Energy Conversion and Management 80 (2014) 229–237

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Adaptive neuro-fuzzy optimization of wind farm project net profit

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ARTICLE INFO

Article history:
Received 17 November 2013
Accepted 20 January 2014
Available online 13 February 2014

Keywords:
Wind farm
Net present value (NPV)
Interest rate of return (IRR)
ANFIS
Optimization

ABSTRACT

A wind power plant which consists of a group of wind turbines at a specific location is also known as wind farm. To maximize the wind farm net profit, the number of turbines installed in the wind farm should be different in depend on wind farm project investment parameters. In this paper, in order to achieve the maximal net profit of a wind farm, an intelligent optimization scheme based on the adaptive neuro-fuzzy inference system (ANFIS) is applied. As the net profit measures, net present value (NPV) and interest rate of return (IRR) are used. The NPV and IRR are two of the most important criteria for project investment estimating. The general approach in determining the accept/reject/stay in different decision for a project via NPV and IRR is to treat the cash flows as known with certainty. However, even small deviations from the predetermined values may easily invalidate the decision. In the proposed model the ANFIS estimator adjusts the number of turbines installed in the wind farm, for operating at the highest net profit point. The performance of proposed optimizer is confirmed by simulation results. Some outstanding properties of this new estimator are online implementation capability, structural simplicity and its robustness against any changes in wind farm parameters. Based on the simulation results, the effectiveness of the proposed optimization strategy is verified.

1. Introduction

The world's fastest growing renewable energy source is the wind energy. Wind turbines are machines which convert the wind energy to the electricity [1,2]. A wind farm contains a number of horizontal wind turbines [3,4]. These wind turbines are positioned and aligned in clusters facing the wind direction. Optimal wind turbine placement on a selected wind farm site is of major importance, since it can lead to a remarkable increase in the produced power and therefore the overall net profit of the wind farm [5–7].

Besides the optimal wind turbine placement, the number of wind turbines installed in the wind farm can also be of major importance to achieve the maximal produced power and net profit of the wind farm. In this article the main focus will be on number of turbines modifying by taking economic aspects into account [8]. Conceptual design of a new wind farm involves the evaluation of alternative farm configurations to determine physical and economic feasibilities [9]. In testing alternatives, designers require both an absolute economic measure and a normalized economic measure in order to make a definitive evaluation [10,11]. In recent years NPV (Net Present Value) [12–16] has often been chosen as the absolute metric and IRR (Internal Rate of Return) [17–19] as the normalized one.

The NPV and IRR are two of the most important criteria for choosing among investment projects [20,21]. In many circumstances investment projects are ranked in the same order by both criteria. In [22] was consider the NPV and IRR as indexes to evaluate the investment risk of wind power project. Paper [23] presented an alternative approach to conceptual design where a compound objective function based on the NPV and IRR aggregate performance metrics. In some situations, however, the two criteria provide different rankings [24]. In [25,26] a sensitivity analysis of the IRR to some economic factors has been carried out.

In an uncertain economic environment, it is usually difficult to predict accurately the investment outlays and annual net cash flows of a project [27]. In addition, available investment capital sometimes cannot be accurately given either [28]. In [29] was addressed the maximization of a project's expected NPV when the activity durations and cash flows are described by a discrete set of alternative scenarios with associated occurrence probabilities. Article [30] presented the concept of NPV curve to estimate the

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http://dx.doi.org/10.1016/j.enconman.2014.01.038
0196-8904/

best investment time for the investor, where the curve is constructed by calculating the NPVs resulting from the investment in successive years.

Optimal performance (maximal net profit) of the wind farm can be obtained if the number of turbines installed in the wind farm is optimal. The aim of the investigation is to change the number of turbines in the wind farm at different interest rates per year and unit sale price of electricity so that the farm may be kept running at maximum profit level or to maximize NPV.

To improve the operations of the wind farm, application of fuzzy logic (FL) [31–36] or artificial neural network (ANN) has attracted much attention in recent years [37–43]. As a soft computing [44], non-linear function, ANNs can be used for identifying the extremely non-linear system parameters with high accuracy. Neural networks can learn from data. However, understanding the knowledge learned by neural networks has been difficult. In contrast, fuzzy rule based models are easy to understand because they use linguistic terms and the structure of IF-THEN rules. Unlike neural networks, however, fuzzy logic by itself cannot learn. Since neural networks can learn, it is natural to merge these two techniques. This merged technique of the learning power of the ANNs with the knowledge representation of FL has created a new hybrid technique, called neuro-fuzzy networks or adaptive neuro-fuzzy inference system (ANFIS) [45]. ANFIS, as a hybrid intelligent system that enhances the ability to automatically learn and adapt, was used by researchers for modeling [46–49], predictions [50–54] and control [55–59] in various engineering systems. ANFIS can be used with systems handling more complex parameters than neural networks or fuzzy logic. Another advantage of ANFIS is its speed of operation, which is much faster than in other control strategies like fuzzy control or neural network control. The basic idea behind these neuro-adaptive learning techniques is to provide a method for the fuzzy modeling procedure to learn information about data [60–67].

In this paper, the application of ANFIS is proposed to optimize the number of turbines installed in the wind farm to extract the maximal net profit throughout determined working period of the wind farm. As inputs in the optimization scheme, interest rate per year and unit sale price of electricity are used. The output should be the optimal number of turbines in the wind farm which generates the maximal net profit or NPV. The objective function of the NPV and IRR for the total relevant costs considered in our model is mathematically formulated. A complete search procedure is provided to find the optimal solution by employing the properties derived in this paper and the ANFIS algorithm. The aim of this paper is to develop a model to determine economically optimal number of wind turbines for wind farms, which include the aerodynamic interactions between the turbines (wake effect) and the various cost factors.

2. Wind farm power production model

Since a wind turbine generates electricity from the energy in the wind, the wind leaving the turbine has less energy content than the wind arriving in front of the turbine. Therefore a wind turbine in a wind farm will always cast a wind shadow in the downwind direction. This is described as the wake behind the turbine, which is quite turbulent and has an average down wind speed slower than the wind arriving in front of the turbine.

For the present study analytical wake model named as Jensen's wake model [68] is chosen. The wake model is based on the Betz theory [69]. Betz theory is useful in determining the wake wind speed after the rotor. The principle of wind turbines is to extract kinetic energy from the wind and convert it into electricity. A limit to the maximum extractable kinetic energy from the wind by a wind turbine was determined to be 59.3% by Betz [69], and is appropriately termed the Betz limit. Betz formulated the limit using simple one dimensional Bernoulli equation to model incompressible wind flow across the rotor. The assumptions used in the derivation were a constant, uniformly distributed velocity and pressure profile across the turbine's seeping area. Due to this model is one dimensional, tip losses due to rotational effects and viscous dissipation are neglected. The Betz limit cannot be achieved with wind turbines due to aerodynamic losses by interactions between turbines, viscous dissipation, and efficiency losses though mechanical and electrical power converting devices.

The Jensen's wake has a radius, at the turbine which is equal to the turbine radius $R_r[m]$ while, $R_1[m]$ is the radius of the wake in the model. $R_1[m]$ is considered as radius of the downstream wake; the relationship between R_1 and X[m] is that downstream distance when the wake spreads downstream the radius R_1; that increases linearly proportional, X; axial induction factor is denoted by a; α is the entertainment constant. The wake expands linearly with downstream distance, as stated in Jensen's model as shown in Fig. 1.

Following equation [68] is used to determine the wind speed after wind turbine rotor as it shown in Fig. 1:

$$u = u_0 * \left(1 - \frac{2a}{1 + \alpha\left(\frac{X}{\left(R_r\sqrt{\frac{1-a}{1-2a}}\right)}\right)^2}\right) \tag{1}$$

In a wind farm, some turbine might or might not be affected by the wake created by another turbine positioned in front of it. Moreover, the effect might be partial or complete. Eq. (1) represents complete wake effect of a wind turbine in front of another. Another interesting state of the wake effect is when a portion of a turbine is affected simultaneously by the wake of two wind turbines as it shown in Fig. 2.

Following equation [68] is used to determine the wind speed for multiple partial interferences of the wake effects after the two wind turbine rotors as it shown in Fig. 2:

$$u_{i+1} = u_i * \left(1 - \sqrt{\left(\frac{2a}{1 + \alpha\left(\frac{X}{\left(R_r\sqrt{\frac{1-a}{1-2a}}\right)}\right)^2}\right)^2 + \left(\frac{2a}{1 + \alpha\left(\frac{X}{\left(R_r\sqrt{\frac{1-a}{1-2a}}\right)}\right)^2}\right)^2}\right) \tag{2}$$

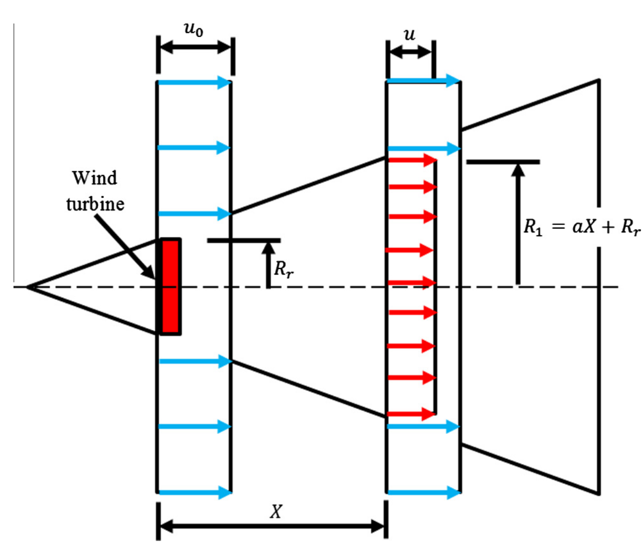

Fig. 1. Schematic of wake model.