches for nonlinear control of synchronous generators: (i) flatness-based control through transformation to the canonical form, (ii) flatness-based control in cascading loops, (iii) differential geometry-based control, (iv) nonlinear H-infinity control, (v) stabilizing control of synchronous power generators in the s-frequency domain. First, the chapter is concerned with proving differential flatness of the permanent magnet synchronous generator. Using differential flatness properties a sensorless control scheme for the electric machine is developed. Next, the chapter proposes a new method for the control of nonlinear dynamics of synchronous generators which is based on demonstrating that differential flatness properties hold for the subsystems which are obtained from the per-row decomposition of the machine's state-space models into subsystems. The controller's design is implemented in successive loops, while asymptotic stability of the control scheme is analytically proven. Finally, the chapter introduces an s-frequency domain method for the stabilization of the synchronous generators connected to the electricity grid. The method is based on interval polynomial's theory and on frequency response analysis techniques (root locus diagrams or Nyquist plots) for local transfer functions through which the generator's model is represented.

Chapter 4 analyzes different approaches for nonlinear control of multi-phase electric machines: (i) H-infinity control of multi-phase synchronous electric machines, (ii) H-infinity control of doubly-fed reluctance machines, (iii) flatness-based adaptive control of doubly-fed reluctance machines. First, in this chapter power generation with the use of multi-phase synchronous machines is considered. The dynamic model of the 6-phase synchronous electric machine undergoes an approximate linearisation, through Taylor series expansion and an H-infinity feedback controller is applied for its stabilization. The controller requires the solution of a Riccati equation at each iteration of the control algorithm. Next, the chapter develops an H-infinity approach for the problem of nonlinear optimal control of doubly-fed reluctance machines. Again the dynamic model of the machines is subjected to linearization round local operating points, through Taylor series expansion and the computation of Jacobian matrices. For the linearized model an H-infinity feedback controller is designed. Finally, the chapter proposes a flatness-based adaptive control approach that is capable of compensating for model uncertainty and parametric changes of the doubly-fed reluctance machines (DFRMs), as well as for the lack of measurements about the DFRM's state vector elements. First it is proven that the DFRM's model is a differentially flat one. The unknown dynamics of the system is identified in real time with the use of neuro-fuzzy approximators. The stability of the considered observer-based adaptive control approach is proven using Lyapunov analysis.

Chapter 5 analyzes different approaches for nonlinear control of AC to DC converters (rectifiers), such as: (i) flatness-based control through transformation to the canonical form, (ii) differential geometry-based control, (iii) nonlinear H-infinity control. Moreover, the chapter presents flatness-based control for the HVDC-VSC transmission system. First, the chapter proposes a method for nonlinear control of the dynamical system that is formed by a DC-DC converter and a DC motor, making use of differential flatness theory. To compensate for parametric uncertainties and external perturbations A Kalman Filter is used as a disturbance observer. Next, the chapter is concerned with proving differential flatness of the three-phase voltage source converter (VSC) model. This enables transformation of the VSC model to the linear canonical form and the design of a stabilizing feedback controller. At a second stage, a Kalman Filter is used as disturbance observer for estimating and compensating for additive input disturbances to the VSC model. Additionally, the chapter proposes nonlinear H-infinity control for the model of the three-phase voltage source converter. The converter's model is locally linearized round its current operating point through the computation of the associated Jacobian matrices. An

H-infinity feedback control law is computed through the solution of an algebraic Riccati equation at each iteration of the control algorithm. Finally, the chapter develops a control method for the VSC-HVDC system, that is for an AC to DC voltage source converter connected to the electricity grid through a high voltage DC transmission line terminating at an inverter. By showing that the VSC-HVDC system is a differentially flat one, its transformation to the linear canonical form and the design of a stabilizing feedback controller becomes possible. To compensate for model uncertainties and external perturbations a Kalman Filter is used as a disturbance observer.

Chapter 6 analyzes different approaches for nonlinear control of DC to AC converters (inverters): (i) flatness-based control through transformation to the canonical form, (ii) differential geometry-based control. Moreover, the chapter presents flatness-based control and nonlinear H-infinity control for DC to DC converters. Finally the chapter analyzes adaptive control of active power filters. First, the chapter proposes a nonlinear feedback control method for three-phase inverters, which is based on differential flatness theory By exploiting differential flatness properties it is shown that the inverter's model can be transformed to the linear canonical form. For the latter description the design of a state feedback controller becomes possible. Moreover, to estimate and compensate for model uncertainty and external perturbation inputs that affect the inverter's model, a Kalman Filter algorithm is used as a disturbance observer. Next, the chapter proposes a differential flatness theory-based approach for adaptive fuzzy control of active power filters. By proving that the active power filter is a differentially flat system, its transformation to the linear canonical (Brunovsky) form becomes possible. In this new description the control input of the active power filter comprises unknown nonlinear terms which are identified with the use of neurofuzzy networks and through an adaptation / learning procedure. These estimated parts of the system's dynamics are used in an indirect adaptive control scheme, which finally makes the outputs of the active power filter converge to the desirable setpoints. The stability of the flatness-based control scheme is confirmed through Lyapunov analysis.

Chapter 7 analyzes flatness-based control for proton exchange membrane (PEM) fuel cells. Additionally it gives results on nonlinear H-infinity control of PEM fuel cells. Moreover, it proposes flatenss-based control for the PDE model of the Li-ions batteries. First, the chapter presents an approach to nonlinear control of fuel cells using differential flatness theory and Kalman Filtering. By exploiting the differential flatness properties of the model its transformation to an equivalent linear canonical form and the design of a state-feedback controller become possible. A Kalman Filter-based disturbance observer is applied to the linearized extended model of the fuel cells aiming at the compensation of perturbations' effects. Moreover, the chapter applies nonlinear H-infinity control to PEM fuel cells. The dynamic model of the PEM fuel cells undergoes approximate linearisation, through Taylor series expansion, and an H-infinity feedback controller is designed. The computation of the optimal control input requires the solution of an algebraic Riccati equation at each iteration of the control algorithm. The known robustness properties of H-infinity control enable compensation of model uncertainty and rejection of the perturbation terms that affect the PEM fuel cells system. The stability of the control loop is proven through Lyapunov analysis. Finally, the chapter analyzes estimation and control for the PDE dynamics describing particles diffusion in Li-ion batteries. It is proven that this PDE dynamics satisfies differential flatness properties and this enables to solve the associate state estimation problem and to design a stabilizing feedback controller. By applying semi-discretization and the finite differences method the particles' diffusion PDE model is decomposed into an equivalent set of nonlinear coupled ODEs and a state-space description is obtained. It is shown that each row of the state-space model is a differentially flat subsystem for which a feedback control law can be found. The feedback controller is implemented in successive loops.

Chapter 8 analyzes synchronization and stabilization for distributed power generation units. First, the problem of stabilization and synchronization is solved for a model of distributed interconnected synchronous power generators with the used of flatness-based control. Next, the problem of stabilization and synchronization of the distributed synchronous generators is solved with the use of flatness-based adaptive control. Moreover, the problem of decentralized control and synchronization is solved for a model of distributed interconnected DC power power generation units photovoltaics. Initially, the chapter develops a flatness-based control method for distributed interconnected power generation units. The power system comprises Permanent Magnet Synchronous Generators (PMSGs) which are connected to each other through transformers and tie-lines. Differential flatness properties for this model are proven and its transformation to a canonical form is performed. A nonlinear Kalman Filter is used as a disturbance observer, thus making possible to estimate at the same time the non-measurable elements of each generator's state vector, the unknown input power (torque) and the disturbance terms induced by interarea oscillations. Next, the chapter proposes a new nonlinear H-infinity control method for stabilization and synchronization of distributed interconnected synchronous generators. Using the linearized description of the distributed generators' dynamics, that is obtained through Taylor series expansion, an H-infinity feedback controller is designed through the solution of a Riccati equation at each step of the control algorithm. The stability of the H-infinity control scheme is proven through Lyapunov analysis. Additionally, the chapter presents an adaptive fuzzy approach to the problem of synchronization and control of distributed power generators, which is based on differential flatness theory and which uses exclusively output feedback. To identify the unknown dynamics of the system adaptive fuzzy approximators are used in the control loop. This adaptive control scheme is exclusively implemented with the use of output feedback, while the state vector elements which are not directly measured are estimated with the use of a state observer that operates in the control loop. Finally, the chapter develops decentralized control for parallel inverters connected to the power grid, using differential flatness theory. By exploiting differential flatness properties it is shown that the multiple inverters model can be transformed into a set of local inverter models which are decoupled and linearized. For each local inverter the design of a state feedback controller becomes possible. To estimate and compensate for disturbance terms that affect each local inverter, the Kalman Filter is used as a disturbance observer.

Chapter 9 analyzes condition monitoring and fault diagnosis for electric power generators with the following approaches: (i) fault diagnosis in the time domain for distributed interconnected synchronous generators and with the use of the local statistical approach to fault diagnosis, (ii) fault diagnosis for asynchronous generators and with the use of neural networks having activation functions that remain invariant to the Fourier transform, (iii) fault diagnosis in the time domain for synchronous generators and with the use of nonlinear filtering methods. First the chapter analyzes a Kalman Filtering -based approach for fault diagnosis in distributed and interconnected power generators. The method is based on a new nonlinear filtering scheme under the name Derivative-free nonlinear Kalman Filter. Statistical processing is performed for the obtained residuals, that is for the differences between the state vector of the monitored power system and the state vector provided by the aforementioned filter when the latter makes use of a fault-free model. It is shown, that the suitably weighted square of the residuals' vector follows the χ^2 statistical distribution. This property allows to use confidence intervals and to define thresholds that demonstrate the existence of parametric changes (faults). Next, the chapter proposes neural modelling and fault diagnosis methods for the early detection of cascading events in electric power systems. A neural-fuzzy network is used to model the dynamics of a distributed power system in fault-free conditions. The output of the neural-fuzzy network is compared to measurements from the power system and the obtained residuals undergo statistical processing using the local statistical approach to fault diagnosis. This allows the detection of incipient parametric changes in the model. Finally, the chapter proposes the use of a neural network with Gauss-Hermite polynomial activation functions Knowing that the Gauss-Hermite basis functions satisfy the orthogonality property and remain unchanged under the Fourier transform, subjected only to a change of scale, one has that the considered neural network provides the spectral analysis of the output of the monitored system. By observing changes in the amplitude of the aforementioned spectral components one can have also an indication about malfunctioning of the monitored system and can detect the existence of failures.

Chapter 10 analyzes condition monitoring and fault diagnosis for components of the electric power transmission and distribution system. Initially, neural modelling and the local statistical approach to fault diagnosis is used for incipient fault detection and isolation in power transformers. Next, the chapter proposes distributed nonlinear filtering for condition monitoring of the power distribution system and for the detection of changes in the quality of the provided electric power (voltage sags, change of harmonics, etc). A neural-fuzzy network is used to model the thermal condition of the power transformer in fault-free operation Its output is compared to measurements from the power transformer and the obtained residuals undergo statistical processing using the local statistical approach to fault diagnosis. If a fault threshold (that is optimally defined according to detection theory) is exceeded, then deviation from normal operation can be detected at its early stages and an alarm can be launched. Moreover, fault isolation can be also performed. Next, the chapter analyzes distributed state estimation methods for condition monitoring of electric power transmission and distribution systems. As suitable approaches for distributed state estimation the chapter proposes the Extended Information Filter (EIF) and the Unscented Information Filter (UIF). With the use of the aforementioned filtering algorithms on processing units located at different parts of the power grid, one can produce local estimates of the system's state vector which in turn can be fused into an aggregate state estimation. The produced global state estimate enables continuous monitoring of the condition of the electric power system.

Regarding the control theoretic part, the monograph introduces systematic methods for compensating the nonlinear dynamics of renewable energy system using global linearization methods (differential flatness theory), approximate linearization methods (H-infinity control) and Lyapunov-based methods. The monograph treats also the problems of (i) uncertainty in the model of the renewable power systems which can be due to incomplete knowlesge about the associated dynamics, external perturbations or varying operating conditions, (ii) stochasticity in the model of renewable energy systems which can be due to inability to measure the complete state vector of such systems or due to randomly varying perturbatio inputs. To handle (i) the monograph studies extensively adaptive and robust control methods for renewable energy systems, while to handle (ii) the monograph introduces new nonlinear filtering approaches which are proven to be more accurate and computationally more efficient.

The monograph is primarily addressed to the academic community. Its content can be used for teaching undergraduate or postgraduate courses on renewable energy systems. Therefore it can be used by both academic tutors and students as a reference book for such a course. The monograph is also addressed to the engineering community. The nonlinear control and estimation methods analyzed in the monograph can be a powerful tool and useful companion for engineers working on practical problems of renewable energy systems. Since the monograph analyzes several critical engineering systems associated with the exploitation of renewable energy sources it is likely to be a useful reference for all engineering sectors involved in the development of such systems (electrical and computer engineers, mechanical engineers, physicist and scientistic working on relevant computation problems).

Athens, Greece
June 2016

Dr. Gerasimos Rigatos
Electrical and Computer Engineer, Ph.D.

Acknowledgements

The author of this monograph would like to thank researchers in the area of renewable energy systems, as well as in the area of dynamic systems modelling and control for contributing to the development and completion of this research work, through reviews, comments and meaningful remarks.

Contents