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Integrated optimal design and sensitivity analysis of a stand alone wind turbine system with storage for rural electrification

M. Belouda [a,b,*], A. Jaafar [c], B. Sareni [c], X. Roboam [c], J. Belhadj [a,b]

[a] University of Tunis, DGE-ESSTT, Tunisia
[b] University of Tunis El Manar, ENIT, L.S.E.B.P. 37, 1002 Tunis, Tunisia
[c] Université de Toulouse, LAPLACE UMR CNRS-INP-UPS, ENSEEIHT 2, Rue Charles Camichel 31071, Toulouse, France

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ABSTRACT

In this paper, the authors investigate a robust Integrated Optimal Design (IOD) devoted to a passive wind turbine system with electrochemical storage bank: this stand alone system is dedicated to rural electrification. The aim of the IOD is to find the optimal combination and sizing among a set of system components that fulfils system requirements with the lowest system Total Cost of Ownership (TCO). The passive wind system associated with the storage bank interacts with wind speed and load cycles. A set of small power passive wind turbines spread on a convenient power range (2–16 kW) are obtained through an IOD process at the device level detailed in previous papers. The system cost model is based on data sheets for the wind turbines and related to battery cycles for the storage bank. From the range of wind turbines, a “system level” optimization problem is stated and solved using an exhaustive search. The optimization results are finally exposed and discussed through a sensitivity analysis in order to extract the most robust solution versus environmental data variations among a set of good solutions.

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* Correspondence to: School of Sciences and Technology of Tunis (ESSTT), 5 Avenue Taha Hussein, (B.P. 56 Bab Menara), 1008 Montfleury-Tunis, Tunisia. Tel.: +216 99 61 41 14.
E-mail address: malek.belouda@gmail.com (M. Belouda).

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Nomenclature

c	scale factor (m/s)
C_0	cost of one deep battery cycle (€)
C_3	battery element nominal capacity (Ah)
C_{BAT}	battery bank cost (€)
C_{Cell}	battery cell cost (€)
C_F	cycle to failure
C_{WT}	wind turbine cost (k€)
DOD	depth of discharge
I_3	battery element nominal discharge current (A)
I_{cel}	battery cell current (A)
I_{ch_max}	battery cell maximum charge current (A)
I_{disch_max}	battery cell maximum discharge current (A)
k	shape factor
N	number of cycles at a given DOD
N_{cel_p}	number of cells in parallel
N_{cel_s}	number of cells in series
N_{CH}	number of the battery bank changes over 20 years
N_{cyc}	equivalent number of cycles
N_{cyc}^{τ}	equivalent number of cycles
P_{ext}	extracted power (W)
P_{load}	load power (W)
P_{WT}	wind turbine nominal power (W)
SOC	battery cell state of charge
T_{aut}	battery bank time autonomy (h)
TCO	total cost of ownership (k€)
V_0	battery element nominal voltage (V)
$V_{1,2,3}$	generated wind speed (m/s)
V_{ref}	reference compact wind speed (m/s)
V_{wind}	wind speed (m/s)
w_{cyc}	weight of a cycle
τ	repeated wind cycle (days)
τ_{op}	operating period (days)

1. Introduction

According to the World Energy Agency [1], some 1.5 billion people had no access to electricity in the world by 2009, with more than 80% of habitants in rural zones. Providing consumers in remote areas with reliable and cheap electricity becomes a priority in several developed and undeveloped countries such as in the case of isolated cities in Tunisia. The steadily increasing demand of fossil fuels along with concerns about global warming, presents natural renewable energy sources as attractive solutions. Among these sources wind energy systems (free in their availability, renewable and non-polluting) with storage are among the most competitive alternatives for electrifying remote consumers and they are widely used in both autonomous or grid connected applications. These systems can also operate in parallel with others available energy sources (fuel cells, diesel generators) and several means of storage (accumulators, H_2 storage, etc.) in order to enhance the system reliability [2–5].

However, the drawbacks of such sources are their TCO which is still expensive, especially for small wind turbine systems. Moreover to assure the service continuity and to protect the battery against deep discharges (subsequently extend the battery bank life), such systems require an additional dynamic source of energy or an optimal wind system design [8,9]). Recently, several researches based on global optimization techniques have been focused on the design of optimal system configurations which meet the load demand for given climatic data [10–12].

Bagul, Borowy and Salameh [6–8] have developed several methodologies for optimally sizing a wind/PV system associated with a battery bank for a given load. These methods are based on the use of long term data for both irradiance and wind speed. However, such approaches are penalized by CPU time due to wide data range. Several studies have used the average hourly wind speed data over a few years simulation period, but this vision strongly filters wind turbine powers. Other researchers [13,14] have developed probabilistic methods to determine the annual energy of a wind system. In particular in [15–19], authors have selected the optimal combination and sizing of wind generators, PV modules and storage batteries.

This paper suggests a systemic methodology for designing the optimal combination and sizing of passive wind turbines associated with electrochemical storage. Generally, deterministic optimization approaches neglect the effects of environmental inputs uncertainties (including variation or perturbation of wind speed and/or load profiles) which can lead to drastic change of optimal solution quality. Several studies [20–26] have taken into account the increased need for sensitivity analyses to perform a robust system design in various research areas.Thus, this study is particularly focused on the sensitivity analysis of a set of "good" solutions to obtain an optimum system quite insensitive to environmental variations.

The remaining of the paper is organized as follows. The passive wind system and the battery characteristics are described in Section 2. In the third section, the systemic optimization procedure is presented. Section 4 is dedicated to the local optimization procedure. The models and the systemic optimization formulation are exposed in Section 5. Section 6 is reserved to the results and the sensitivity analysis.

2. Description of the system

The considered system is a "low cost" full passive wind turbine (WT) battery charger (Fig. 1) without active control and with minimum number of sensors as studied in [27,28]: this local optimization loop is not detailed in this paper but only referred to previous studies. An experimental prototype of the optimized system, especially the PM synchronous generator, has been built in LAPLACE Lab and had confirmed the ability of the passive structure to draw a power close to the optimal range with small losses. This prototype and subsequent study is detailed in [29]. The wind turbine parameters have been obtained by applying similitude relationships with reference to a 1.7 kW wind turbine which had been previously optimized by the local IOD process in [30,31].

Both wind speed and load profiles used in this study are considered as deterministic data. These data were acquired at a typical farm in Tunisia. The load profile is set on 24 h and day by day repeated (Fig. 2). The wind speed profile has been obtained from a previous study [32] by applying a "compact synthesis process" on an actual wind speed profile of 200 days duration considered as reference data, with the aim of generating a

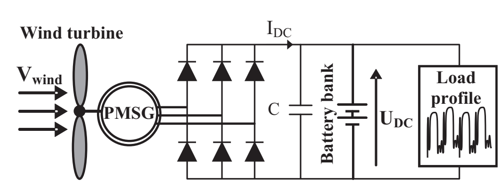

Fig. 1. WT system with battery for stand alone application (rural site electrification).