Renewable Energy 75 (2015) 550–559

Contents lists available at ScienceDirect

Renewable Energy

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

Energy management strategy based on receding horizon for a power hybrid system

Diego Feroldi*, [1], Pablo Rullo, David Zumoffen [2]

French-Argentine International Center for Information and Systems Sciences (CIFASIS-CONICET-UNR-AMU), 27 de Febrero 210 bis, S2000EZP Rosario, Argentina

A R T I C L E I N F O

Article history:
Received 16 July 2014
Accepted 30 September 2014
Available online

Keywords:
Renewable energy sources
Bioethanol
Wind energy
Solar energy
PEM fuel cells
Autoregressive models

A B S T R A C T

This paper presents an energy management strategy to operate a hybrid power system with renewable sources (wind and solar), batteries, and polymeric electrolyte membrane fuel cells. The fuel cells are fed with hydrogen from bioethanol reforming. The energy management strategy uses the concept of receding horizon with predictions of the future generation from the renewable sources, the future load, and the state of charge in the battery bank. Several tests are done in order to analyze the performance of the proposed methodology. The results, compared with the case without predictions, show a reduction in the loss of power supply probability (LPSP) up to 88%.

1. Introduction

The renewable energy sources have a large amount of advantages, including sustainability, low emissions, and economical benefits. However, most of these energy sources have an intermittent behavior due to atmospheric conditions. Therefore, it is necessary to combine more than one type of renewable source to improve the robustness of the power system. This is, therefore, a hybrid power system based on renewable energy sources. One of the possible options is to combine wind and solar energy, together with a battery bank to store energy, as is presented in the paper of [7]. In this work, it is also shown the benefit of using polymeric electrolyte membrane (PEM) fuel cells to improve the robustness of the power system. The hydrogen that feeds the fuel cells is produced through bioethanol reforming.

The PEM fuel cells reinforces the power generation from the renewable sources, providing energy when is necessary according to an adequate management strategy. The proposed configuration decreases the probability of incapacity of power supply, decreasing at the same time the amount of wind turbines, solar panels, and batteries.

There are several approaches in the literature to address the energy management in hybrid power systems. These approaches are mainly based on heuristic rules that modify the system operation on the basis of the powers and state of charge in the energy storing devices [20]. In Ref. [21] a decision algorithm with a few rules is done. In Ref. [14] a more complex algorithm of decision based on rules is done. In Ref. [29] a supervisory control is done, switching the operation mode according to heuristic rules. In Ref. [18] an optimum load management strategy (minimizing a function with constraints over a period of predictions) for a wind/diesel/battery hybrid power systems is presented. In Ref. [26] a hierarchical control composed by a master control strategy and a slave control strategy is presented for an off-grid photovoltaic (PV)/wind turbine/hydrogen/battery hybrid system. In Ref. [25] a control algorithm based on DC bus voltage regulation for a fuel cell (FC)/PV/ultracapacitor system is presented. In Ref. [27] an energy management strategy based on Model Predictive Control (MPC) is presented for the same system. In Ref. [34] it is proposed a control scheme with double hysteresis. In Ref. [11] three strategies are proposed based on switching between different modes of operation, taking into account the state of charge in the batteries. In Ref. [4] three strategies based on rules are presented, taking into account also the pressure in the hydrogen tank, which is fed from an electrolyzer. In Ref. [6] a fuzzy logic based strategy is presented. In Ref. [7] an energy management strategy is proposed, which

---

* Corresponding author. Tel.: +54 341 4237248 304; fax: +54 341 482 1772.
E-mail address: feroldi@cifasis-conicet.gov.ar (D. Feroldi).

[1] Also with Universidad Nacional de Rosario – FCEIA-DCC, Pellegrini 250, S2000BTP Rosario, Argentina.

[2] Also with Universidad Tecnológica Nacional – FRRo, Zeballos 1341, S2000BQA Rosario, Argentina.

http://dx.doi.org/10.1016/j.renene.2014.09.056
0960-1481/© 2014 Elsevier Ltd. All rights reserved.

operates between five modes of operation. The strategy is formalized through the concept of finite state machine, defining modes of operation (states) and events that produces the change of state depending on the previous state and the active events according to a mapping function.

The receding horizon concept is commonly used in model predictive control formulation. In order to improve the system performance and efficiency, a prediction of meteorological variables and load power requirements must be used. In Ref. [22] a supervisory predictive control is presented, but is considered the case where the future load for certain length of time is known and environment conditions remain constant. In Ref. [32] the predicted wind, solar and temperature data are obtained and updated hourly from an official database. In Ref. [13] an autoregressive model is proposed for the prediction of wind speed and then used to calculate future wind turbines output power.

This work presents an energy management strategy based on receding horizon with a performance significantly better than the presented in Ref. [7]. This strategy takes advantage of prediction of the future generation in the power sources, the load requirement, and the evolution of the state of charge in the batteries. The predictions of the power sources and the load are performed using autoregressive models and historic data of wind speed, ambient temperature, solar radiation, and load demand. Thus, at a given time step, the energy management strategy takes decisions based on the future predictions over a finite prediction horizon. At the next time step new decisions are taken starting from the new state and over a shifted horizon, leading to a receding horizon policy. The design of the power system in this paper is done according to the results in Ref. [8].

The organization of the paper is the following. In Section 2 the description of the hybrid power system is done (electric topology and main characteristics of the system elements). In Section 3 the proposed energy management strategy is presented. In Section 4 the results are presented and confronted to the strategy without predictions. Finally, in Section 5 some conclusions and guidelines about future works are presented.

2. Description of the system

The hybrid power system is composed of several types of power sources and energy storing devices that are able to supply the load. The power sources are wind turbines, photovoltaic (PV) modules, and PEM fuel cells, while the energy storing devices are batteries. All these elements are connected to a direct-current bus through power converters. The power system has no connection to other electric grid. The PEM fuel cells are fed with high purity hydrogen from a bioethanol reforming process. Fig. 1 shows a scheme of the hybrid power system.

The detail description of the component of the power system is done in Refs. [7,8]. In particular, in the second work a methodology for the optimal sizing of the system integrated with the energy management strategy was proposed. The main objectives in the sizing process are the following: (a) achieve a reliable power supply under varying atmospheric conditions, (b) minimize the cost of the power system, and (c) minimize the bioethanol consumption. The following optimization problem is solved in the sizing methodology:

$$\min_{\mathbf{x}}\{C_{\mathrm{T}}(\mathbf{x}) + \rho C_{\mathrm{Et}}(\mathbf{x}, \mathrm{SOC}_i, \mathrm{EMS})\}, \tag{1}$$

where $\mathbf{x} = [N_w, N_{\mathrm{PV}}, N_b, N_{\mathrm{FC}}]$ is the vector of decision variables, being N_w the number of wind turbines, N_{PV} the number of PV modules, N_b the number of batteries, and N_{FC} the number of PEM fuel cells modules. On the other hand, SOC_i is the initial state of charge ($\mathrm{SOC}_i = \mathrm{SOC}(t=0)$) in the battery bank. The SOC, at discrete time $k = t/T_s$ with $k = 0, 1, \ldots$, is defined as follows:

$$\mathrm{SOC}(k) = \frac{C_b^{\max} - C_b^u(k)}{C_b^{\max}} \times 100[\%], \tag{2}$$

where $C_b^{\max}$ is the maximum capacity of the batteries, in units of Ah, and $C_b^u(k)$ is the amount of Ah already used at time k, which can be computed as

$$C_b^u(k) = C_b^i + \sum_{j=1}^{k} \eta_c I_b(j) T_s [\mathrm{Ah}], \tag{3}$$

where η_c is the charge/discharge battery coulombic efficiency, in this case $\eta_c = 0.975$, and I_b is the battery current in units of A ($I_b > 0$ when the battery is in discharging mode and $I_b < 0$ when it is in charging mode), T_s is the sampling time, and C_b^i is $C_b^u(k=0)$, which corresponds to SOC_i.

The minimization is done subject to the following constraints:

$$\underline{\mathbf{x}} \leq \mathbf{x} \leq \overline{\mathbf{x}}, \tag{4}$$

which means that each decision variable in $\mathbf{x}$ is limited between a lower and an upper bound, and

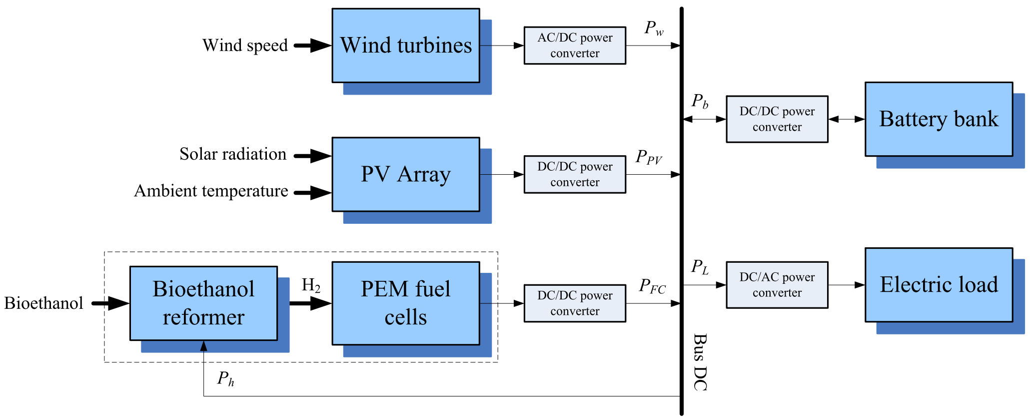

Fig. 1. Schematic diagram of the hybrid power system based on renewable sources and bioethanol.