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Real-time replication of a stand-alone wind energy conversion system: Error analysis

Ciprian Vlad [a], Antoneta Iuliana Bratcu [b,*], Iulian Munteanu [b], Silviu Epure [a]

[a] "Dunărea de Jos" University of Galaţi, 47 Domnească, 800008 Galaţi, Romania

[b] Grenoble Image, Speech, Signal and Automatic Control Laboratory (GIPSA-lab), Grenoble Institute of Technology, 11 Rue des Mathématiques, 38402 Saint-Martin d'Hères, France

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ABSTRACT

This paper provides adequate information about the problem of real-time replicating in laboratory conditions. The dynamic behavior of stand-alone low-power wind energy conversion systems (WECS) in response to the wind speed variations and also to the electrical load variations is replicated. The investigated system consists of a variable-speed wind turbine based on a permanent-magnet synchronous generator (PMSG), a diode bridge rectifier, a DC–DC step-down converter and a wide range DC load. Because of reduced noise level and better steady-state accuracy, a speed-driven hardware-in-the-loop physical WECS simulator has been used to accomplish this task. Its significant drawback – that is, a reduced bandwidth – has been significantly alleviated by using an enhanced software simulator structure which uses a feed-forward compensation of the inherent physical disturbance produced by the generator torque variations. Both time-domain experimental results and a thorough frequency-domain error analysis show good replication performance in the frequency range of variation of both wind speed and electrical load.

1. Introduction

Because the primary resource of wind energy conversion systems (WECS) varies stochastically, the experimental investigation of such systems – usually performed after the preliminary off-line simulation analysis – must be rendered possible irrespective of the actual, uncontrollable wind conditions [1,2]. Laboratory investigation under controlled wind conditions is aimed at, especially for control purposes. Wind turbine physical simulators (WTPS) have thus become necessary, having as main goal to provide a physical shaft replicating the dynamical behavior of a wind turbine defined by a given mathematical model.

Hardware-in-the-loop simulation (HILS) concept has been recently used for a wide palette of applications, including automotive systems [3], power systems [4], power electronic converters [5], photovoltaic generators [6] and WECS [7–11]. In general, the structure of a WTPS is based upon the HILS concept and supposes the closed-loop connection of two subsystems, namely (see Fig. 1):

- A real-time software simulator (RTSS), which implements the mathematical model of the simulated wind turbine and that of the wind.
- An electromechanical tracking servo-system (TS), based upon an electrical motor (EM) offering the wind-like shaft, to be coupled to the electrical generator (EG) of the wind system.

The wind turbine's mathematical model implemented in the RTSS is organized as a dynamical system whose output, $y(t)$, is send as reference to the TS. Depending of the output's physical nature, the TS can be controlled in [12,13]:

- Rotational speed, when the reference of TS is the rotational speed computed within the RTSS, $\Omega(t)$; in this case the measured (or else response) variable within the control loop is the motor torque, $T_m(t)$ (usually, one uses the motor estimated torque).
- Torque, when the reference of TS is the wind turbine's effective torque computed within the RTSS and the response variable is the rotational speed, $\Omega(t)$.

An important issue when using WTPS is how to assess its performance in terms of replication accuracy. Results related to this issue can be found in the literature; thus, in [12,13] it is shown that the dynamical properties of the wind-speed-to-rotational-speed transfer are superior when the TS is torque-controlled, because a torque control loop is faster than a rotational speed control loop. The other way round, torque control has the drawback of introducing noise, which affects the replication quality. This can easily be

* Corresponding author. Tel.: +33 476826384.
E-mail addresses: ciprian.vlad@ugal.ro (C. Vlad), antoneta.bratcu@gipsa-lab.grenoble-inp.fr (A.I. Bratcu), iulian.munteanu@gipsa-lab.grenoble-inp.fr (I. Munteanu), silviu.epure@ugal.ro (S. Epure).

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Nomenclature

WECS	wind energy conversion system	T_G	PMSG torque
HILS	hardware-in-the-loop simulation	T_{IM}	IM torque
PMSG	permanent-magnet synchronous generator	V_R	rectified voltage
IM	induction motor	I_R	rectified current
Ω	rotational speed	I_{DC}	load current
v	wind speed	P_{wt}	wind turbine power
λ	tip speed ratio	P_{DC}	electrical power measured at the chopper's output
$C_p(\lambda)$	power coefficient of the wind turbine	$K_{\Omega VR}$	steady-state gain from Ω to the rectified voltage
J_{wt}	inertia of the simulated wind turbine	K_T	steady-state gain from rectified current to PMSG torque
J_{tr}	total inertia of the physical simulator		
T_w	wind torque		

deduced if considering the turbine's motion equation. In this case, the torque reference is the effective torque:

$$T^*_{ef} = T_{wt}(\Omega, v) - J_{wt}\frac{d\Omega}{dt},$$

where $T_{wt}(\Omega, v)$ is the wind turbine torque, J_{wt} is the total inertia of the turbine-generator coupling and $J_{wt}\frac{d\Omega}{dt}$ is the dynamic torque. This latter term of the above relation contains a derivative, which amplifies noise. Use of filters in order to reduce noise also results in the bandwidth being reduced.

The goal of this paper is the WTPS's frequency-domain error assessment in dynamic regime. Two problems are approached, as follows. The first is to establish a solution for improving the dynamic properties of a rotational-speed-controlled WTPS. Because the noise level is quite low in this case – as the turbine's dynamical model implemented in the RTSS is strictly causal – improvement of dynamics could render the speed control more attractive than the torque control. The second problem approached is to establish a solution for global assessment of dynamic regimes of WTPS, namely by using frequency-domain models. It is well known that a generic fixed-pitch WECS has two dynamic transfer channels: from the wind speed to the rotational speed and from the electrical load (e.g., generator current or torque) to the rotational speed. Yet, the concerned literature deals with the wind speed synthesis and the physical replication of the rotational speed variations in response to the synthesized wind speed, whereas the electrical load influence on the WECS rotational speed is almost entirely omitted.

WECS based on permanent-magnet synchronous generator were investigated in recent researches, but most of them are intended for grid connected systems. In [14] is presented a simple control strategy for an optimal extraction of output power from grid connected PMSG-based variable-speed wind energy conversion system. The electronics part consists in a diode bridge rectifier and a DC–DC boost converter. In [15,16] are illustrated the performance of a PMSG based wind system with back-to-back converters for grid interconnection.

The speed-driven simulation technique for 1:1 low-power WECS has been reconsidered in this paper and an enhanced software simulator structure has been proposed. This technique is used to assess the real-time replication of the dynamic behavior of a fixed-pitch rotor driving a genuine wind turbine permanent-magnet-synchronous-generator (PMSG) which supplies a mainly resistive DC load through a customized power electronic interface. Its performance will be assessed not only in time-domain but also using the frequency-domain error evaluation method [12,13,17].

The paper is organized as follows. The next section describes the structure of the studied WECS. The third section lists the requirements imposed to the WECS simulator and describes the proposed software simulator configuration. The fourth section illustrates the overall performance of the simulator by means of time-domain results in various WECS regimes. Frequency-domain error analysis is performed in the fifth section, emphasizing the frequency range of accurate real-time replication. Conclusion and future issues are given in the final section, the sixth.

2. Structure of the considered stand-alone WECS

A low-power WECS, rated at about 1 kW at 11 m/s, is studied in this paper (Fig. 2). This architecture allows the feeding of a low-voltage charge or inverter by using a minimum number of electrochemical accumulators, meanwhile suitably controlling the turbine operating point and the accumulators charging current. The wind turbine directly drives the PMSG; they are both taken from

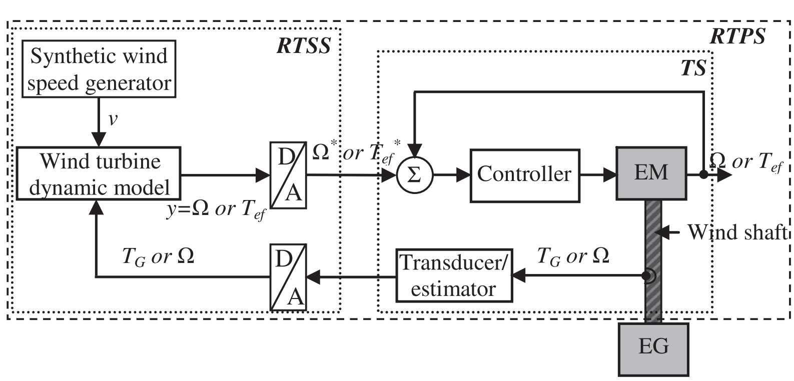

Fig. 1. General structure of a real-time simulator based on the HILS principle.