Applied Energy 212 (2018) 196–209

Contents lists available at ScienceDirect

Applied Energy

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

Optimal operation of fuel cell/wind turbine hybrid power system under turbulent wind and variable load

Nicu Bizon*

University of Pitesti, Faculty of Electronics, Communications and Computers Science, 1 Targu din Vale, Arges, 110040 Pitesti, Romania
University Politehnica of Bucharest, Doctoral School, Bucharest, Romania

HIGHLIGHTS

- The Extremum Seeking Control (ESC) algorithm is efficient optimization tool.
- 99.9% accuracy and 0.12 s searching time for Wind Energy Conversion (WEC).
- Global ES (GES) Real Time Optimization (RTO) strategy is tested for 6 kW FC/WEC HPS.
- Up to 10% fuel economy for GES-RTO strategy as against Static Feed-Forward strategy.
- The fuel economy is less dependent on wind turbulence.

ARTICLE INFO

Keywords:
Extremum Seeking Control (ESC)
Wind Turbine (WT)
Maximum Power Point (MPP)
Fuel Cell (FC)
Fuel economy
Real-Time Optimization (RTO)

ABSTRACT

In this paper is proposed a new Extremum Seeking Control (ESC) algorithm for optimal operation of Wind Turbine (WT) under turbulent wind. In this proposal the dithers' amplitude is WT system dependent, not constant or decreasing exponentially as in the classic ESC schemes. So, instead of one, the proposed ESC scheme has two loops: (1) the classic ESC loop controlled by the loop gain (k_1) to accurately find the Maximum Power Point (MPP); (2) the anticipative ESC loop controlled by the dither gain (k_2) to speed-up the localization of the current MPP under turbulent wind. The obtained results for a 100 Hz dither highlight the performance of the ESC-based MPP tracking algorithm proposed: about 99.9% tracking accuracy and a searching time less than 120 ms. This performance assures a tracking efficiency higher than 99% even for gusts of wind that may occur. The Fuel Cell is proposed as backup energy source for WT Hybrid Power System to sustain the load demand and reduce the size of the Energy Storage System (ESS), even for a high variability of the WT power. In comparison with Static Feed-Forward (sFF) strategy, a fuel economy of 5 lpm can be obtained using the ESC-based Real-Time Optimization (RTO) strategies proposed here, which means about 10% from the nominal fuel consumption.

1. Introduction

The energy generated from the renewable energy sources (RES) is in attention of all specialists due to environmental concerns that will become more grave than now if the government policies to reduce the energy generated from the conventional sources based on fossil fuels, such as oil, coal, and natural gas, will not be strongly promoted.

Besides this, the control and optimal operation of the RES Hybrid Power Systems must be implemented based on intelligent concepts and advanced technologies [1–5]. Thus, the Wind Energy Conversion (WEC) system must be operated at Maximum power point (MPP) using a MPP tracking (MPPT) algorithm [1]. A detailed analysis of control and optimal operation of the HPSs is performed in [2]. The energy efficiency of HPSs is approached in [3] based on experimental results for different HPS topologies. The optimal design of grid-connected HPS is shown in [4], but here the power flow of the grid-connected inverter is modeled by load demand on DC bus in order to focus the analysis on optimal operation of the Fuel Cell (FC) system, which is used here as backup energy source. Anyway, if the issue of partial shading has to use Global MPPT (MPPT) algorithms [6,7], then these algorithms could be also used for FC system to optimally operate the FC HPS. The fuelling rate may be both controlled to track the Maximum Efficiency Point (MEP) based on different Energy Management Strategy (EMS) [8].

The multimodal optimization algorithms locate all peaks in the search space, because the Global Maximum Point (GMP) may not be always available due to operational constraints. Furthermore, the GMP

* Address: University of Pitesti, Faculty of Electronics, Communications and Computers Science, 1 Targu din Vale, Arges, 110040 Pitesti, Romania.
E-mail address: nicu.bizon@upit.ro.

https://doi.org/10.1016/j.apenergy.2017.12.034
Received 17 September 2017; Received in revised form 14 November 2017; Accepted 3 December 2017

is not unique in some cases, so the GMMs' knowledge may be useful for the user to switch from the current solution to other more appropriate from the GMPPs set in order to maintain the system efficiency to an acceptable level [4,9,10].

In practice, the GMPPs can be located based on off-line or real-time identification algorithms, which will search these points on the dynamic multimodal function that models the process, but with different performance due to the physical constraints and high dynamic of the process [11]. A typical case is the Hybrid Power Source (HPS) of the Fuel Cell Vehicle (FCV) that depends by: (1) the HPS topology chosen [9]; (2) the k_{ESS} ratio, which defines the operating mode of the Energy Storage System (ESS), such as the charge-sustaining mode ($k_{ESS} = 0$), the charging-mode ($k_{ESS} < 0$), and the discharging-mode ($k_{ESS} > 0$), related to load cycle and HPS energy efficiency [2,3]; (3) the regenerative braking factor, k_L, which is the percentage from load power profile of the total braking energy that can be regenerated by the electric motor [12]; (4) the k_{FC} ratio, which sets the controlled ratio from FC power flow that will charge the ESS [2,3]; (5) the energy efficiency of the power converters involved in that topology [13]; (6) the EMS applied for optimal control of the FC System [14]. Thus, the optimal operation of the FCV is still a challenging task because it is necessary to be used a RTO strategy in order to control the fueling flows rates considering the above mentioned parameters, besides the load demand, the data from the signaling sensors and the communication unit, and the driver requests [2,3]. Also, even if the optimal control of wind energy systems is global approached in [15], the optimal operation of the WEC system is still challenging due to need of advanced control, without measuring the wind and a prior knowledge of the WT characteristics, but simple to be designed, and with high efficiency and robustness during the wind turbulence.

The MPPT algorithms used for WEC system are classified in [1,4,15–17] and compared in Table 1.

Some MPPT methods generally require a priori knowledge of some WT parameters from direct measurements, such as the optimum power coefficient [29], the pitch angle [30], the wind speed [31] etc. Other MPPT methods, such as the P&O and HCS algorithms, do not require a priori knowledge of WT parameters from direct measurements, but they fail to search the MPP when are used for large WT under high dynamic profile of wind speed due to the inertial loads on WT rotor [32].

The adaptive MPPT algorithms can search accurately the MPP or Maximum Torque Point (MTP) without measuring the wind or a prior knowledge of the power or torque characteristics [1,33], or of the WEC system losses [34]. The Extremum Seeking Control (ESC) algorithms based on sliding mode schemes [35] or dither schemes [36] are of adaptive type, but have some shortcomings related to high values of the power ripple and low tracking accuracy of the MPP, if the ESC loop gain is set large to increase the MPP searching speed [2,3,33]. Besides the ESC algorithms, different other adaptive algorithms are proposed to optimize the power coefficient, such as the nonlinear sliding mode control [37], the optimal direct shooting control [38], and the Lyapunov-based control [39]. Compared with the previous MPPT algorithms, the nonlinear controller proposed in [38] increases the tracking efficiency while maintaining the drivetrain ripples within the interval of safe operation. The tracking accuracy is improved using the optimal direct shooting control [38], but the knowledge of the profile of incoming wind is the major deficiency of this method. The Lyapunov-based control [39] improves the searching speed and maintains the tracking accuracy despite the large variations in profile of incoming wind. Furthermore, this method can use both the generator torque and blade pitch angle to optimize the power coefficient, but its design is system dependent, with too many parameters which must be redesigned for a different WEC system.

The ESC scheme proposed in [40] to track the MPP on the PV power characteristic is simple to be designed and is improved here considering the new features of GMPPT algorithms proposed in [6,7]. So, besides the classic ESC loop [41], an additional dither loop is added to locate the MPP or the MTP on the power or torque characteristics. This additional loop will generate an anticipated effect to the dither amplitude based on the profile of the wind speed. So, in other words, the amplitude of the dither is not constant or decreasing exponentially as in classic ESC schemes [41,42], being WEC system dependent.

It is obvious that the changes in incoming wind produce variations on the WT power and WT torque as well. So, the proposed ESC scheme can use the power or torque characteristic as optimization function, being in both cases a ESC scheme with one input (dimension), named below as ESC 1D – scheme. As it was mentioned above, the ESC 1D – scheme has two loops: (1) the classic ESC loop is controlled by the loop gain (k_1) to find accurately the MPP; (2) the anticipative ESC loop is controlled by the dither gain (k_2) to speed-up the localization of the current MPP under turbulent wind. The results presented here highlight the high performance of the proposed ESC-based MPPT algorithm in comparison with other MPPT algorithms proposed in the literature [1,17,33]: 99.9% tracking accuracy and a searching time lower than six dither periods (about 120 mss for a 100 Hz dither). Thus, the tracking efficiency may be higher than 99% even for noisy wind profiles.

To sustain the load demand and reduce the size of the ESS, even for a high variability of the WT power, the Fuel Cell (FC) is proposed in this study as backup energy source for the FC/WT Hybrid Power System (FC/WT HPS). In general, the Static Feed-Forward (sFF) strategy [43] is used as reference to evaluate the performance of new real-time optimization (RTO) strategies. Note that the fuel economy for FC/WT HPS could be larger if the optimization of the FC system operation is

Table 1
Comparison of the MPPT algorithms used for WEC system.

		Performance indicators				
Class	Algorithm	Tracking speed	Tracking accuracy	Power ripple	Robust-ness	References
Indirect power controller (IPC)	Tip Speed Ratio (TSR)	High	Average	Average	Average	[18]
	Optimal Torque (OT)	High	Average	Average	Average	[19]
	Power Signal Feedback (PSF)	High	High	Average	Average	[20]
Direct power controller (DPC)	Hill Climb Search (HCS)	Low	Average	Average	Average	[21]
	Incremental Conductance (INC)	Low	Average	Average	Average	[22]
	Optimal-Relation-Based (ORB)	Average	Average	Average	Average	[17,23],
	Hybrid MPPT algorithm	High	Medium	Average	High	[23–25]
	Perturb and Observe (P&O)	Low	Average	Average	Low	[23]
	Multivariable P&O (MVPO)	Low	High	Low	Average	[1]
Soft Computing-based MPPT Algorithm	Fuzzy Logic Control (FLC)	Average	High	Average	Very High	[1,26,27]
	Neural Network (NN)	Average	High	Average	Very High	[1,17,28]
Adaptive MPPT algorithm	Extremum Seeking (ES) control	High	High	Average	High	[35,36]
	Proposed Global ES control	Very High	Very High	Low	Very High	