SOFT COMPUTING APPLICATIONS IN WIND POWER SYSTEMS: A REVIEW AND ANALYSIS

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Abstract
This paper reviews, analyses, discusses and summarises the recent research and development and trends in the applications of soft computing in the field of wind power systems. We show the usage and the influence of soft computing on the different aspects of wind power systems especially in the field of operation and maintenance. This work provides the state of the art in this area which will be a good guidance for future research work. The main results achieved from the study show that the soft computing techniques are adequate for solving the different challenges at the different phases of the life cycle processes of wind power systems. Using the various soft computing techniques with wind power systems proved to be useful for the wind energy business. Using these tools contribute by improving the robustness of the decisions at different phases of the system's life cycle. Soft computing can enhance the efficiency and effectiveness of the operation and maintenance of offshore wind power systems through improving the availability levels. Thus, providing secure, sustainable and competitive energy supply for the future.

Keywords
Offshore Farms, Wind Power Systems; Condition Monitoring; Soft Computing; Intelligent Maintenance Systems; Neural Network; Artificial Intelligence.

1. Introduction

According to the European Wind Energy Association's scenarios the market annual wind power investments are expected to be stable at around €10 billion per annum up to year 2015, with a gradual increasing share of investment going to offshore. By 2030, annual wind energy investments in EU-27 will reach almost €20 billion with 60% of investments offshore. The safe and reliable operations of wind energy systems depend on the right design, manufacture, construction, smooth operations and proper maintenance of several pieces of components (parts) that compose these systems. Knowing that large percentage of total life cycle cost of wind power systems is attributed to operation and maintenance activities, which is more significant with offshore farms which are operated in remote locations with extreme weather conditions that are not accessible in certain periods of the year. Therefore, the availability levels of offshore wind turbines are very critical and the need of research to improve both their reliability and maintainability is very high. For example the size of modern wind turbines requires big investments in terms of cost and time when replacing components. Furthermore, offshore applications with restricted access are increasing the need for detailed information on the machine status. Therefore, more emphasise is given to condition monitoring and developing intelligent maintenance systems using soft computing. Soft computing is a collection of computational techniques which intend to complement each other. The aim of soft computing is to exploit the tolerance for imprecision, uncertainty, approximation, and partial truth to achieve tractability, robustness, and low solution cost [1]. Components of soft computing include: fuzzy logic, neural computing, evolutionary computing and probabilistic computing. Although more efforts are focusing on soft computing application for improving the performance of wind power systems. However, there is a need for a systematic review for available literature of soft computing applications in the field of wind power systems. For that reason, the main objectives of this review are:

- To identify the current soft computing applications with wind power systems.
- To suggest a systematic classification of available literature in field of soft computing application with wind power systems.
- To identify trends and suggest directions for future research.

This paper is organised as follows: Section two presents the suggested classification methodology. Section three presents soft computing techniques. Section four summarises the reviewed soft computing applications and classifies them according to the suggested classification methodology. Section five presents an analysis and discussion of the main findings. Finally, the conclusions are presented.

2. The classification methodology

In this review we classified the literature into the following five main areas based on relevant life cycle processes of wind power systems [2]:

Design and Development

The role of this phase is capturing the stakeholder requirements. It consists of systems analysis, optimisation and synthesis, trade-offs, definitions, system test and evaluation. Provisioning and acquisition of logistics and maintenance support elements is considered very critical at this stage [3]. A considerable portion of systems' life cycle cost stems from the consequences of the inherent reliability and maintainability decisions made during the early phases of planning and conceptual design of a system [4]. For example, optimizing design and acquisition costs could have a negative effect on equipment maintenance expenses.

Production and Construction

This phase is concerned with all the activities and intermediate processes required for the production, construction and integration of wind power system's components. It includes material flow, procurement and inventory requirements, manufacturing, packaging, warehousing, physical distribution, and transportation, communication, data processing and logistics management. All these activities should be performed with the right quality and cost. Usually, quality and assembly faults, installation errors, design errors, and operator errors are the causes of the stoppages (problems) that appear at the early phase of system lifetime. Normally, the original equipment manufactures (OEMs) bear much of the burden associated with these stoppages under warranty agreements.

Operation and maintenance

This phase is concerned with how the system is operated, used and maintained. It aims at sustaining maintenance and logistics support so that the system can achieve its objectives cost effectively. Usually, maintenance tasks are aimed to reduce failures of industrial plant, machinery and equipment and their consequences as much as possible. These tasks can take several forms and practices. Maintenance practices are decsribed and classified, empirically, into the following approaches [5]:

1) The Reactive Approach is focused mainly on fire fighting, installing new equipment, using work in progress (WIP) inventory between the machines to guarantee the runnability of the production lines, and performing annual overall.

2) The preventive approach is characterised by performing maintenance tasks only based on the OEM and the usage of statistical methods to model the life function of the critical components based on failure data.

3) The predictive approach is characterised by the usage of computerised maintenance and management systems (CMMS), investment in training and improving the personnel competence, using condition monitoring (CM) technology, and using methods suggested by reliability centred maintenance (RCM) such as failure analysis, failure mode effect and criticality analysis (FMECA) and statistical modelling.

4) The diagnostic (expert systems) approach is characterised by the usage of remote and automatic diagnostic technology.

5) The autonomous approach is based on total productive maintenance (TPM) philosophy that depends mainly on measuring the overall equipment effectiveness (OEE).

6) The lean approach is focusing on reducing the losses resulting from, for example, having high level of spares parts inventory and long time needed to repair the machines.

7) The proactive approach is characterised by the following practices: helping in improving the production process; helping in purchasing new equipment and selecting suppliers based on their previous experience; using cross functional groups to solve production problems; helping in the efforts of designing and improving production processes; using the information available at the company to perform maintenance tasks and perform periodic planned replacement of critical components.

System Retirement

This stage deals with issues related to how the system will be disposed of (by destruction or recycling of different components and material) when it reaches its design life or if a significant improvement in technology occurs. It involves the removal of all evidence of a wind power project after it has reached the end of its design life such as turbines, towers, concrete foundations, substation equipment, and operation and maintenance buildings.

3. Soft Computing techniques

Soft computing is a collection of artificial intelligence techniques that uses the human mind as a model, work synergistically, and aim to exploit the tolerance for imprecision, uncertainty, approximation, and partial truth to achieve tractability, robustness, and low solution cost [1, 6]. Soft computing provides intelligent processing techniques which overcome the problem of time consuming and complexity for the hard computing techniques [7].

There exist several soft computing methods such as: fuzzy logic, artificial neural networks (ANN), genetic algorithms (GA), and rough sets. The applications of the soft computing techniques are extensively taking place at the data mining step in the Knowledge Discovery in Databases (KDD) process as shown in Figure 1.

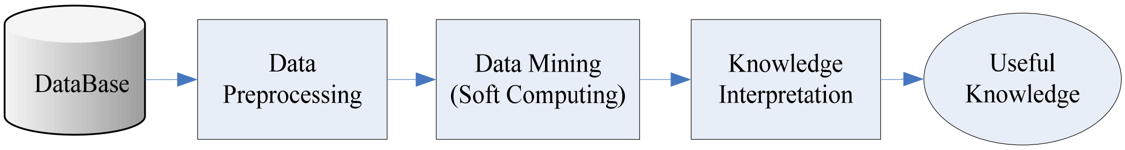

Figure1. Flow chart showing the Knowledge Discovery in Databases (KDD) process

While the neural networks, which are used for learning and curve fitting, and rough sets, which are used for handling uncertainty, are widely used for classification and rule generation, genetic algorithms are mostly used in various optimization and search processes, for example: query optimization and template selection. On the other hand, case based reasoning and decision trees are widely used to solve data mining problems while fuzzy logic deals with imprecision and uncertainty [6].

4. Soft Computing Applications – Results of Literature Review

The literature review is conducted utilising several databases including ScienceDirect (Elsevier) and IEEE along with literatures published by universities on the World Wide Web. The search terms included: maintenance practices, wind power, wind energy, life cycle cost, condition monitoring, maintenance management, soft computing, neural network, artificial intelligence. The search resulted in 15 related articles. Table 1 shows the classification of the articles according to the proposed classification methodology.

Table 1 classification of the articles according to the proposed classification methodology

Theme	Literature	Quantity
Design and Development	[8,9,10,11,12,13,14,15,16,17,18,19]	**12**
Production and Construction	-	**0**
Operation and Maintenance:		**5**
Reactive	-	0
Preventive	-	0
Predictive	[20, and21]	2
Diagnostic	[22, and23]	2
Autonomous	-	0
Lean	-	0
Proactive	[24]	1
Retirement	-	**0**

Brief descriptions for the collected articles under each theme are presented in the following subsections:

Design and Development

An application of neural network in predicting the dynamic response of a grid-interactive wind energy conversion system (WECS) was presented in [1]. Since the prediction accuracy of the model was very high, the model could be utilized by designers for developing a control system capable to protect the WECS from gusts.

To enhance the effectiveness of wind power systems an efficient control system for extracting the maximum energy from variable speed wind turbines was implemented in [2]. A Takagi-Sugeno-Kang(TSK) fuzzy model was employed for this purpose. The model used the fuzzy clustering method for partitioning the input-output space, while the genetic algorithm and the recursive least-square (LS) methods were used for the optimization purpose.

Wind speed prediction for any area is an important issue in site selection, performance prediction and planning of wind turbines [10]. For that, the artificial neural network was utilized by [10] and [11] to predict the wind speed based on the reference stations data and the historical data.

A method based on the artificial neural network, used to predict the power generation from wind farms, was presented in [12]. The purpose of this work was to improve the prospects for the wind power industry. The result of the proposed method exhibit a good agreement with the real values, therefore, the model was assistive for future planning and execution.

A system reliability analysis method integrated with support vector machine (SVM) algorithm was presented in [13]. A benchmark example had been used to asses the efficiency of the proposed method. The result showed that due to the use of SVM: the cost of meta-model is reduced; the model is applicable for both component and system level reliability problem as well as problems with non-normal variables.

An artificial neural networks model, used to increase the prediction accuracy for long term wind data, was presented in [14]. The proposed method was useful in reducing uncertainty of project design by assessing the feasibility of wind farms development.

An effective way in predicting and assessing the performance of the wind turbines was presented in [15]. The suggested method was based on the artificial neural network to predict the power ratio and torque of wind turbines. The results showed that the model is able to estimate the maximum power of rotors and maximize the efficiency of the wind turbines.

Easy and fast way to assess the costs of availability and O&M for offshore wind farms was presented in [16]. The developed method, an expert system based on Monte Carlo simulation, was able to make a trade-off between investment costs for increasing reliability and exploitation costs for O&M in a profitable manner. Furthermore, the system was able to calculate the costs for achieving the desired availability level.

A control strategy, based on artificial neural network, for attaining maximum power tracking and to regulate the load voltage for a permanent magnet generator applied in WECS was presented in [17]. The results showed that the proposed control system had a fast response and a high accuracy and robustness.

An application of neural networks to predict the suitable gain for an adaptive output feedback controller was presented in [18]. The controller was used to improve the dynamic stability of the wind turbine generators. For that, it was useful in avoiding unnecessary mechanical stress and assuring that the units are operating in their rating limits.

Due to the importance of predicting the flicker emissions, at the design stage or before installation of the wind turbines, the neural network method had been utilized in [19] to calculate the wind turbine flicker under normal operating conditions. The result showed that the model achieved sufficient accuracy in estimating the flicker levels without effort computation.

Production and Construction
No articles belong to the production and construction phase were found.

Operation and maintenance
Predictive
The intelligent system for predictive maintenance (SIMAP) software and its features was presented in [20]. SIMAP uses different intelligent methods such as: ANN, fuzzy expert system, and fuzzy genetic algorithm for the purpose of predictive maintenance. SIMAP is able to make online condition monitoring, failure detection and diagnostic, predictive maintenance scheduling, and measure the effectiveness of the applied maintenance actions. The software was applied successfully to monitor the health condition of the wind turbines gearbox; moreover, the result showed that the artificial intelligence methods are capable to achieve the aims of the predictive maintenance strategy.

The integrated maintenance management system Terology Integrated Modular System (SMIT), applied to a renewable energy, was introduced in [21]. SMIT manages the incorporation of the developed prediction algorithms such as: Support Vector Regression (SVR), Autoregressive Moving Average (ARMA) and Autoregressive Integrated Moving-Average (ARIMA) along with the information system and the hardware itself. SMIT, which can be accessed through a client-server system, includes useful modules such as: fault diagnosis module, non-periodic maintenance planning module, and generic on condition maintenance module and it has the ability to add more modules. The result showed that SMIT is a powerful tool for maintenance management and can be used as the background for the new developments.

Diagnostic (expert systems)
The design of a vibration data acquisition along with an intelligent fault diagnostic system for wind turbines was presented in [22]. For early detection of wind turbines faults, the wavelet neural network (WNN) was used to predict the vibration trends. On the other hand, the C Language Integrated Production System (CLIPS) expert system tool was used for the diagnostic purpose. The result showed that the system is effective on wind turbine vibration fault diagnostic. An application of the artificial neural network for predicting the power produced by the different wind turbines was presented in [23]. The predicted power generation can be used for the diagnostic purpose. This can be achieved by comparing the expected power generation, which can be found by looking to the manufactures rating for a given wind speed, with the predicted one. Having a predicted power less than the expected is an early indicator for a need for maintenance.

Autonomous and Lean
No articles belong to these categories were found.

Proactive

A wave forecasts method based on the artificial neural network was presented in [24]. Wave forecast is helpful in planning and O&M work for offshore wind power systems. The results showed that the artificial neural network was able to perform well for 6 to 12 hours wave prediction and moderately well for 18 to 24 hours.

System Retirement

No articles belong to the system retirement phase were found.

5. Analysis and Discussion

The review showed that most of the reviewed articles used the soft computing for the prediction purpose. Among the 17 collected articles, 12 references discussed the usage and the benefits of applying soft computing techniques at the design and development phase. Five references discussed the applications of soft computing at the operation and maintenance of wind power systems phase. At least one article found discussing the soft computing applications in the Predictive, Diagnostic, and Proactive maintenance approaches, while no articles found for Reactive, Preventive, Autonomous, and Lean maintenance approaches. No soft computing applications found at the production and construction and retirement phases of wind power systems.

Table 2 summarizes based on the reviewed papers, the main challenges(s), under each life cycle phase of wind power systems, and the suggested soft computing technique to solve the problem.

Table 2 the phases, challenges, and the suggested techniques to solve the different wind power systems problems

	Challenge	**Tool**
Design and Development	Developing a control system capable to protect the WECS from gusts.	Recurrent Neural Network (RNN).
	Developing a control system to extract the maximum energy from variable speed wind turbines.	TSK fuzzy model (fuzzy clustering, GA, and LS).
	Site selection, performance prediction and planning of wind turbines.	Predicting wind speed using ANN.
	Future planning and execution.	Predict the power generation from wind farms using ANN.
	Developing a System reliability analysis.	A model based on SVM.
	Assessing the feasibility of wind farms development.	Increase the prediction accuracy for long term wind data using ANN.
	Assessing the performance of the wind turbines.	ANN.
	Assessing the costs of availability and O&M for offshore wind farms.	Expert system based on Monte Carlo simulation.
	Developing a controller to achieve maximum power tracking and output voltage regulation.	Controller based on ANN.
	Developing a controller to improve the dynamic stability of the wind turbine generators.	ANN
	Predict the flicker emissions at the design stage or before installation.	ANN
Production and Construction	-	-
Operation and Maintenance		
Predictive	Online condition monitoring, failure detection and diagnostic, predictive maintenance scheduling, and measure the	ANN, fuzzy expert system, and fuzzy genetic algorithm.

	effectiveness of the applied maintenance actions. Build a fault diagnosis module, non-periodic maintenance planning module, and generic on condition maintenance module.	SVR, ARMA and ARIMA
Diagnostic	Design an intelligent fault diagnostic system Diagnostic system	WNN and CLIPS expert system ANN
Proactive	Planning and O&M work for offshore wind power systems.	Wave forecasts method based on ANN
Retirement	-	-

In the design and development phase, many challenges were solved by applying the soft computing tools. As we see from Table 2 the soft computing tools such as neural network, fuzzy logic, and genetic algorithm were successfully used to solve the following challenges:

- Developing a control system capable to protect the WECS from gusts.
- Developing a control system to extract the maximum energy from variable speed wind turbines.
- Site selection, performance prediction and planning of wind turbines.
- Future planning and execution.
- Developing a System reliability analysis.
- Assessing the feasibility of wind farms development.
- Assessing the performance of the wind turbines.
- Assessing the costs of availability and O&M for offshore wind farms.
- Developing a controller to achieve maximum power tracking and output voltage regulation.
- Developing a controller to improve the dynamic stability of the wind turbine generators.
- Predict the flicker emissions at the design stage or before installation.

We noticed that most of the applications used the neural network as a soft computing tool for solving their problems. This is due to its advantages in requiring less formal statistical training, detecting complex nonlinear relationships between the inputs and the outputs, detecting all possible interactions between predictor variables, and the availability of multiple training algorithms [25].

In the operation and maintenance phase, a number of challenges were solved by applying the soft computing tools. Table 2 shows that different soft computing techniques such as ANN, fuzzy expert system, genetic algorithm, and SVR work synergistically to solve the different O&M challenges. We identified the challenges, which have been solved by using the soft computing methods, under the various maintenance approaches. For the predictive approach, the main challenges are:

- Online condition monitoring.
- Failure detection.
- Failure diagnostic.
- Predictive maintenance scheduling.
- Measure the effectiveness of the applied maintenance actions.

For the diagnostic (expert system) approach, the challenge is to design an intelligent fault diagnostic system, while for the proactive approach, the challenge is planning and Operation and Maintenance work for offshore wind power systems.
No soft computing applications found at the production and construction and retirement phases of wind power systems. However, the success of the soft computing in the design and development and O&M phases leads to think about applying it in the production and construction and retirement phases.

Finally, we found that the soft computing techniques are adequate for solving the different challenges at the different phases of the life cycle processes of wind power systems. This due to its advantages in [6, 20, 25]:

- Detecting complex nonlinear relationships between the inputs and the outputs, by using the artificial neural networks.
- Detecting all possible interactions between predictor variables, by means of neural networks.
- Optimizing and searching processes by using the genetic algorithms, for example: query optimization and template selection.
- Ability to deal with imprecision and uncertainty, by means of fuzzy logic.
- Characterizing the quantitative knowledge coming from historical data, by means of artificial neural networks.
- Characterizing the qualitative knowledge coming from maintenance and operation experts, by means of expert systems.
- Solving data mining problems, by means of case based reasoning and decision trees.

6. Conclusion

Using the various soft computing techniques with wind power systems proved to be useful for the wind energy business. Using these tools contribute by improving the robustness of the decisions at different phases of the system's life cycle. Soft computing can enhance the efficiency and effectiveness of the operation and maintenance of offshore wind power systems through improving the availability levels. Thus, providing secure, sustainable and competitive energy supply for the future. Conducting this review provides the state of the art in this area which is a good guidance for future research work.

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