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Adaptive Neuro-Fuzzy Inference System modelling for performance prediction of solar thermal energy system

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This study investigates in details the applicability of Adaptive Neuro-Fuzzy Inference System (ANFIS) approach for predicting the performance parameters of a solar thermal energy system. Experiments were conducted on the system under a broad range of operating conditions during different Canadian seasons and weather conditions. The experimental data were used for developing the ANFIS network model. This later was then optimised and applied to predict various performance parameters of the system.

The predicted values were found to be in excellent agreement with the experimental data with mean relative errors less than 1% and 9% for the stratification temperatures and the solar fractions, respectively. The results show that ANFIS approach provides high accuracy and reliability for predicting the performance of energy systems.

Furthermore, the ANFIS prediction results were compared against the ANNs predictions of Yaïci and Entchev [Appl Therm Eng 2014; 73:1346–57]. Results showed that the ANFIS model performed slightly better than the ANNs one. However, the ANNs method provided more flexibility in terms of model implementation and computing speed capabilities.

Finally, this investigation demonstrates that ANFIS is an alternative powerful and reliable method comparable to the ANNs; they can be used with confidence for predicting the performance of complex renewable energy systems.

1. Introduction

With the fast development of the global economy, energy requirements have increased remarkably, particularly in developing countries. The realisation that fossil fuel resources required for energy and power generation are becoming scare and that climate change is related to carbon emissions to the atmosphere, has increased interest in energy saving and environmental protection. The first strategy to reduce dependence on fossil resources is based on reducing energy consumption by applying energy-savings programmes focused on energy demand reduction and energy efficiency in industrial and domestic fields. The second strategy to achieve this objective consists of using renewable energy sources. In developed countries, fuel consumption in the building sector accounts for 40% of the world's energy end use. Most of this consumption is used for heating, cooling, ventilation and sanitary hot water of which two-thirds is used in households where heating alone accounts for more than 50%. Among renewable energy systems, solar thermal energy has received considerable attention in recent decades as an alternative energy resource. Solar water and space heatings represent the majority of solar thermal applications in domestic, commercial and industrial sectors. They are considered as the most cost-effective alternatives among all the solar thermal technologies currently available [1–6].

With such increasing pressure on reducing energy consumption and pollutant emissions, extensive research has been carried out to model these systems. Performance analyses of thermal energy systems are too complex; analytical computer codes usually require a large amount of computing power and time to give accurate predictions. It is very important for designers and engineers to be able to select the optimum system quickly and accurately [8,9]. To reduce cost of the studies and save computing time, Artificial Intelligence (AI) methods such as Artificial Neural Networks (ANNs), Fuzzy-Logic (FL) or Adaptive Neuro-Fuzzy Inference Systems (ANFIS) can be used as alternative methods for modelling and predicting the performance of complex energy systems [10].

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Nomenclature

AE	absolute error
AH	air handler
AI	artificial intelligence
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANNs	artificial neural networks
Aux	auxiliary
a	actual value
CCHT	Canadian Centre for Housing Technology
C_p	specific heat of the fluid, J/kg K
cl	cloudy
com	combined weather conditions
DHW	domestic hot water
FIS	fuzzy inference system
FLT	Fuzzy Logic Toolbox
Gh, Gi	solar total incident radiation on horizontal plane or inclined plane, W/m^2
gly	glycol
HX	heat exchanger
MF	membership function
MN	membership number
MAE	mean absolute error
MRE	mean relative error
meas	measured
NNT	Neural Network Toolbox
N	number of output data
p	output or predicted value
pc	partly cloudy
RE	relative error
R^2	correlation coefficient
S	summer
SDHW	solar domestic hot water
SF	solar fraction
SH	space heating
STD	standard deviation
STES	solar thermal energy system
su	sunny
T	temperature, °C
TES	thermal energy system
T1	solar preheat tank temperature, top, °C
T2	solar preheat tank temperature, second from top, °C
T3	solar preheat tank temperature, third from top, °C
T4	solar preheat tank temperature, fourth from top, °C
T5	solar preheat tank temperature, fifth from top, °C
T6	solar preheat tank temperature, bottom, °C
t	time (s)
W	winter

Subscripts and superscripts

avg	average
col	collector
in	inlet
gly	propylene glycol-water mixture
meas	measured
out	outdoor (ambient air)
pred	predicted
th	thermal
tilt	tilted
ts	thermosiphon
w	water

In recent decades, the AI techniques have been successfully applied in many scientific research and engineering fields. ANN modelling of energy systems has been recently studied by numerous investigators as summarised by Kalogirou [11], Kalogirou and Sencan [12] and Mohanraj et al. [13,14], including the authors' recent work. The results from ANN applications for STES explored by Yaïci and Entchev [15] demonstrated the effectiveness of the ANN method for cases characterised with high non-linearity, incomplete information and data uncertainty. The back-propagation learning algorithm with two different variants, the Levenberg–Marguardt (LM) and scaled conjugate gradient (SCG) algorithms were used in the ANNs. It was found that the optimal algorithm and topology were the LM and the configuration with 10 inputs, 20 hidden and 8 output neurons/outputs, respectively. The results confirmed the effectiveness of the ANN method and provided very good accuracy even when the input data were distorted with different levels of noise.

Fuzzy models offer advantages over mathematical ones; the inference process is close to human thinking and it is easier to deal with complex non-linear systems. ANFIS tunes a fuzzy inference system with a back-propagation algorithm based on collection of input/output data. The fuzzy modelling and identification toolbox constructs Takagi–Sugeno fuzzy models from data by means of product space fuzzy clustering [16]. Fuzzy systems have gained increasing popularity in engineering over the past few decades, finding a large variety of applications in control theory, pattern recognition, power systems and expert prediction systems. In addition to the above advantages, fuzzy models can be combined with ANNs to create ANFIS [17–25].

Although the ANFIS approach was first introduced by Jang in early 1990s [18], its application to the modelling of thermal energy systems is somewhat recent. Some studies using ANFIS for modelling, control, performance prediction in energy systems have been published [26–54]. Nevertheless to the knowledge of the authors, they did not find any published studies relative to the modelling of integrated solar thermal energy systems for DHW and SH heating applications using ANFIS.

For instance, the ANFIS method was used for predicting the performance of energy systems such as ground-coupled heat pump systems [26–28], thermal energy storage [29], refrigeration systems [30–33], photovoltaic systems [34,35]. It has been used for controls in HVAC systems and power generation [36–38], fault detection and diagnosis [39,40], for forecasting regional electric load [41,42] and estimating building energy needs [43], modelling the performance in heat exchangers [44–50], wind turbines [51–53] and combustion engines [54].

This work is part of a Federal Government funded project, aiming at development of user-friendly, efficient, and cost effective tools for modelling, predicting, monitoring and controlling of full scale STES plants. Among the AI methods, ANNs and ANFIS are the most powerful ones used in the modelling of complex energy systems. The ANN technique was fully demonstrated in the authors' study [15]. The results demonstrated that the method provides high accuracy and reliability for predicting the performance of an STES.

In this investigation, the detailed development of transient models using ANFIS for predicting the performance of an STES is reported. For this aim, an experimental STES was setup and tested during 2 years under different Canadian seasons and weather