

Wind Energy Conversion under an Integrated Generator–Rectifier Architecture for Continuous Maximum Power Operation

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Abstract

One of the emerging renewable energy technologies is offshore wind power. The attainment of the aggressive levelized cost of energy implies the employment of multi-megawatt wind turbines combined with high-performance, high-power-density, and high-reliability power conversion systems. One solution that is being proposed and is expected to work well is an integrated approach to the conventional electromechanical energy conversion systems where a multi-port permanent magnet synchronous generator is coupled with a single active rectifier and a number of passive rectifiers. To effectively apply such integrated systems in offshore wind the concept of maximum power point tracking (MPPT) becomes necessary but this is difficult to achieve because there are various passive rectifiers that cannot be controlled. This research paper shows that effective MPPT is possible by capitalizing on the fact that the d-axis current of the active rectifier is able to control the overall system output power. The offered MPPT capability opens up new possibilities of the integrated power conversion systems in the offshore wind energy usage.

Keywords: AC–DC power conversion, dc power systems, maximum power point trackers (MPPT), power conversion, rectifiers, wind energy, wind energy generation.

1. Introduction

Offshore wind power has become a fast growing renewable energy source with capacity growing greatly in recent years (2)–(5). Offshore wind turbines with considerably greater power rating than those applied in onshore applications have been developed to attain a competitive levelized cost of energy (LCOE). An example is the Gamesa 10X (6), Haliade-X (7) and Vestas V164 (8) turbines with rated powers of 10-12 MW. It has not been easy to design electromechanical energy conversion systems with such high-power generators that are capable of providing high power density, high efficiency, and high reliability in converter topologies based on the conventional topology. High switching losses and voltage and current rating of power electronic devices are the key limitations (9).

Some of the most popular converter topologies include neutral-point-clamped (NPC) converters and pulse-width modulation (PWM) converters at the two levels. Two-level PWM converters have a complex design and simple control plan (10); nevertheless, every switch has to support the completely dc-side voltage and the ac-side current. Power electronic devices are thus linked in series or parallel in order to process the multi-megawatt power levels and may result in less reliability in the entire system. NPC converters, conversely, minimize voltage stress per switch on devices, although the distribution of losses between and within devices may cause local thermal stress and early failures.

In order to handle these issues, multiport generator architectures have been suggested in order to reduce the power rating demands of single power converters (17)(19). In the traditional architecture, ac-dc conversion continues to use active rectifiers to its entirety. The most promising alternative includes an integrated generator-rectifier system of the permanent magnet synchronous generator (PMSG), as shown in Fig. 1(a). This design with multiport PMSG is used to convert the mechanical shaft power of a turbine into ac electrical power with each port going to a passive or active rectifier. The rectifier outlets are stacked in series to create a high-voltage dc bus, and each rectifier can only support a fraction of the entire dc-bus voltage. Passive rectifiers therefore are able to rectify about 60 percent of the total power, which results in a 47 percent decrease in conversion losses under rated conditions of operation. Both the total power density and the reliability of the system are enhanced by the smaller size of the active rectifier. The fact that many passive rectifiers are present however complicates the issue of control of power flow in the integrated system of generator-rectifier.

2. Objectives

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The main contribution of the work is to show that even with a series string of uncontrolled passive rectifiers it is possible to have a controllable overall power flow in the dc-bus. This allows the maximum power point tracking (MPPT) that is critical towards the effective conversion of wind energy (10). The proposed control framework to make use of the relation between the d-axis current of the active rectifier and total dc-bus power can be used to achieve MPPT. Moreover, the filter capacitors of the passive rectifiers are removed. The ripple in the voltage delivered by the dc-bus is decreased effectively by appropriately time-phasing the ac voltages delivered to the passive rectifiers in the various generator ports.

The proposed integrated generator-rectifier system has high prospects of lowering the LCOE of offshore wind power, with MPPT control and elimination of bulky filter capacitors. The rest of this paper is structured in the following way: Section II provides the power flow control scheme of the integrated generator-rectifier system and how it applies to MPPT. Section III and IV offers simulation and experimental outcomes to confirm the effectiveness of the proposed approach, respectively. Lastly, a conclusion is made in Section V.

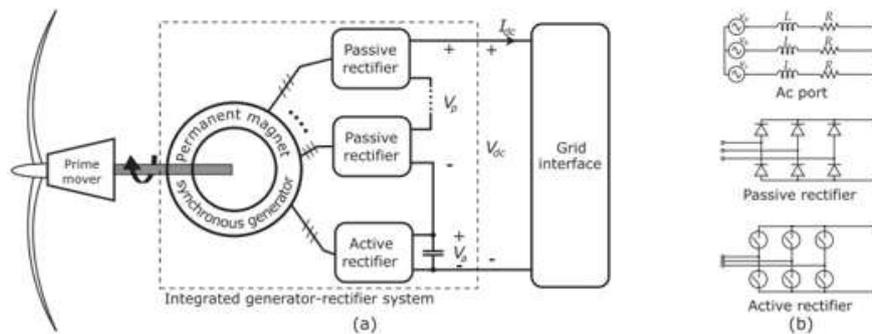


FIGURE 1 Wind turbine energy-factor monitoring architecture: a variable-pace wind turbine serves as the principle driver

Permanent magnet synchronous generator (PMSG) multiport and the wind turbine have an identical shaft. The rectifier generator system is an integrated system that transforms the produced ac power into the dc power which is sent to a stiff dc interface at the output. The combination of generator and rectifier system utilizes maximum power point tracking (MPPT) to retrieve the maximum power of the turbine.

(a) The phases of a three-phase ac port are described as a series of back electromagnification sources (EMF) and series connected to both the generator inductance and resistance L and R . The active rectifier is used in form of three-phase, two-level converter, and the passive rectifier is used in form of six pulse diode rectifier.

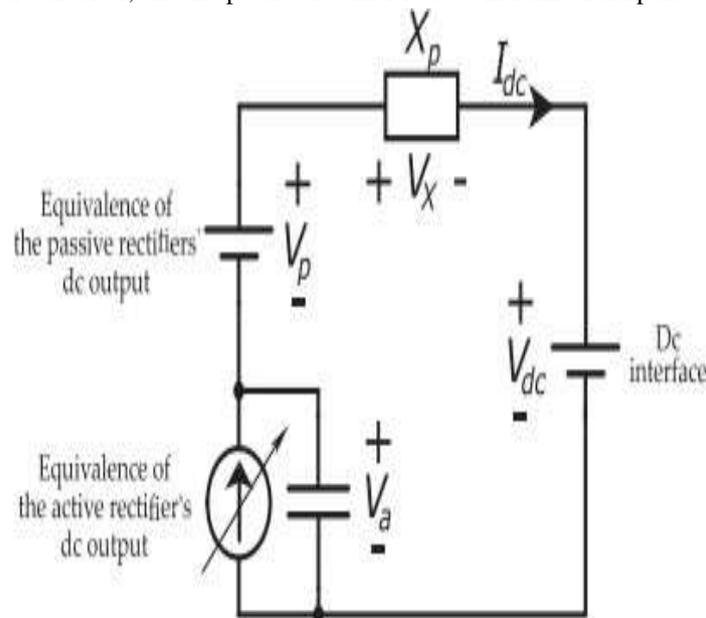


FIGURE 2 Simplified version of the included generator-rectifier gadget's equal circuit. A voltage supply is used to simulate the dc output of the passive rectifiers. A controlled contemporary source simulates the energetic

rectifier's output. The dc interface is represented with the aid of a steady dc voltage this is coupled to the serial voltage and present day sources.

3. Proposed system

This section presents the power-flow control framework developed for the proposed integrated generator–rectifier system. A stiff dc interface is assumed to be connected to the dc output of the system. This assumption is valid for both ac and dc series grid connections (9). In the ac-grid case, the interface is realized through an intermediate dc link regulated by a grid-side converter, whereas in the dc-grid case, the dc voltage is controlled by a converter located at the dc-grid substation .

Figure 1 illustrates a simplified equivalent circuit of the integrated system. The combined output of the passive rectifiers is modeled as a generator-speed-dependent voltage source V_p connected in series with a commutation reactance X_p . As discussed in Section II-A, the voltage ripple at the overall output of the passive rectifiers can be neglected by introducing appropriate phase shifts among the multiple ac ports.

The dc-side voltage of the active rectifier, denoted as V_a , is equal to the difference between the passive-rectifier output voltage and the stiff grid-interface voltage V_{dc} . The dc-side current of the active rectifier is determined by the power it draws and is therefore controllable. Accordingly, the active rectifier is modeled as a controllable current source. As described in Section II-B, because of the series connection, the current flowing from the active rectifier governs the total power delivered to the dc bus. For practical implementation, cascaded proportional–integral (PI) controllers are proposed. In Section II-C, this power-flow control framework is applied to achieve maximum power point tracking (MPPT).

3.1 Passive-Rectifier Voltage Ripple Minimization

In the proposed system, $(k-1)$ ports of a k -port PMSG supply passive rectifiers without output filter capacitors. As shown in Fig. 3(a), the dc output voltage ripple of each passive rectifier exhibits a peak every $\pi/3$ radians. The voltage ripple factor defined as the ratio of the peak-to-peak ripple to the average dc value can be minimized by connecting the dc outputs in series with an appropriate phase shift.

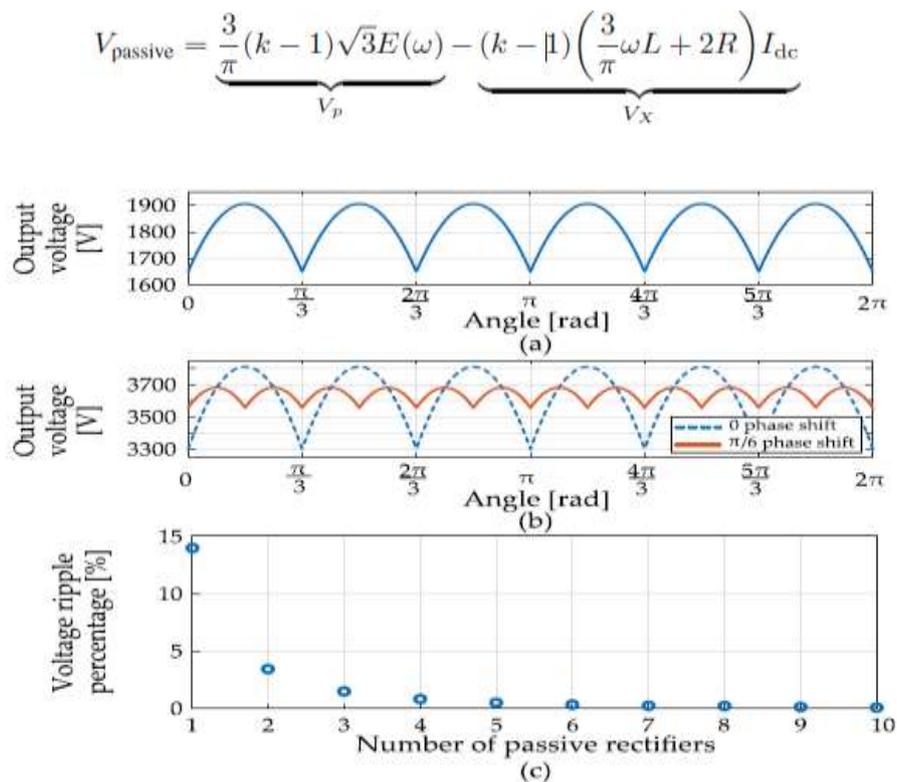


FIGURE 3 shows pattern output voltage waveforms from the included machine, wherein each ac port produces a top line-to-neutral voltage of 1.1 kV at a frequency of 20 Hz. (a) One passive rectifier's DC output voltage. (b) Two passive rectifiers related in series, without or with segment moving among the corresponding ac ports, and their DC output voltage. (c)

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For example, as illustrated in Fig. 3(b), applying a phase shift of $\pi/6$ between two passive rectifiers reduces the ripple factor to approximately 3%, compared to 14% when no phase shift is applied. In general, for a system with $(k-1)$ passive rectifiers, a phase shift of $\pi/(3(k-1))$ radians effectively reduces the dc-bus voltage ripple. As shown in Fig. 3(c), increasing the number of ac ports further decreases the ripple factor, although with diminishing returns. This principle is analogous to harmonic reduction in high-power drive systems using phase-shifting transformers and multipulse diode rectifiers (27).

$$E(\omega) = \frac{\omega}{2\pi f_0} E_0$$

Assuming a small voltage ripple and a constant dc-bus current I_{dc} , the total dc output voltage of the $(k-1)$ passive rectifiers at the electrical frequency can be expressed accordingly. As the number of passive ports increases, the ratio between the average dc voltage and the peak-to-peak ripple of V_p decreases. Each ac port is characterized by a synchronous inductance L and an equivalent series resistance R per phase [28], while the back electromotive force $E(\omega)$ depends on the electrical frequency.

The rated electrical frequency and rated line-to-neutral peak back EMF of each ac port are denoted by f_0 and E_0 , respectively. The combined effects of synchronous inductance, phase resistance, and dc-bus current on the dc-side voltage of the passive rectifier are captured by the term V_{XV_XVX} . Mode-I operation of a conventional six-pulse diode bridge rectifier is assumed, which is valid when the synchronous inductance is sufficiently small such that the current commutation time is less than one-sixth of the electrical period.

3.2 Power-Flow Control Using the Active Rectifier

The next step is to establish the relationship between the dc-bus power and the ac-side current of the active rectifier. Neglecting conversion losses in the active rectifier, power balance between the ac and dc sides yields a direct relationship between the dc-bus power P_{dc} and the d-axis current of the active rectifier. According to this relationship, the power injected into the dc bus—and hence the power extracted from the turbine can be regulated by controlling the d-axis current of the active rectifier.

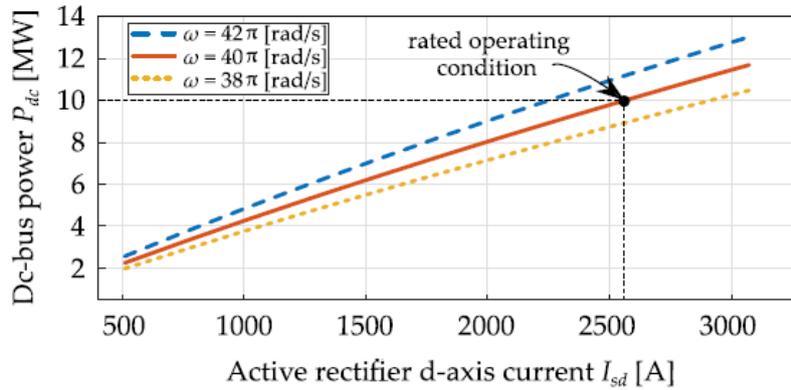


FIGURE 4 At Each generator speed, the power drawn from the integrated rectifier system depends on the active rectifier d-axis current

Figure 4 illustrates the relationship between the d-axis current I_{sd} and the dc-bus power P_{dc} for a 10-MW wind turbine system based on a three-port PMSG. Each port has a synchronous inductance of 0.47 mH, an equivalent series resistance of 12 m Ω , and a rated back EMF of 1.1 kV at 20 Hz. At rated operation, these parameters correspond to 0.1 p.u. synchronous reactance and 0.02 p.u. resistance. To demonstrate the feasibility of power control for generator speed regulation, this relationship is also shown at higher electrical frequencies.

A cascaded control structure is adopted to achieve power-flow control, as depicted in Fig. 5. The inner control loops regulate the d- and q-axis currents of the active rectifier. The d-axis current controls the power flow, while the q-axis current controls the power factor. The outer power-control loop generates the d-axis current reference required to deliver the desired dc-bus power P_{dc}^* . This power reference is produced by an MPPT algorithm that uses the generator rotational speed as its input. The active rectifier operates at unity power factor by setting the q-axis current reference to zero.

$$L \frac{dI_{sd}}{dt} = -RI_{sd} + \omega LI_{sq} + E - V_{rd} \text{ and}$$

$$L \frac{dI_{sq}}{dt} = -RI_{sq} - \omega LI_{sd} - V_{rq}$$

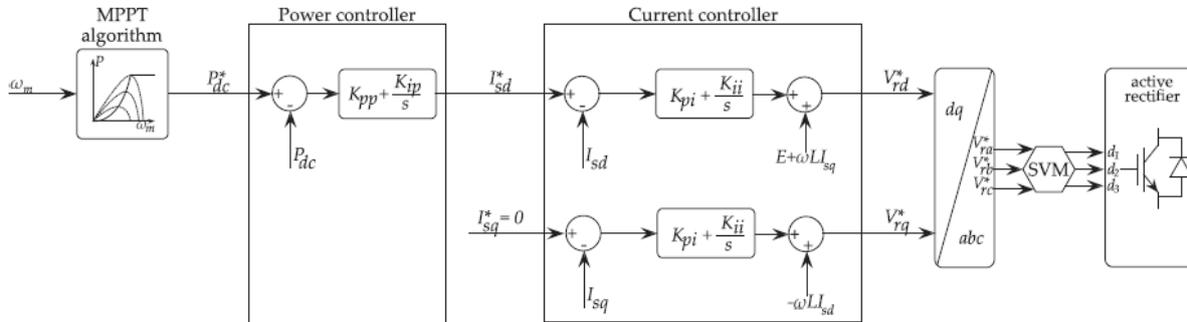


FIGURE 5 Cascaded architecture applied to the active rectifier to accomplish power-flow control for the entire integrated generator rectifier system

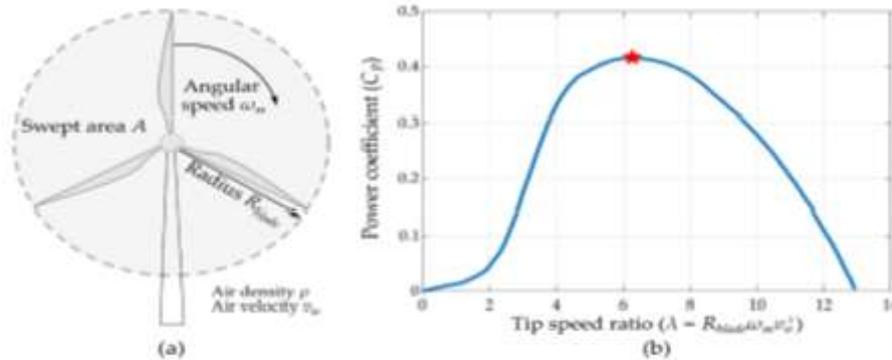


FIGURE 6 (a) Illustration of a three –bladed wind turbine (b) Typical wind -turbine

The current controllers are designed based on the ac-port current dynamics in the synchronous reference frame. The d-axis lags the q-axis by 90°. The d-axis voltage reference is generated using a PI controller with feedforward terms. Proportional and integral gains are applied to regulate the current accurately, and a similar control strategy is used for the q-axis current. If accurate values of LLL and RRR are known, the d-axis current reference required for a given power demand can be computed directly. However, an outer-loop PI controller is employed to mitigate the effects of parameter uncertainties on power-flow regulation.

$$V_{rd}^* = K_{pi}(I_{sd}^* - I_{sd}) + \int K_{ii}(I_{sd}^* - I_{sd})dt$$

$$+ E + \omega_0 LI_{sq}$$

3.3 MPPT Using the Integrated Generator–Rectifier System

The proposed power-control framework is used to achieve maximum power point tracking of the wind turbine. MPPT is achieved when the electrical power extracted at each generator speed follows the turbine’s maximum power curve [23]. Consider the wind turbine shown in Fig. 4, with a blade radius of 164 m, operating at a rated wind speed of 12 m/s and an air density of 1.15 kg/m³. Figure 5 illustrates the turbine’s mechanical power curves at different wind speeds using dashed lines. The maximum power curve is obtained by connecting the peak points of these mechanical power curves.

For operation at a wind speed of 12 m/s, the graph can be divided into two regions by a vertical line passing through the intersection of the mechanical power curve and the maximum power curve. In the shaded region, the mechanical power input to the generator exceeds the electrical power output, causing the generator speed to increase. The system then transitions into the unshaded region, where the electrical power exceeds the mechanical

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input, resulting in a reduction in generator speed. Eventually, the generator speed stabilizes at the boundary between these two regions, where the extracted power reaches its maximum value of 10 MW.

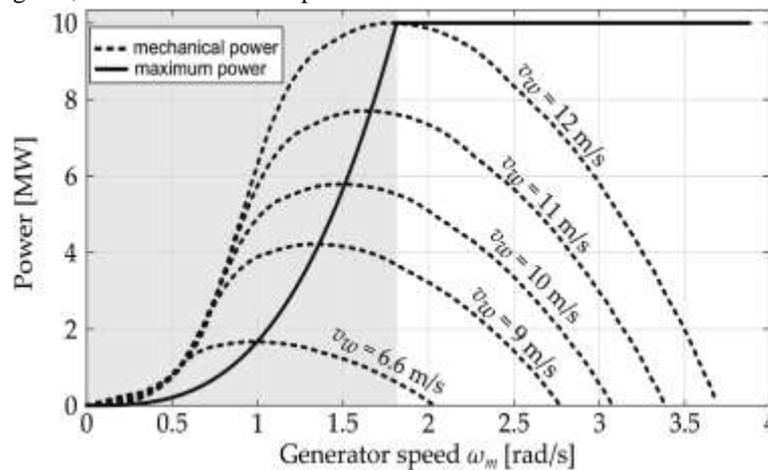


FIGURE 7 Mechanical power curves and maximum power curve of a 10 MW Wind turbine

5. Conclusion

This paper is a presentation of an MPPT system of an integrated system of generator-rectifier. All these are achieved using both simulation and experiment to establish and prove an analytical relationship between current on the active-rectified-axis and the dc-bus power. In practice, cascaded control architecture should be used. The inner loop consists of PI current controllers consisting of feed-forward terms, and the outer loop consists of a PI power controller. The performance in power tracking has been attained at an average level. The power flow management renders the wind turbine MPPT possible as it regulates the power contained in the dc-bus. This feature provides an opportunity to design combined generator-rectifier systems in the wind energy systems..

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Conflicts of interest

The authors have no conflicts of interest to declare

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