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Editorial

Special Issue "Intelligent Control in Energy Systems"

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Abstract: The editor of this special issue on "Intelligent Control in Energy Systems" have made an attempt to publish a book containing original technical articles addressing various elements of intelligent control in energy systems. The response to our call had 60 submissions, of which 27 were published submissions and 33 were rejections. This book contains 27 technical articles and one editorial. All have been written by authors from 15 countries (China, Netherlands, Spain, Tunisia, United States of America, Korea, Brazil, Egypt, Denmark, Indonesia, Oman, Canada, Algeria, Mexico, and Czech Republic), which elaborated several aspects of intelligent control in energy systems. It covers a broad range of topics including fuzzy PID in automotive fuel cell and MPPT tracking, neural network for fuel cell control and dynamic optimization of energy management, adaptive control on power systems, hierarchical Petri Nets in microgrid management, model predictive control for electric vehicle battery and frequency regulation in HVAC systems, deep learning for power consumption forecasting, decision tree for wind systems, risk analysis for demand side management, finite state automata for HVAC control, robust μ-synthesis for microgrid, and neuro-fuzzy systems in energy storage.

Keywords: intelligent control; artificial intelligence; energy management system; smart micro-grid; energy systems; intelligent buildings; forecasting; multi-agent control; optimization

1. Introduction

Energy systems (ES) are a complex and constantly evolving research area. Since energy systems are multi-layered and distributed, there is a growing interest in integrating heterogeneous entities (energy sources, energy storage, micro-grids, grid networks, buildings, electrical vehicles, etc.) into distribution systems. The challenge in handling the vast volume of information is the requirement of the use of modern efficient management control strategies such as intelligent control technologies.

Intelligent control (IC) describes a class of control techniques that use various artificial intelligence techniques such as neural network control, Bayesian control, fuzzy logic control, neuro-fuzzy control, evolutionary computation, machine learning, and intelligent agents. IC systems are very useful when no mathematical model is available a priori. IC is inspired by the intelligence and genetics of living beings.

IC, communications infrastructure, and wireless networking play an important role in a smart grid network in achieving reliable, efficient, secure, distribution, cost-effective generation and consumption. IC on energy storage devices provide reliability and economic impacts on the energy systems.

Buildings consume a large portion of the world's energy and they are a source of greenhouse gas emissions. The concept of sustainable and zero energy buildings is emerging as an important area for the smart micro-grid initiative. In addition, effective energy management is becoming more feasible using the innovative smart micro-grid technologies and IC. These changes have resulted in an environment of high complexity, uncertainty, and imprecision. The IC can play a remarkable and vital role in handling a significant part of this high uncertainty and nonlinearity by providing new smart solutions for a more efficient and reliable operation of ESs.

This Special Issue is focused on to bring together innovative developments and emerging synergetic technologies in the fields of intelligent control and energy systems. The particular topics of interest in the original call for papers included, but were not limited to:

- Energy management and IC in energy micro-grids
- ESs modeling and IC
- IC and optimization for zero energy buildings
- Evolutionary control in ESs
- IC in hybrid ESs of isolated areas
- Fuzzy logic control in ESs
- Intelligent multiagent control systems in ESs
- Artificial neural networks for control in ESs
- IC of holonic ESs
- IC in energy storage systems
- IC in sustainable smart ESs
- Fault diagnosis and IC in ESs
- Chaos control in ESs
- Bayesian control in renewable energy systems
- Neuro-fuzzy control in ESs
- Machine learning in ESs
- IC in distributed electrical energy generation system
- IC in smart grid network
- IC and ESs stability
- IC and demand side forecasting in ESs
- IC and uncertainty analysis of ESs.

2. Brief Overview of the Contributions to This Special Issue

This Special Issue focused on bringing together innovative developments and synergies in the fields of intelligent control and energy systems. Therefore, a variety of topics were presented:

In [1], AbouOmar, Zhang and Su presented a fractional order fuzzy PID controller for a Proton Exchange Membrane Fuel Cell (PEMFC) air feed system, in order to achieve maximum power point tracking for the PEMFC stack, used the Neural Network Algorithm (NNA), a new metaheuristic optimization algorithm inspired by the structure and operation of ANNs to optimize the controller. A detailed simulation on MATLAB/SIMULINK environment proved the efficiency of the proposed controller over other types of controllers. The NNA optimized FOFPID controller achieved a better set point tracking and disturbance rejection with minimal fluctuations around the set value, with better transient response and minimum time domain performance indices. It was also shown that the system had satisfactory robustness against the considered parameter uncertainty range. In the future, the modification of the original NNA algorithm for improving its convergence with applications to PEMFC control using new control schemes may be expected.

Shen, Tang, Yi et al. [2] proposed an online switching methodology to relieve voltage violations based on a three-stage strategy which includes screening, ranking, and detailed analysis and assessment stages for high speed and accuracy. This online methodology rapidly identified effective candidate lines, ranking the effective candidates performing detailed analysis of the top ranked candidates, and supplied a set of solution for the power system, balanced speed and accuracy for online applications by combining linear and nonlinear methods. A significant feature of this methodology is that it can provide a set of high-quality solutions, allowing the operators to select a preferred solution. The results showed that this scheme led to promising results that could provide single-line switching as well as multiple-line switching and also, in comparison to other methods has more advantages in accuracy and speed, but also requires less CPU time, especially in a large-scale system.

A control architecture aimed at performing frequency regulation with renewable hybrid power plants comprised of a wind farm, a solar photovoltaic and a battery storage system while considering the causes that lead to inertia loss in worldwide grids, was the focus in [3]. The proposed architecture considered the latest regulations and recommendations published by ENTSO-E when implementing the fast frequency response and the frequency containment reserve, the first two stages of frequency control. The proposed system architecture was tested against two scenarios studying the same event: One according to the ENTSO-E recommendations, and ROCOF (Rate of Change of Frequency). The results showed a great improvement of the system's frequency behavior. Additionally, the dynamic response of the generators in the system was smoother in scenario II, satisfying the concerns of wind turbine manufacturers about mechanical stresses and premature aging due to frequency support provisions. The impact of the proposed architecture was the speed in event identification, which gave the plant, the time to react to a fault. ROCOF was proposed in event identification, since it allowed the identifications of fast excursions before the frequency could reduce its value and thus eased the system necessary reactions.

Kong, Ma, Zhao et al. [4] proposed an online estimation method for the operating error of electric meters which used the recursive least squares (RLS) and introduced a double parameter method with dynamic forgetting factors λ_a and λ_b to track the meter parameters changes in real time. The case analysis results showed that the estimated performance of the proposed approach was better than other estimation methods, with a false detection rate below 2%. By this proposed method, the parameters of the electric meter error and line loss could simultaneously be estimated and thus, the accuracy of the online estimation of electric meter errors could be improved. Finally, the proposed method was based on the elimination of abnormal data such as light load data and null data. The reduction of these effects in the process of the data processing and algorithm solving need further study.

In [5], three intelligent control systems (fuzzy logic, artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS)) were used to carry out a strategy of controlling the air discharge of a small scale compressed air energy storage (SS-CAES) prototype to produce a constant voltage according to the user set point. The purpose was to simplify the control of the SS-CAES, so that it could be integrated with a grid based on a constant voltage reference. The experimental evaluation used two scenarios, demonstrating that ANN had the best performance in both of them since it had less iteration than the other controls resulting to a fast response. A high overshoot was observed in the second scenario due to the effect of high pressure when the load was still installed.

Choi and Cho [6], proposed an advanced continuous voltage control method that implemented multiple-point control to ensure peak power system performance. The utilization of generators to regulate the pilot point voltage of a control area was common in most of the control schemes. The influence of adjacent areas in a meshed power system made the exact control of a single pilot point difficult. In the proposed method, multiple pilot points were accessed to mitigate the effects of the neighboring area. The Multiple Continuous Voltage Control (MCVC) algorithm demonstrated effectiveness in regulating the voltages at a group of pilot points to remain around set-point values while dealing with the evolution of those voltages separately. Simulation with realistic data obtained from the Korean power system demonstrated the feasibility of this control scheme for reducing the severity of mutual interactions between adjacent zones. The same dynamic simulations were also used to study how the MCVC could return the system to stability from more severe conditions.

An adaptive damping control strategy of a wind integrated power system was analysed in [7], by tracking the variation of system operating points and updating the controller's functions to achieve a robust damping control effect. This occurred in three steps, including the division of the space of the operating point into operating subspaces by the even interval of wind power outputs, the pre-design of the coordinated Power System Stabilizers (PSSs) for each operating subspace, and the formation of a classification tree by training the distances to the hyperplanes and the regression tree was used to identify the subspaces with the help of on line measurement from PMUs. The proposed adaptive control demonstrated robustness to stochastic varying operating conditions and showed good performance in the case of multiple wind farms connected at different buses.

In [8], a repetitive controller used in a SEPIC PFC converter was designed using a third-order model approximation-instead of fifth-order for reasons of simplicity in order to reduce the input current distortion and the stability of the controller was verified with an error transfer function. The proposed controller was then validated by simulation in 100 W to 800 W load conditions in buck and boost mode. The THDs of the input current were significantly decreased in both modes. The experimental result also showed that the controller based on simplified model was well designed.

A simple strategy for controlling an interleaved boost converter that was used to reduce the current fluctuations in proton exchange membrane fuel cells was presented by Barhoumi, Ben Belgacem, Khiareddine et al. in [9], which had a high impact on the fuel cell lifetime. A neural network controller was employed in order to keep the output voltage at the desired reference value under the fluctuations of the fuel flow rate, the fuel supply pressure and temperature. The proposed converter has reduced the ripples of load voltage to less than 2 V. The simulation results indicated that the controller demonstrated robustness and efficiency of the converter to regulate the load voltage as well as minimize the voltage ripples. It also showed that using limited number of tests allows one to develop efficient ANN controllers for the regulation of the load voltage.

Tchoketch Kebir, Larbes, Ilinca et al. in [10] proposed a control method that offered high performance to get a maximum power output tracking by using a fuzzy logic approach which entailed a maximum speed of power achievement, a good stability, and high robustness. A fuzzy controller was used, based on a special choice of a combination of inputs and outputs. The choice of inputs and outputs as well as fuzzy rules, was based on the principles of mathematical analysis of the derived functions for the purpose of finding the optimum. It was also proved that using the simplest possible fuzzy model by using only 3 sets of linguistic variables to decompose the membership functions of the inputs and the outputs of the fuzzy controller could achieve the best results and answers for a PV system. A comparison of the fuzzy controller model with conventional perturb and observe controllers' models proved higher efficiency in maximum power point tracking for the fuzzy logic controller and in maximum power tracking time delay, stability, and robustness in all cases. The fuzzy logic algorithm was a robust and efficient algorithm which worked at the optimal point without oscillations and with a good transient behavior.

In [11], a solution in load balancing issue in urban μgrids with the use of hierarchical Petri Nets (PNs) in phase-load balance method was presented. The new system design composed of combined algorithms, called Load-Balance Control (LBC) system contributing to the load amount identification to transfer between feeders, and with the single-phase consumer unit selection to the switch operation of load balance procedure. The hierarchical PN was used to represent and validate the workflow of each inner algorithm of the control system for LV and for the upper hierarchical levels as Microgrid Central Control (MGCC) and the legacy LV grid as well. Both networks were tested through dynamic simulation, verifying reliable and reliable dynamic performance in both, free of conflicts, stops, and deadlock. The attainability of all its states also verified identifying that were both limited and safe networks. The identification of two inviolable workflows in both networks guarantees the efficient execution of the load transfer algorithm and its evaluation of each fuzzy inference rule used to identify load transfer. This provided an efficient and reliable load-balancing algorithm that ensured a single and admissible load-balancing solution to the integrated control flow as well as a unique and admissible inference rule to the load transfer. Furthermore, the combined algorithm of the LBC system was also tested by dynamic simulation which presented load imbalance between its phases, showing the identification of the load transfer amount in each phase, the limits of variation of load in relation to the discrete states of consumption in each phase, the future consumption matrix and the future load consumption states. A second application of the LBC system was also tested demonstrating the efficiency of the proposed system.

A study for the design of an active equilibrium control strategy based on model predictive control (MPC) for series battery packs is presented in [12]. Bidirectional active equalization was modelled and analyzed, and the MPC algorithm was applied to the established state space equation. The optimization problem that minimized the equilibrium time transformed to a linear programming form in each cycle. The solution of the linear programming problem gave a group of control optimal solutions and the series equalization problem was decoupled. The dynamic adjustment of the equalization current shortens the equalization time. The experimental result indicated that the equilibrium time was reduced by 31%. The main idea of this method was that the balance current was adjustable. One drawback of computation process of local optimal solutions was that it was a time-consuming process, so in the future other optimization algorithms must be tried to reduce the computation time, increasing the efficiency further.

In [13], atmospheric pollution and Total Suspended Particle emissions control was analysed; the development of a non-linear model for TSP emissions estimation from an industrial boiler based on a one-layer neural network was reported. The model used expansion polynomial basic functions combined with an orthogonal least square and model structure approach and required five independent boiler variables for TSP emissions estimation. The experimental results demonstrated that orthogonal least square algorithms were a great tool that provided extra information about internal model behaviors. It also showed that finite expansion polynomial basic functions could be implemented with one-layer ANN and agreed with the universal approximation theorem. The precision of the PBF network was excellent in predicting TSP emissions and this methodology can be replicated for other pollutants emitted into the atmosphere such as NO_x and CO emissions etc.

A hybrid deep learning neural network framework that combined Convolutional Neural Network (CNN) with Long Short Term Memory (LSTM) with a multi-step forecasting strategy was proposed in [14] in order to fill the research gaps that existed in power consumption forecasting problems and were considered as disadvantages in practical applications of LSTM: The prediction's accuracy and the shortness of the forecasting time. The proposed framework was tried against some of the known existing approaches, such as ARIMA, persistent model, SVR, and LSTM alone. Additionally, a k-step power consumption forecasting strategy was demonstrated in order to promote the proposed framework for real world application usage. The results obtained based on five real world households using MAPE as the error metric and the CNN-LSTM framework with multistep forecasting strategy outperforms the conventional methods.

The planning of an Integrated Energy Micro-Grid (IEMG), formed by connecting multiple regions' Integrated Energy Systems (IES) was the subject in [15]. Compared with isolated IES, an IEMG, could further improve the reliability, flexibility, cleanliness and the economy of a regional energy supply. An IEMG planning model was presented with distributed photovoltaic developed by Mixed Integer Linear Programming (MILP). First, the capacity construction configuration of the energy production equipment by known electricity, heating and cooling loads was determined. Second, an operational cost analysis of heating, cooling, transitional and extreme load scenarios was conducted, in order to improve the feasibility of the planning results. As the main investors, the model takes the district energy suppliers, and the optimized capacity configuration could meet the overall energy demand of the region in different scenarios and, at the same time, give the construction and operation cost of different sub-regions. A case study was given to improve the validity of the model and, according to the results of the model calculation, the proposed model could be seen as a theoretical reference for the planning of multi-district IES (an IEMG).

Su, Dong and Shen [16] introduced an improved adaptive backstepping method based on error compensation (ABEC), a method which considered the damping coefficients. Then, an improved adaptive backstepping sliding mode variable control based on error compensation method (ABSMVCEC) was introduced. This method stabilized the system more quickly and with a κ-class function addition to the selection of the intermediate virtual variable function, the convergence of the system speeded up. The nonlinear controller for the Static Var Compensator (SVR) system simulated with the two above mentioned methods and the method of adaptive backstepping. The proposed methods had better performance. Additionally, the ABSMVCEC method was more effective in improving the transient stability.

A static switch in order to feed a High-Speed Train (HST) through the Neutral Section (NS) was proposed by Canales, Aizpuru, Iraola et al. [17]. An NS operation was analyzed to identify impacts within the electric system and solution requirements were developed. A low-scale prototype switch was used to experimentally validate the solution which was based on Thyristor technology and the medium-voltage AC static switch was designed. The final tests took place on the Cordoba-Malaga High-Speed Railway. The thyristor demonstrated the ability to feed high-speed trains in neutral sections, avoiding the electrical transient of connection and disconnection of traction transformers and failure of the train's main breaker. The AC switch solution was suitable for conventional railways where the train's speed can be very low and there is a risk of stopping in a neutral section without electrical power.

Blaauwbroek, Nguyen and Slootweg [18] were presenting a time horizon three-phase grid supportive demand side management methodology for low voltage networks by using a universal interface established between the DSM application and the network's operator monitoring and network analysis tools. By using time horizon predictions of the system stated that the probability of operational limit violations was identified. Contributing with a probabilistic approach by presenting a Monte Carlo as well as a Neural Network based approach, they reduced the probability of geographical dependent operation limit violations to acceptable levels. Numerical simulations showed that NN-based approach offered a significant benefit over the PPF based approach in terms of computational complexity. Moreover, from the findings of the proposed approach, it seems that the research could be extended in several directions.

The development of an innovative solar monitoring system was presented in [19]. The system aimed at measuring the main parameters and characteristics of solar plants; collecting, diagnosing and processing data. The system communicated with the inverters, electrometers, metrological equipment and additional components of the PV arrays using special data collecting technologies. This monitoring system contributed in quality management of plants and provided data for scientific purposes; it helped to identify and eliminate installation errors and contributed to the continuous operation of the PV arrays by providing information to the staff about the potential error. The increased number of input lines and secured communications were some of the benefits of the system. The high frequency of data saving allowed a higher accuracy of the mathematical models. Moreover, a significant advantage was the capability to collect additional data from other power plant components.

The improvement of the efficiency of HVAC systems was the target of the study in [20], by providing accurate occupancy prediction to the HVAC control in order to ensure that HVAC is not run needlessly when a room or a zone is unoccupied. Simple but effective algorithms were proposed to predict occupancy, along with an algorithm for automatically assigning temperature set-points. The three techniques for occupancy prediction were carried out by utilizing past occupancy observations. The methods employed were Expectation Maximization (EM), Finite State Automata (FSA) reconstructed by a General Systems Problem Solver (GSPS) and an alternative stochastic model based on uncertain basis functions. All three methods achieved more than 70% accuracy in experimental studies. Along with a Model Predictive Control (MPC) algorithm to assign temperature set point based on occupancy information, the paper delivered a novel end to end solution.

In [21], the mechanical vibration characteristics of a dry-type transformer winding were studied. A vibration simulation model of a dry type transformer was established based on actual short circuit experimental conditions of an SCB10-1000/10 dry type transformer in which the vibration signal at the surface was measured. The model has been developed using COMSOL Multiphysics software. A Multiphysics coupling simulation of the circuit, magnetic field and solid mechanics of the transformer was performed on the model. After the validation, the model used to develop simulation models of winding failures, such as looseness, deformation or insulation failure. The results then were used as a basis for analyzing and detect the mechanical state of transformer windings.

Xu, Mao et al. [22] investigating a dynamic optimization energy management strategy called Hybrid Electric Vehicle Based on Compound Structured Permanent Magnet Motor (CSPM-HEV) which had obvious advantages on power density, heat dissipation efficiency, torque performance and energy transmission efficiency. The topology and working principle of CSPM-HEV were described and an analysis of its operating mode and corresponding energy flow laws were also analyzed. Back Propagation neural network was employed for the real time energy management of CSPM-HEV, solving the problem of complex algorithms and poor real time performance. It was shown that the instantaneous optimal control of the vehicle target achieved, along with a real time energy management strategy based on a BP neural network and the instantaneous optimal control of CSPM-HEV which were also fulfilled. As a future research topic, a global optimization algorithm is expected to improve the fuel economy of CSPM-HEV.

Bhuiyan and Lee [23] proposed a position control method for a low cost exhaust which had a recirculation (EGR) valve system for automotive applications, that could be applied under the high difference friction mechanical system and overcome the restrictions that common position control systems with the conventional P-PI linear controller faced because of the large differences in static and Coulomb friction resulting in position and current vibrations. The mathematical analysis showed that the proposed system could achieve the proper control performance with errors within the acceptance boundaries.

Two control strategies that allowed HVAC systems in commercial and residential buildings to provide frequency regulation services were investigated in [24]. The first was based on model predictive control acting on a variable air volume HVAC system. The second strategy was rule-based control acting on an aggregate of on/off HVAC systems considering the hardware constraints. The first strategy could be applied in large commercial buildings and the second to residential and small to medium size commercial buildings. The second strategy provided the required flexibility for ancillary services to the grid with little impact on indoor environments. The presented strategies demonstrated a novelty: to use HVAC loads as ancillary service to the grid. A study for the design of a decentralized framework for the rule-based control strategy would be expected in the future.

In [25], a preventive control methodology to increase the capacity of voltage sag recovery (Fault Ride Through Capability-FRTC) of a doubly-fed induction generator connected in an electrical network was presented. The methodology was based in decision trees (DT) technique and assisted with monitoring and support for security and preventive control, ensuring that wind systems remain connected to the system even after the occurrence of disturbances in the electric system. The presented methodology was tested using the IEEE 39 bus system, which was modified by the insertion of doubly fed induction generators. The presented results verified that the wind power system voltage and the reactive power of synchronous generator contribute to the systems operation security and to the continuity of electricity supply from a wind turbine after the occurrence of a disturbance in the electrical network. It was also possible to verify that active power and voltage contribute to the continuity and lack of wind system shutdown. Furthermore, it was shown that the decision tree classified the system's operational state with goof accuracy and indicated the way to maintain the electrical system dynamic security for each topology. The use of the optimization tool may guarantee optimal operating conditions. Conclusively, the presented methodology consisted of a DT based support tool which could be directly integrated into operation centers.

Li, Wang and Xiao [26] investigated the secondary load frequency controller of the power systems with renewable energies taking into account internal parameter perturbations and stochastic disturbances induced by the integration of renewable energies and the power unbalance caused between the supply and the demand side. The robust μ-synthesis approach was used for load frequency control in a microgrid power system. A load frequency control state space model with uncertainty was established. The results showed that ultracapacitors could enhance the frequency stability of microgrid power systems with μ-synthesis controller which demonstrated robustness and better nominal performance than the H∞ controller and could greatly improve the load frequency stability of a μgrid power system.

In [27], a detection method for the internal short circuit of a Lithium-Ion battery pack was proposed by estimating the resistance with the whole terminal voltages and the load currents of the pack. The open circuit voltage of a faulted cell in the pack was extracted to reflect the self-discharge phenomenon obviously yielding accurate estimates of the resistance. The proposed algorithm was verified for various soft ISCr fault conditions such as diverse magnitudes of true R_{ISCr} and two load current profiles in both the simulation and the experiment. Additionally, through estimating the R_{ISCr} from the normal battery pack and analyzing it, it was checked that estimated resistances in the various scenarios were reliable. With the proposed algorithm, it was possible to estimate accurately the R_{ISCr} and the soft ISCr in the battery pack could be calculated using the R_{ISCr} as the fault index. The error of estimated resistance did not exceed 31.2% in the experiment, enabling the battery management system to detect the internal short circuit early.

The above-mentioned articles that constitute this book critically reviewed various intelligent control technologies in energy systems and provided systematic solutions for the readers to easily understand the concepts used and outcomes produced. The editor believes that this book will be useful to many researchers and industries working on intelligent control in energy systems. The editor of the book would like to record their sincere thanks and acknowledgements to all the contributors of the articles and the continuous support they received from the Energies journal editorial staff team, without whose dedication it would have not been possible to publish this book.

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