Renewable and Sustainable Energy Reviews 28 (2013) 597–615

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

An analytical literature review of stand-alone wind energy conversion systems from generator viewpoint

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ARTICLE INFO

Article history:
Received 21 February 2013
Received in revised form
26 July 2013
Accepted 11 August 2013
Available online 3 September 2013

Keywords:
Wind energy conversion system
Variable speed
Stand-alone
Generator

ABSTRACT

The purpose of this paper is to provide an analytical review of wind turbine-generator systems for stand-alone applications. The review focuses on variable-speed wind turbines, as the future trend in wind energy conversion, in contrast with the traditional fixed-speed wind turbines. Indirect-drive and direct-drive turbines are comparatively evaluated. The concerns about long-term availability of permanent magnet materials and its impact on the future of permanent magnet synchronous generator are addressed. Having cost and efficiency in mind, viability of indirect-drive squirrel cage induction generator for stand-alone wind energy conversion systems is discussed. As an efficient induction machine design, permanent magnet induction generator is also examined. Finally, the potential of using switched reluctance machine, as a generator, in a direct-drive wind turbine system is investigated.

Contents

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http://dx.doi.org/10.1016/j.rser.2013.08.027

1. Introduction

Recently, utilization of wind energy has achieved a rapid growth in Europe, North America and Asia. Global Wind Energy Council (GWEC) reported that the total capacity of wind energy, installed in 2012 alone, exceeded 44 GW worldwide [1]. By 2020, European Union aims to have 20% of its electricity demand supplied by wind energy [2]. The US Department of Energy reports that wind energy can supply 20% of the country′s total demand by 2030 [3]. Although still lagging behind many other countries in support for wind energy, Canada plans to stay on track by having 20% of its demand supplied by wind energy by the end of 2025 [4]. Asia is still the largest regional market for wind energy. In China alone, the target is to install 150 GW of wind power capacity by 2020 [5].

Along with such a rapid growth, an enormous volume of research and development is being undertaken in the academia and industry on wind energy conversion systems (WECS). Different configurations of grid-connected WECS have been reviewed in a number of papers and books based on the types of generator and power electronic converter employed [6–15]. However, there is, to the best of the knowledge of the authors, insufficient review and comparative study on off-grid WECS.

Off-grid or stand-alone small wind turbines provide a very attractive renewable energy source for remote communities and small business. These wind turbines help in reducing the stress on the grid, diminish the pollution [16] and save on fuel cost by reducing or even eliminating the need for diesel generators, which consume a lot of polluting fuel, have high operating and maintenance costs, and may require additional significant costs if installed in a remote area where fuel transportation and refueling is a complicated mission [17]. Moreover, stand-alone wind turbines can be installed wherever wind resource is adequate and there is no access to the grid, or connection to the grid is very costly [18], or is not permitted or is difficult due to the required official approvals. Although the concept of operation is the same in both on-grid and off-grid WECS, the absence of grid in the off-grid case adds to the hardware and control requirements. In spite of the fact that wind energy is intermittent and cannot be dispatched to meet the assigned commitment, connection to the grid allows for extracting maximum power available from wind resources at any moment of time. In contrast, for an off-grid WECS to satisfy time-varying power demand and maintain balance of power, at least an energy storage unit is required to compensate for the power deficit and absorb the excess power. In some remote areas, a hybrid system might be required to complement wind power with other sources such as photovoltaic, small hydro and diesel generator. A combination of wind and solar energy is the most common complementary system [16]. This combination is frequently integrated with diesel generators to form a micro-grid, supplying off-grid communities. [19]. In such cases, a more complicated control is required in order to achieve an efficient power management [20]. Another issue with off-grid WECS is the reactive power required by some generator types that has to be supplied by a VAR source such as a capacitor bank, synchronous condenser, SVC or STATCOM [21].

Unlike fixed-speed wind turbines, variable-speed wind turbines require a partial- or full-scale power converter for power flow control, maximum power point tracking and ensuring a high quality for the power delivered. Fixed-speed wind turbines, in general, use squirrel-cage induction generator, with no power electronic interface [8–10]. On the contrary, variable-speed wind turbines enjoy a rather wide range of options for appropriate generator and power converter types. Asynchronous and synchronous machines are the most common generators employed in variable speed wind turbines. If the generator is coupled to the turbine′s shaft through a gearbox, the wind turbine is called indirect-drive or geared-drive wind turbine. If no gearbox exists, the wind turbine is called direct-drive or gearless-drive wind turbine. Selection of the right generator is of key importance to successful capturing of wind energy under different wind speed conditions, especially at low wind speeds, where the low power available has to be processed by a high-efficiency conversion system. Selection of electrical generator for stand-alone turbine has been briefly discussed in reference [22]. Induction and synchronous generators are compared and it has been concluded that the generator for stand-alone turbine must be a permanent magnet (PM) machine in order to avoid excitation requirement. Nevertheless, there are other issues that have to be addressed in addition to excitation requirements. Reference [23] has reviewed the key technologies of small-scale off-grid wind turbines. However, among all possible machines, the review has focused on PM generators only. PM generators, especially direct-drive PM synchronous generators, are the most commonly used electric machine for small-scale wind turbines [23] and have been of interest to many researchers as a typical solution for stand-alone WECS [24–28]. However, the attraction to direct-drive PMSG has been based on the criteria of high power density and reliability only. Other factors such as cost, and maintenance and control requirements should also be considered for a more thorough evaluation. Moreover, there is no definite proof that a direct-drive wind turbine is more reliable than an indirect-drive wind turbine [29]. A good number of published papers, listed in [30], have focused on induction generators as mature machines for stand-alone wind energy applications. Squirrel-cage induction generator, in particular, has been recommended by [31–34] as a simple, robust, brushless and cost-effective generator for stand-alone WECS. However, the attractiveness of such a generator may diminish if its efficiency is considered.

The above discussion points to the fact that a more comprehensive list of factors should be considered in the study leading to selection of the most appropriate generator for a stand-alone WECS under specific conditions. Some principles for generator selection in small off-grid wind turbines were listed in [23]. However, some important factors such as control requirements and construction complexity were not considered. Furthermore, excitation requirement was not an issue in [23], since the paper has focused on PM generators only. Therefore, in order to select the right generator for a stand-alone wind turbine, there is a need for a thorough study, considering all possible options, to be conducted on the basis of efficiency, reliability, cost, operation and maintenance requirements, construction complexity, control complexity, excitation requirements and noise level associated with each generator type.

This paper makes an analytical review and a comparative evaluation of the main configurations for variable-speed off-grid WECS from the generator type viewpoint to enable selection of the most appropriate solution subject to the given conditions. Besides covering conventional generator types, the potential of permanent magnet induction generator and switched reluctance generator for WECS application will also be investigated. To the best of the authors′ knowledge, such a thorough critical review, considering all possible generators and all factors stated, has not been conducted before. In addition to the outcomes of the evaluation process, the paper can serve as a source of information and relevant references for researchers interested in stand-alone wind turbine systems.

The paper starts with describing main components of variable-speed stand-alone WECS. Then, an overview of different wind generator systems, available in the market and reported in the literatures, is given. The appropriateness of each generator for small-scale off-grid WECS is examined based on the criteria stated