Int. J. Sci. R. Tech., 2025 2(8)
A Multidisciplinary peer-reviewed Journal
www.ijsrtjournal.com [ISSN: 2394-7063]

Original Article

Power Electronics in Renewable Energy Systems

Ndjabu Dhedonga Elisée[1], Joel Nzanzu Kanduki*[2], Pascal Mushage Bondo[2]

[1]*Université Chrétienne Bilingue du Congo/Beni, UCBC/Beni/Technology and Engeenering Sciences*
[2]*Université Catholique la Sapientia/Goma, UCS/Goma/Technology and Applied Sciences*

ABSTRACT

The shift to more sustainable energy sources has been sped up by the rapid increase in global energy consumption and the consequences of greenhouse gas emissions. Utilizing renewable energy sources like wind, solar, and fuel cells, distributed generation (DG) has become increasingly necessary. Intelligent energy management techniques, affordable high-performance devices, and sophisticated power electronic systems are all thought to be crucial elements of efficient, sustainable, and renewable energy systems. The features of DG are briefly summarized in this paper. An overview of solar, fuel cell, and wind-based energy conversion systems is given. The function of power electronics in solar, wind, and photovoltaic systems has been qualitatively described.

Keywords: Fuel cell, Photovoltaic, Wind energy conversion, Wind Turbines, Z-source converter

INTRODUCTION

Over the past century, global energy consumption has experienced a consistent upward trend. According to official estimates, global energy consumption is projected to rise by 44 percent between 2006 and 2030 [1]. Fossil fuels, including liquid fuels, coal, and natural gas, can be regarded as the predominant energy sources of the modern world. The ongoing processes of urbanization, industrialization, and the expanding access to electricity have resulted in an extraordinary reliance on fossil fuels. Currently, the primary issues associated with fossil fuels are the emission of greenhouse gases and the irreversible exhaustion of natural resources. According to the US Government's official Energy figures, worldwide carbon dioxide emissions would increase by 39% between 2006 and 2030, reaching 40.4 billion metric tons [1]. Greenhouse gas emissions, as well as the threat of global warming and the depletion of fossil fuel supplies, have highlighted the significance of alternate and greener energy sources. The current electricity transmission and distribution infrastructure is also significantly impacted by the search for cleaner and more dependable energy sources. Transmission lines are typically used to generate and distribute the majority of the power to the significant load centers. Power was always transferred from the utilities to the customers in a single direction. Renewable energy sources alone cannot sustain the entire grid in the near future [1]. They must be connected to the main grid to serve as auxiliary power sources, lessening the load on major power producing units. They could also be used to serve load units that are separated from the main grid. A distributed power generation (DG) system is one that uses wind turbines, fuel cell-based sources, micro generators, and solar systems in addition to the main power grid. End users in a distributed generation system do not have to be passive consumers; they can also be active grid suppliers. Traditionally, big power generation units (often made up of synchronous generators) monitor and manage critical power delivery characteristics such as frequency and voltage. In DG systems, the power electronic interface must regulate the voltage, frequency, and power to connect the energy source to the grid. The emphasis will be on high power density, robust dc-ac and ac-ac modules with sophisticated control and safety requirements. This paper provides some of the power electronic interface requirements as they apply to wind, fuel cell, and solar power production units, as well as a qualitative examination of the existing power electronic topologies that can be utilized. Energy storage is also critical for DG; however, this study focuses primarily on the power electronics components of DG. Section II provides an overview of wind power generating and its attendant issues. Sections III and IV include overviews of

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

power generation using fuel cells and photovoltaics, as well as the implications for the accompanying power electronic circuits. Section V offers the conclusion.

Wind Energy Systems

The majority of renewable energy is produced by wind [1], [3]. The cost of power generated by wind energy-based systems has decreased to one-sixth of its value in the early 1980s, and grid-connected wind capacity has more than doubled over the past 20 years [3]. A wind energy conversion system's salient characteristic is:

- Available wind energy
- Wind turbine type
- Electric generator and power electronic circuits for grid connection

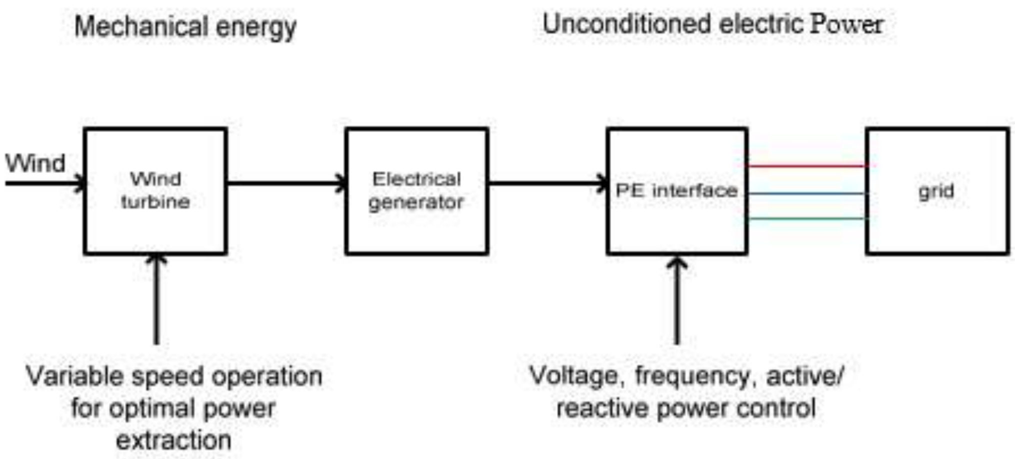

Fig. 1. Variable speed wind energy conversion system

Wind energy – Wind speeds, air pressure, atmospheric temperature, earth surface temperature etc., are highly inter-linked parameters. Due to the inherent complexity, it is unrealistic to expect an exact physics-based prediction methodology for wind intensity/sustainability. However, distribution-based models have been proposed, and employed to predict the sustainability of wind energy conversion systems [4]. This document is not intended to provide a detailed description of wind energy resources. According to studies, the variance in mean output power over a 20-year period has a standard deviation of less than 0.1 [4]. It is plausible to conclude that wind energy is a reliable source of clean energy. The basic physics of wind energy can be described as follows. Wind power can be extracted as

$$Pw = \frac{1}{2}\rho A v^3 Cp \qquad (1)$$

where P is Power extracted from the wind (Watts), ρ is Air density (typically ~1.225 kg/m³ at sea level), A is Swept area of the turbine blades ($A = \pi r^2$, where r is the blade length), v is Wind speed (m/s), Cp is Power coefficient (Betz limit: max Cp=0.593, real turbines ~0.35–0.45) [4].

The tip speed ratio is defined as the ratio of the tip speed to wind speed.

$$\lambda = \frac{\omega R}{v} = + \frac{2\pi \times RPM \times R}{60 \times v} \qquad (2)$$

Where ω = Angular velocity (radians per second), R is Rotor radius (length of the blade, in meters) and RPM is Rotations per minute of the turbine [3]. Cp versus λ characteristics are important indicators of the aerodynamic efficiency of a wind turbine. Based on the aerodynamic blade theory, there is an optimal λ opt corresponding to the maximum power. Wind turbines are characterized as drag-based or lift-based, depending on the aerodynamic concept used. Wind turbines are characterized as horizontal or vertical axis based on their mechanical structure. Wind turbines are characterized as fixed or variable speed turbines based on the rotation of the rotor. The current focus is on horizontal axis, lift-based variable speed wind turbines [2], [3]. Power electronic circuits play an important part in variable speed wind energy conversion systems. Fixed-speed wind turbines are simple to operate, dependable, and durable. However, the grid frequency determines the speed of the rotor. As a result, they are unable to maintain the optimal aerodynamic efficiency. Fixed-speed wind turbines are unable to determine the optimal power extraction point *Cp* max when wind speeds vary. In variable speed wind turbines, power electronic circuitry partially or entirely separates the rotor mechanical frequency from the grid electrical frequency, allowing for variable speed operation. The power electronic (PE) interface's needs are determined by the type of electric generator used and grid conditions. Figure 1 shows a variable-speed wind energy conversion system. Doubly-fed induction generators are often used in partially variable speed wind energy conversion systems [5]. Figure 2 displays a doubly-fed induction generator in which the power converter system controls the rotor circuit via slip rings while the stator circuit is connected to the grid. This strategy is useful because the power converter must handle around 25% - 50% of the system's total power [5]. As seen in Fig. 2, the power converter system consists of a rotor-side ac-dc converter, a dc link capacitor, and a dc-ac inverter connected to the grid. The power converter enables vector control of the field which facilitates active/reactive power control.

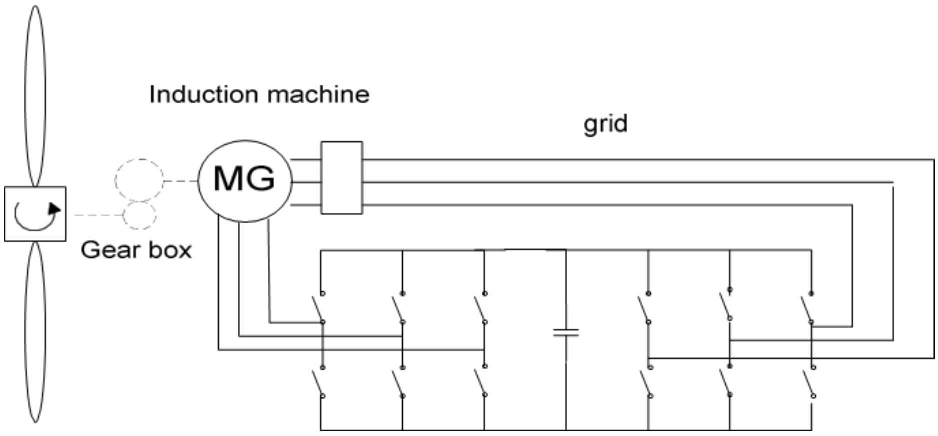

Fig. 2. Limited range, variable wind energy conversion system

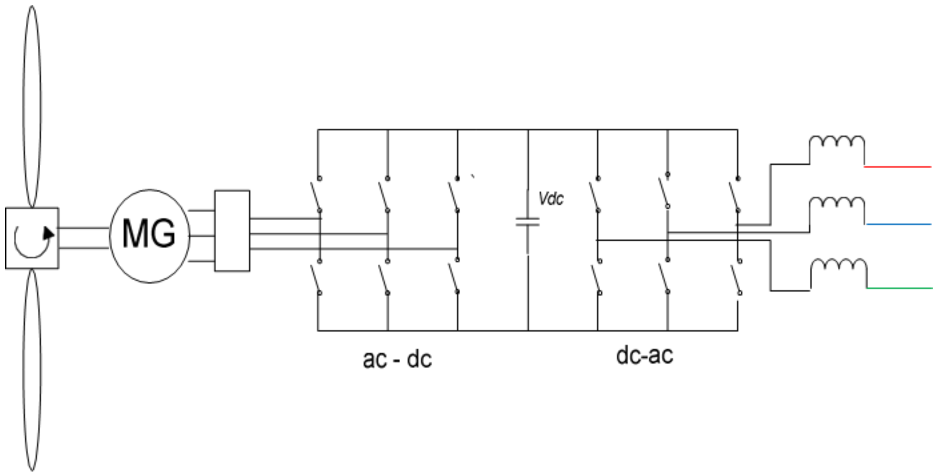

Fig. 3. Fully variable wind energy conversion system

The rotor side converter regulates the rotor's speed and torque, while the stator side converter maintains a constant voltage across the dc link capacitor regardless of the rotor's power. This method is more efficient than the constant speed system, but it does not capture the maximum efficiency. By using a full-scale ac-ac converter system, the wind turbine can be completely disconnected from the grid, allowing for a broader range of optimal operation. Figure 3 depicts such a setup. The variable frequency ac from the turbine is routed into the three-phase ac-dc-ac converter. The generator side ac-dc converter is adjusted to achieve a predetermined Vdc value at the dc link capacitor terminals. The voltage is then inverted using a six-switch dc-ac inverter. Inversion is inherently a buck operation, so the turbine side ac-dc converter must ensure that sufficient voltage is obtained in order to integrate with the grid. If more voltage is required, an extra dc-dc boost converter can be used. This raises the overall cost and complexity.

To address these shortcomings, a Z-source inverter-based conversion system can be used [9]. The Z-source inverter is a relatively innovative topology with the following advantages over traditional voltage source/current source inverters:

- Buck-boost ability
- Inherent short circuit protection due to Z-source configuration
- Improved EMI as dead bands are not required

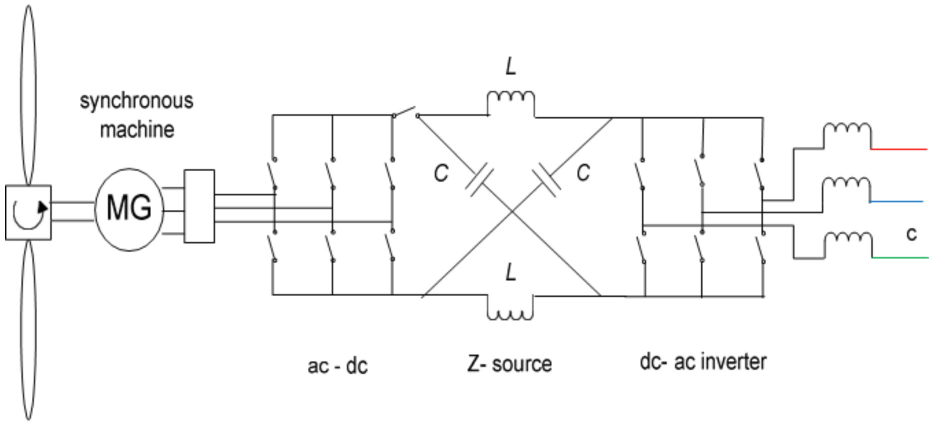

Fig. 4. Z-source based variable speed wind energy conversion system

Z-source inverter-based wind power conversion systems are relatively new, but research is being conducted to determine their application. A Z-source converter-based wind energy system has been researched and presented in [9]. Figure 4 depicts a wind energy conversion system based on a Z source. [10] describes a single stage three phase alternating current to alternating current Z-source converter. Table I provides a qualitative summary of the wind energy conversion systems.

TABLE I

Comparison of wind energy conversion systems

WEC based on	Generator	Grid integration	Key points
Fixed speed system	Induction generator	Direct	Constant speed Simple Low controllability
Partially variable system	Doubly-fed-induction-generator	ac-dc-ac voltage source converter	Highly controllable Vector control of active and reactive power
Fully variable system	Induction generator or synchronous generator	ac-dc-ac voltage source converter or potentially Z-source converter	Highly controllable Wide range of speeds. For Z-source, short circuit protection Improved EMI feature.

Fuel Cell Systems

Fuel cells provide clean, non-toxic energy at relatively high energy densities (greater than lead-acid batteries) and with high reliability. Fuel cells, unlike batteries, cannot store energy but can continuously produce electricity. Currently, the fuel cells most commonly used are :

- Solid oxide
- Molten carbonate
- Proton exchange membrane
- Phosphoric acid
- Aqueous alkaline

Fuel cell systems have an efficiency of approximately 50%. With heat recovery systems, efficiency can reach around 80% [2]. The scope of this paper does not include a description of the electrochemical processes involved in fuel cell power generation. This section briefly covers fuel cells' electrical properties and their consequences for power electronic interface circuitry. Figure 5 illustrates the usual V-I parameters of a fuel cell [11].

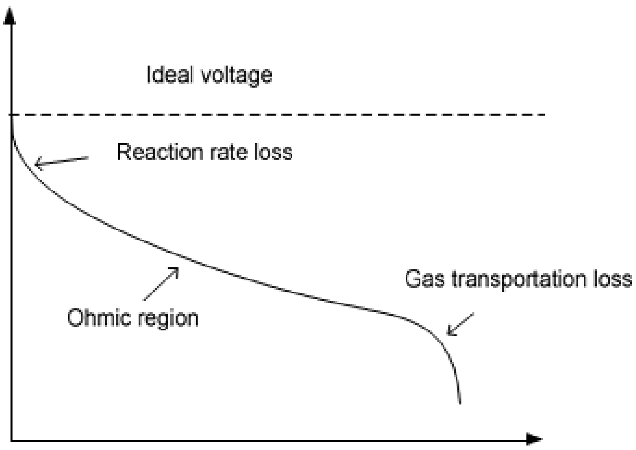

Fig. 5. Typical terminal voltage and current characteristics of a fuel cell [11]

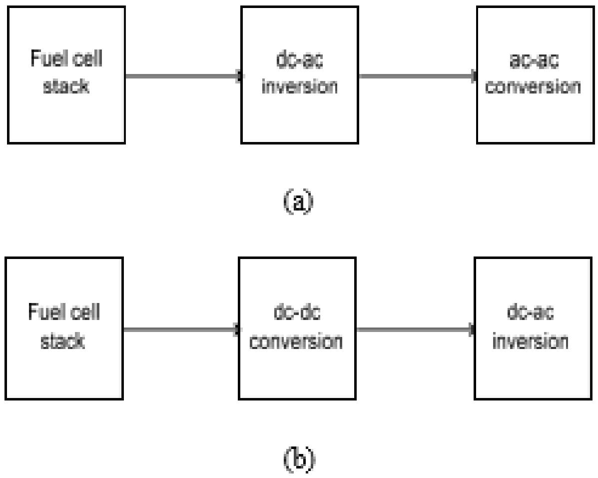

Fig. 6. Fuel cell-based energy conversion systems (a) dc-ac-ac conversion (b) dc-dc-ac conversion

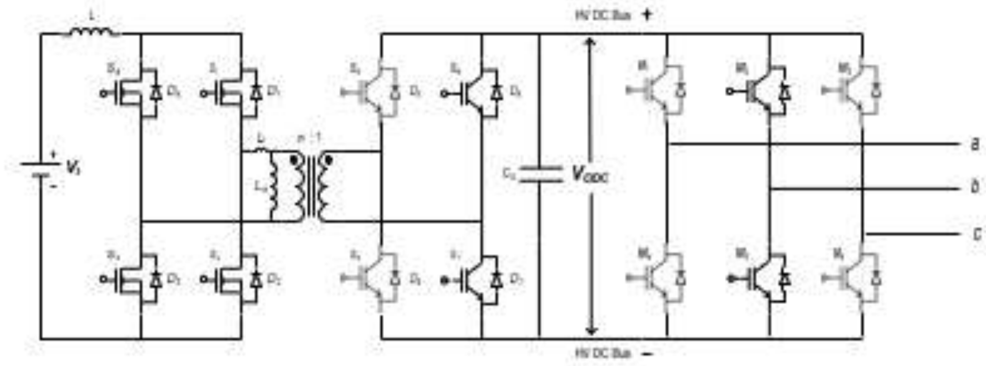

Fig. 7. Energy conversion system with dc-dc converter followed by 3 phase VSI

The main drawbacks of fuel cells are:

- Difficulty starting from cold due to insufficient energy storage.
- Low output voltage changes with load, requiring a boost step and control.
- Low slew rate reduces dynamic performance and requires backup energy storage

Because of the aforementioned problems, extra energy storage, in conjunction with PE-based power conditioning, is required to create a workable fuel cell system. The output voltage is low dc, and in many circumstances line frequency ac is required (grid integration), which necessitates voltage step-up and dc-ac inversion. To accommodate dynamic load variations, energy backup (battery or ultracapacitor) is required. Researchers have already studied various dc-dc converter topologies as well as dc-ac inversion approaches for this purpose [2], [11], and [12]. Non-isolated boost converters have limited boosting capability; hence isolated versions have been chosen. This also provides electrical isolation, increasing overall reliability. Figure 6 depicts two approaches for producing useable ac output from a fuel cell. In Fig. 6 (a), the fuel cell's dc output is first inverted using a conventional voltage source (VSI) inverter or a current source inverter (CSI), and the ac voltage is then increased using a transformer. Inversion from dc to ac via VSI is fundamentally a buck operation, hence this method always requires a step-up transformer. In Fig. 6 (b), a dc-dc converter is used to step up the fuel cell output voltage, which is then inverted to line frequency alternating current (ac). Traditionally, this method has been more common due to the lack of a transformer and the controllability of the dc-dc converter. The options for isolated dc-dc converters [15] and their characteristics are discussed below.

- Forward converters have limited duty cycles and require an excitation resetting tertiary winding.
- Push pull requires a center-tap transformer and is not ideal for high-power applications.
- The full bridge converter is suitable for fuel cell applications. It has more components than a half bridge dc-dc converter, but device current stresses are lower.
- Half bridge dc-dc converter is ideal for fuel cell applications. For higher efficiency, an H-bridge-based soft switching series resonant converter is preferable. Other advantages of this topology include inherent short circuit protection and no saturation problem with the transformer.

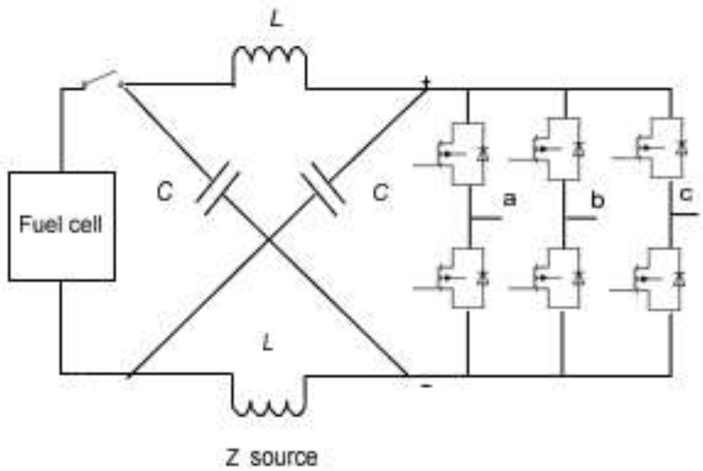

Fig. 8. Fuel cell energy conversion system employing a Z-source converter.

Historically, three phase, six-switch VSIs have been widely utilized for dc-ac conversion. This technique is well-established, as are the control strategies. The key disadvantage of VSI is that it is fundamentally a step-down procedure. The Z-source inverter provided in [8] combines the boost function into the VSI while maintaining the VSI's intrinsic capabilities. This topology appears to be particularly suitable for fuel cell and other renewable energy applications. Figure 7 depicts fuel cell energy conversion using a current-fed full-bridge dc-dc converter and a typical dc-ac VSI. Figure 8 depicts a fuel cell energy conversion system using a Z-source dc-ac inverter. Most real-time power-electronic energy systems include energy backup in the form of a capacitor bank, ultracapacitor, or battery to supplement the primary energy supply during dynamic loads. Because the grid voltage level and frequency are fixed in dc-ac grid connected inverter systems, the control variable is restricted to the current. The real and perceived power being injected into or pulled from the grid must be monitored and controlled using various control mechanisms.

Photovoltaic Energy Conversion Systems

Photovoltaic energy systems are made up of solar cell arrays that convert irradiated light into electricity. Photovoltaic systems' (PV) yield is primarily determined by the intensity and duration of illumination. PV provides clean, emission-free, and noise-free energy conversion without the use of any active mechanical systems. Because it is all electric, it has a long lifespan (> 20 years) [2]. A lot of work is being done to improve the efficiency of the solar cell, which is the fundamental component of PV. In this sense, the attention is mostly on electro physics and materials. Some of the existing PVs and their efficiency are [2] :

- Crystalline and multi-crystalline solar cells with efficiencies of ~11 %.
- Thin film amorphous Silicon with an efficiency of ~10%.
- Thin-film Copper Indium Diselenide with an efficiency of ~12%.
- Thin film cadmium telluride with an efficiency of ~9%.

PV panels are created by connecting a specific number of solar cells in series. Because the cells are connected in series to provide the terminal voltage, the current flowing is determined by the weakest solar cell [2], [13]. Paralleling the cells might fix the low current issue, but the resulting voltage is quite low (< 5 V). These panels are further connected in series to increase their power handling capacity. The entire PV system can be viewed as a network of small direct current (DC) energy sources, with PE power conditioning interfaces used to improve system efficiency and reliability.

The role of PE is mainly two-fold:

I. To interconnect solar panels, use a dc-dc converter to maintain required current and voltage, and enhance overall efficiency through control. Several non-isolated dc-dc converters were used for this purpose. Buck, buck-boost, boost, and Cuk topologies with appropriate modifications can all be used for this purpose [13]. Figure 9 shows a PV system with a DC-DC module used to connect the PV panels.
II. Connecting the PV system's direct current output to the grid or load, including dc-dc-ac and dc-ac-ac conversion. The topologies explored for fuel-cell system grid connectivity correspond to the grid interconnection of PV-based systems, which includes the use of a Z-source inverter.

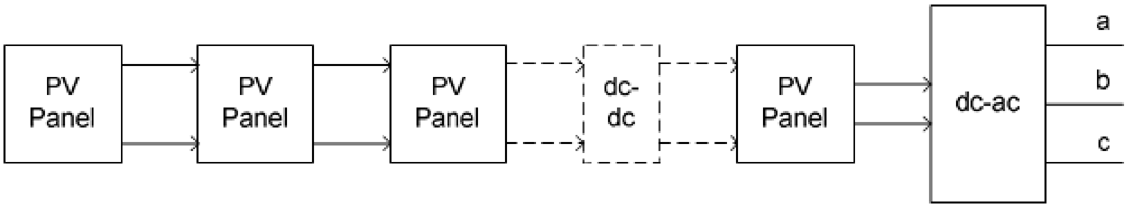

Fig. 9. PV system with dc-dc module

CONCLUSION

The value of renewable energy, renewable energy-based energy conversion technologies, and distributed power generation has been emphasized. A fundamental review of wind energy has been provided, as well as a qualitative discussion of existing PE interface needs and methodologies. The fundamental electrical properties of fuel cell and photovoltaic-based devices have been described. The many approaches for integrating these technologies into the grid have been briefly discussed. The advantages of using a Z-source inverter over a standard dc-ac VSI have been highlighted. It is possible to conclude that, with advances in renewable energy and distributed power generation, power electronics will play an increasingly important and crucial role in the future of efficient power generation and distribution.

REFERENCE

1. www.eia.doe.gov/oiaf/ieo/highlights.html
2. Frede Blaabjerg, Zhe Chen,and Soren Baekhoej Kjaer, “Power Electronics as Efficient Interface in Dispersed Power Generation Systems,” IEEE Trans. Power Electron.,vol. 19, no. 5, pp. 1184-1194, Sep. 2004.
3. Thomas Ackermann, Lennart Soder, “Wind energy technology and current status: a review,” Renewable and Sustainable Energy Reviews, Elsevier, 2000.
4. T. Burton, D. Sharpe, N. Jenkins, E. Bossanyi, Wind Energy Handbook. John Wiley & sons, ltd, 2001.
5. Munteanu, L., Bratcu, A.I., Cutululis, N. A, and Ceanga, E., Optimal Control of Wind Energy Systems, Springer, 2008.
6. Juan Manuel Carrasco, Leopoldo Garcia Franquelo, Jan T. Bialasiewicz, Eduardo Galvan,

Ramon C. Portillo Guisado, Ma. Angeles Martin Prats, Jose Ignasio leon, and Narciso Moreno-Alfonso, “Power- Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey,” IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 1002-1016, Aug. 2006.

7. R. Pena, J. C. Clare, and G. M. Asher, “Doubly fed induction generator using back-to-back PWM converters and its application to variable speed wind-energy generation,” Proc. Inst. Elect. Eng., Elect. Power Appl., vol. 143, no. 3, pp. 231-241, May 1996.
8. F. Z. Peng, “Z-source inverter,” Industry Applications, IEEE Transactions on, vol. 39, pp. 504-510, 2003.
9. D. Mahinda Vilathgamuwa, Wang Xiaoyu, Gajanayake, “Z-source Converter Based Grid-interface for Variable-speed Permanent Magnet Wind Turbine Generators,” in Proc. PESC2008. Conf, 2008, pp. 4545-4550.
10. Fan Zhang, Xupeng Fang, Fang Z. Peng, Zhaoming Quian, “A New Three-Phase AC-AC Z-source Converter,” in Proc. APEC’06 Conf., 2006, pp. 13- 126.
11. E. Santi, D. Franzoni, A. Monti, D. Patterson, F. Ponci, N. Barry, “A fuel Cell Based Domestic Uninterruptible Power Supply,”, in proc, APEC 2002 Conf, 2002, vol. 1, pp. 605-613.
12. Jin Wang, Fang Z. Peng, Joel Anderson, Alan Joseph and Ryan Buffenbarger, “Low-Cost Fuel Cell Inverter System for Residential power generation,” in proc, APEC’ 04 Conf, 2004, vol. 1, pp. 367-373.
13. Geoferry R. Walker, Paul C. Sernia, “Cascaded DC- DC Converter Connection of Photovoltaic Modules”, IEEE Trans. Power, Electron., vol. 19, pp. 1130-1139, July 2004.
14. Roberto Gonzales, Jesus Lopez, Pablo Sanchis, and Luis Marroyo, “Transformerless Inverter for Single- Phase Photovoltaic Systems,” IEEE Trans. Power, Electron., vol. 22, no. 2, pp. 693-697, July 2004.
15. Marian K. Kazimerczuk, “Pulse-Width Modulated DC-DC Power Converters,” John Wiley & Sons, New York, NY, 2008.

HOW TO CITE: Ndjabu Dhedonga Elisée, Joel Nzanzu Kanduki*, Pascal Mushage Bondo, Power Electronics in Renewable Energy Systems, Int. J. Sci. R. Tech., 2025, 2 (8), 110-117. https://doi.org/10.5281/zenodo.16787964