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A design methodology for selecting ratios for a variable ratio gearbox used in a wind turbine with active blades

Hamid Khakpour Nejadkhaki, Swanil Chaudhari, John F. Hall*

Department of Mechanical and Aerospace Engineering, University at Buffalo, State University of New York, Buffalo, NY 14260, USA

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A B S T R A C T

This paper investigates the performance of a variable ratio gearbox (VRG) used in a small fixed-speed wind turbine with active blades. The major components of the VRG-enabled drivetrain are an automatic-manual gearbox and squirrel cage induction generator that connects directly to the grid. The simplicity of this system may be appealing for applications when cost and reliability are of concern. It is an alternative to variable speed systems, which necessitate a modified generator and power conditioning equipment. During partial load operation the VRG provides a discrete set of rotor speeds. This allows the controller to track the wind speed and to achieve a greater efficiency. This study suggests three VRG ratios are sufficient to improve performance when used with active blades. A case study is presented where the performance is simulated using three different wind data sets. The study suggests that the VRG can improve production between 7 and 8.5% in low wind areas. The design procedure also illustrates a technique for finding the lowest and highest gear ratios needed for VRG design. These ratios allow the system to achieve the lowest cut-in and rated speeds. The approach also has useful implications for the design of a continuously variable transmission.

1. Introduction

The use of renewable energy is projected to expand through the year 2050 [1]. This trend will help mitigate the dependency on fossil fuel energy, which contributes to global warming. Therefore, it is imperative that the cost of renewable energy continues to decline to promote its implementation. Wind, solar, and hydroelectric are examples of burgeoning sources of renewable energy [2]. Still, the wind and solar farms necessitate large areas of land [3,4], while hydroelectric dams must be strategically placed based on water availability, geological formations, and river topology [5]. Due to the requirements, renewable energy production sites are often located away from the load centers. Moreover, the need for power transmission lines increases the cost of renewable energy, and thus, hinders its implementation [6]. In the case of wind energy, transmission lines costs account for roughly 25% of the overall costs.

Distributed energy is produced at the point of demand without the need for transmission lines [7]. On-site renewable systems can provide power to farms, schools, small factories, and rural communities. In recent years micro-hydro turbines have experienced rapid growth in remote areas [8]. This has been preceded by improvements in drivetrain efficiency that increase electrical production at a reduced cost [9]. Similarly, research in material science continues to improve the efficacy of photovoltaic energy conversion [10]. These developments have contributed to the proliferation of solar energy use in both the commercial and residential markets [11]. Among other breakthroughs are those in thermoelectric technology [12], which has the potential to produce power from sources of heat generation. Nevertheless, the ubiquity of wind provides one of the greatest opportunities for distributed energy. However, provisions to increase the efficiency of small wind systems are not always practical with respect to cost [13]. Because of this, small and medium-size wind turbines have lower efficiency and higher cost for energy production than the large wind turbines [7].

In general wind energy systems have two modes of operation [14,15] as shown in Fig. 1. Region 2 refers to the range between the cut-in and rated speed. Wind speed in this range is only capable of driving the generator at partial power. In this mode of operation, maximum aerodynamic efficiency is sought to boost production. The conventional technique for increasing efficiency is through

* Corresponding author.
E-mail address: johnhall@buffalo.edu (J.F. Hall).

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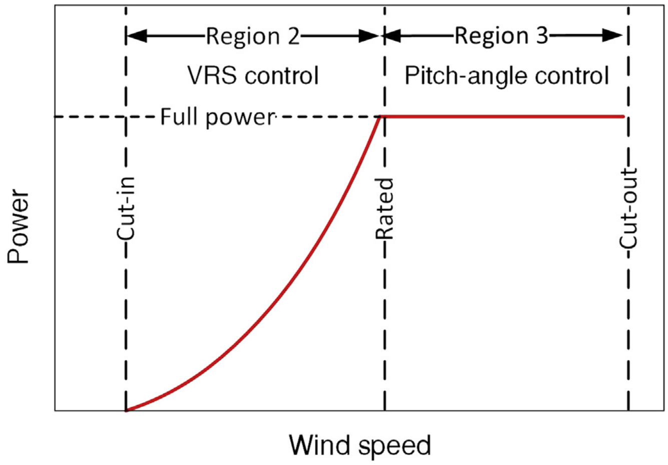

Fig. 1. Modes of operation for wind turbine systems.

variable rotor speed (VRS) control [16,17]. Pitch control has little, if any, effect in Region 2. In this range, the pitch angle is held at (or near) zero degrees. For conventional blade designs, this particular angle corresponds to maximum efficiency irrespective of wind speed. In Region 3 the wind speed is at or above the rated speed of the wind turbine system. The rated speed corresponds to the rated power capacity of the system. For wind speed above this point, it is necessary to dissipate a portion of the wind energy. This limits the amount of torque applied to the generator, which would otherwise overheat. In Region 3, inefficiencies are introduced to the system using stall-regulated blades or pitch-angle control [18]. The blade pitch angle can be increased to dissipate energy as needed to maintain a constant speed. During full-power operation the generator operates at a constant speed and power. Hence, most systems do not implement VRS in Region 3.

Variable rotor speed capability increases the aerodynamic efficiency, and thus, energy production during partial load operation. VRS requires a variable speed generator and a power converter to condition the electrical power. According to Blaabjerg and Ma, VRS systems now dominate the market among large wind turbines [19]. The performance can be improved in small wind systems using a maximum power point tracking (MPPT) controller. Eltamaly and Farh applied control to power converters used on the generator and grid [20]. The generator converter enabled the rotor speed to be controlled to achieve MPPT, while the grid converter controlled the active and reactive power through the direct and quadrature axes. Narayana et al. investigated VRS control using a hill-climbing approach with fuzzy logic to find the operating point for maximum power. This improved both the generator and aerodynamic efficiency [21]. Still, a drawback to VRS technology is the cost and losses associated with the power converter [22]. This has made it less practical for small systems. Moreover, the power conversion systems used in small wind turbines are often commercially-available converters intended for use in photovoltaic systems [23]. There have been reliability problems with this approach. Variations in wind speed also have a significant effect on the reliability of power conditioning equipment [24]. This can be even more problematic for small wind systems, which experience greater wind speed fluctuations due to the ground roughness.

Another approach to VRS is through the use of a continuously variable transmission (CVT), which has appeared a number of times in wind energy literature over the years [25–27]. In more recent times, Zhao and Maiβer proposed a hybrid planetary system where the low-speed shaft drives the sun gear that delivers power to three planets [4]. Each planet connects to another planet that is part of a second planetary gear system. The secondary sun then delivers power to the generator. The novelty of this design is a control motor that rotates the carrier frame and thus provides a means for controlling the output speed. Yin et Al. analyzed a CVT that utilized a hydro-viscous transmission to maintain a constant level of power during full-load operation [28]. The performance of this system was compared to the conventional approach that applies pitch control. A simulation study suggests that the hydro-viscous transmission responds more readily to variations in wind speed, and thus, regulates output power more effectively. The CVT is now being used in some low-torque automotive applications. A common type is the Reeves drive [29], which features a V-belt that transfers power between variable diameter pulleys situated on both the input and output shafts. Each pulley consists of two conical sheaves that move in and out to vary the depth to which the belt is seated. This changes the ratio of torque and speed between the shafts. However, this conventional approach of using frictional surfaces to transfer power has limited durability in wind energy applications [30]. The replacement of belts is a maintenance issue that reduces the reliability and uptime of the CVT-enabled system. Other challenges for implementing CVT technology relate to the complexity of the system, such as the need for hydraulics and control motors. These devices also introduce energy losses to the system.

The CVT technology is continuing to evolve and, at this time, it is promising for small wind applications up to a production capacity of around 75 kW. Similarly, the performance and cost of power conditioning equipment has improved in recent years and is widely used at the megawatt scale. It is also gaining use in small wind turbines. Still, small and medium wind systems have a higher cost per watt. This suggests a need for low-cost drivetrain concepts that can reliably improve efficiency. A variable ratio gearbox (VRG) is a low-cost device similar to the automatic-manual automobile transmission. It can provide discrete variable rotor speed to improve the efficiency of the wind turbine during partial load operation. The geared teeth transmit power efficiently and reliably [31]. Previous work has demonstrated that a VRG can increase the energy production of a fixed-speed wind turbine with stall-regulated blades [7]. This was achieved through the application of five lower gears. These ratios enable a higher tip speed that provides higher efficiency below the rated speed. A recent National Renewable Energy Laboratory (NREL) study also suggested that tip speeds up to 100 m/s may improve system performance and design [32].

This study focuses on the design framework for a VRG-enabled system with active blades. It is sufficient to implement the VRG with only three gear ratios. This is due to the actively controlled blades being used to reduce the aerodynamic efficiency once the low gear achieves full power. This is in contrast to the previous work, where additional VRG ratios were needed to maintain power near full level. Another contribution of this study focuses on the use of gear ratios that are higher than that used in the fixed speed system. The work suggests that using high gear ratios can reduce the cut-in speed of the system. A technique is also presented to determine the lowest and highest gear ratios that should be considered for gearbox design. Hence, this approach can also have implications for CVT design.

2. System modeling

The VRG-enabled drivetrain consists of a rotor, low-speed shaft, main gearbox, VRG, high-speed shaft, clutch, and induction generator as illustrated in Fig. 2. In this arrangement, the main gearbox performs the majority of the speed increase. The VRG delivers power from the main gearbox to the electric generator. The