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Original Research Article

Real-time testing of energy storage systems in renewable energy applications

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ABSTRACT

Energy storage systems provide a promising solution for the renewable energy sector to facilitate large-scale grid integration. It is thus very important to explore means to validate their control scheme and their behaviour in the intended application before actual commissioning. This paper presents a reduced-scale hardware-in-the-loop simulation for initial testing of the performance of energy storage systems in renewable energy applications. This relieves the need of selecting and tuning a detailed model of the energy storage element. A low-power test rig emulating the storage element and the power converter is interfaced with a real time digital simulator to allow dynamic experimental tests under realistic conditions. Battery energy storage for smoothing the output power of a variable speed wind turbine is considered in this paper; however the proposed test methodology can be easily adapted for other storage elements in renewable energy, distributed generation and smart grid applications. The proposed HIL simulation is detailed and the experimental performance is shown.

Introduction

In the last decade, the global installed capacity and the generation of electricity from renewable energy sources have shown a substantial growth [1]. Wind energy, in particular, is a rapidly maturing technology with proven reliability and competitiveness. Despite the slowdown in 2013, more than 51 GW of new wind power was brought online in 2014. This sets a new record at an increase of 44% in the annual market and raises the total installed capacity to above 369 GW [2]. As opposed to the use of conventional sources, renewable energy generation is not able to follow a set reference as it depends on the availability of the natural resource. The negative effect of the variable output on the power system can be mitigated through the use of an energy storage system (ESS) that acts as a buffer between the renewable energy source and the grid [3].

Different technologies have been proposed in the literature for the implementation of ESS [4]. This paper focuses on electrochemical solutions, which includes several types of batteries and supercapacitors. Batteries are a well-established storage technology with the advantage of being modular and scalable [5]. Supercapacitors are also finding increasing applications due to their fast response. Battery-supercapacitor hybrid energy storage systems have also been proposed to increase both the technical and economic indexes of the ESS [6].

Battery energy storage systems (BESS) provide flexible energy management that allows renewable energy generation to achieve different objectives. These include smoothing of output power fluctuation [7–12], storage for dispatch at times with more favourable tariffs [13] and peak shaving [14]. Recently, BESS are also finding applications in grid frequency regulation, grid stabilization, provision of spinning reserve, load levelling and others [15]. To these effects, several BESS configurations and control strategies have been published [16]. It is essential however that such proposed configurations and control strategies be thoroughly tested to validate their performance.

Software simulation is an invaluable tool for the initial evaluation of control strategies and system configurations. Simulation studies are based on a model of the real system, making the obtained results largely dependent on the accuracy of the used models [17]. BESS are generally comprised of a battery storage element and a bidirectional DC–DC converter. The difficulty generally arises in selecting the battery model. A wide selection of models is published in the literature, covering a wide range of applications. The models are pitched at representing different aspects of battery

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Nomenclature

RTDS™	real-time simulator from RTDS technologies
BESS	battery energy storage system
VRLA	valve regulated lead acid [battery]
AGM	absorbed glass material
PMSG	permanent magnet synchronous generator
IGBT	insulated gate bipolar transistor
PWM	pulse width modulation
PI	proportional integral (controller)

performance, which are relevant to particular applications; however the majority are not tuned for the operating conditions prevalent in BESS applications [12]. On top of this, the diverse BESS control algorithms impose different demands on the batteries. The model options range from simple voltage-sourced models to dynamic ones, which consider the influence of external parameters on the behaviour of the battery through variable parameters [18–20]. The simpler models are based on battery data that is generally available but they do not represent the behaviour with sufficient detail. The introduction of more parameters, which can also be dynamic to represent external variables, can reproduce sufficient detail however tuning the additional parameters is not a trivial task. Other approaches include impedance based models that rely directly on experimental test of the batteries under different operating conditions [21]. As an example, the lead-acid battery model proposed by [19], which applies for both discharging and charging operation, is shown in Fig. 1. The model includes a number of *RC* blocks, whose parameters are a function of the battery state-of-charge and electrolyte temperature. E_b and R_b are the battery electrochemical emf and the internal resistance respectively, both of which vary during operation. The parasitic branch models the non-ideal effects.

Increasing the number of *RC* blocks opens the potential of more accurate simulations, but at the cost of making the process of parameter identification increasingly complex. Accurate determination of the parameters generally requires a number of experimental tests [22]. Models that are tuned for the particular conditions encountered in the considered application are typically used in the literature for the study of BESS in both wind and solar PV applications. The third order model proposed by [19] is used in [9,10], where the parameters are taken from [19] itself. The dynamic model described in [20] but with some modifications is used in [12].

Both the uncertainty and the complexity of the battery model can be overcome through the use of an experimental test rig. Experimental hardware, however, presents the challenges of development time and cost. Real-time hardware-in-the-loop (HIL) simulation combines software models with focused experimental hardware to provide a solution in between [23]. Different levels of HIL simulation are possible. These range from the implementation of control algorithms on actual microcontrollers [24] to the use of the simulator for the control of the full-scale hardware [25]. Reduced-scale HIL simulations control actual hardware but use focused, lower-power representative rigs, thus overcoming the challenges of full-scale hardware to provide a convenient intermediary step [26,27] before embarking on a full-scale prototype. A reduced-scale test bench for BESS in vehicular applications is proposed in [28]. A Li-ion battery is interfaced to a simulator through a high bandwidth amplifier, which sources or sinks the current demanded by the vehicle controller. The battery's terminal voltage is then used to assess the performance of software models. Lead-acid and Li-ion batteries are similarly interfaced to a simulator in [29]. The batteries emulate a storage element that is interfaced to an induction generator wind turbine. The battery terminal voltage is read and forced on the voltage source representing the battery in the simulated BESS to enhance the battery model. A 16 kVA virtual synchronous generator (VSG) is interfaced through a power interface to a simulator in [30]. The voltage at a chosen bus in the simulation model is used as reference to set the voltage at the VSG terminals. The VSG current response is measured and injected onto the chosen bus through controlled current sources. In this way, the simulated power system is influenced by the external hardware.

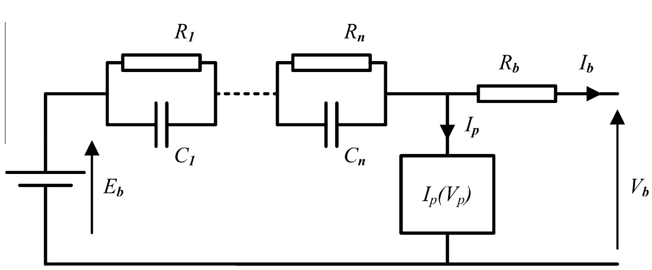

Fig. 1. Lead-acid battery model for both discharge and charge operation.

This paper proposes a reduced-scale HIL simulation that can be used to test the performance of energy storage systems in renewable energy applications, without the need of specifying complex models for the energy storage elements. An experimental rig comprising of a low power ESS, including both the storage element and the power converter, and a loading unit is proposed. The test rig can be used to examine the behaviour of various battery technologies and supercapacitors. It is interfaced to a commercial real-time simulator for HIL simulation. This paper tests the effectiveness of the proposed HIL simulation by considering the case of a BESS, interfaced through a DC–AC converter at the output of a variable-speed wind turbine, to smoothen the net power flow to the grid. The experimental rig, its control and the coupling to the modeled wind system are detailed. Experimental results detailing the performance of a VRLA AGM battery in wind output power smoothing application are shown.

Wind energy system model

This section deals with modeling of the wind energy conversion system together with the BESS used for smoothing the net power transfer to the grid. The characteristics of the wind turbine are presented, followed by an introduction to the used real-time simulator, i.e. the RTDS™ platform. Finally the modeled wind energy conversion system together with the integrated BESS is described and the chosen operating values are specified.

Wind turbine

Variable-speed wind turbines allow for higher energy yield than fixed-speed wind turbines as the rotational speed can be varied for optimal aerodynamic energy conversion. The mechanical power extracted from the wind by a variable speed wind turbine P_w can be expressed mathematically by Eq. (1). ρ is the air density, A is the turbine swept area, C_p is the power coefficient and V is the wind speed. For wind turbines with blade pitch control, C_p is a function of the tip speed ratio λ and the blade pitch angle β. The tip speed