ROLE OF POWER ELECTRONICS IN RENEWABLE ENERGY SYSTEMS

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Abstract: The rapid increase in global energy consumption and the impact of greenhouse gas emissions has accelerated the transition towards greener energy sources. The need for distributed generation (DG) employing renewable energy sources such as wind, solar and fuel cells has gained significant momentum. Advanced power electronic systems, affordable high performance devices, and smart energy management principles are deemed to be an integral part of renewable, green and efficient energy systems. This paper briefly describes the attributes of DG. An overview of wind, fuel cell, solar based energy conversion systems has been presented. A qualitative description of the role of power electronics in wind, solar, and photovoltaic systems has been presented.

Key Words: Fuel cell, Photovoltaic, Wind energy conversion, Wind Turbines, Z-source converter.

I. INTRODUCTION

The global energy consumption has been continually increasing over the last century. Official estimates indicate a 44 percent increase in global energy consumption during the period 2006 - 2030 [1]. It can be said that fossil fuels (liquid, coal and natural gas) have been the primary energy source for the present day world. Sustained urbanization, industrialization, and increased penetration of electricity have led to unprecedented dependency on fossil fuels. Presently, the most important concerns regarding fossil fuels are the green house gas emissions and the irreversible depletion of natural resources. Based on the official energy statistics from the US Government, the global carbon dioxide emissions will increase by 39 percent to reach 40.4 billion metric tons from 2006 to 2030 [1]. Green house gas emissions and the related threat of global warming and depleting fossil fuel reserves have placed a lot of importance on the role of alternative and greener energy sources.

The quest for cleaner and more reliable energy sources has considerable implications to the existing power transmission and distribution system as well. Traditionally bulk of the power is generated and distributed to the large load centers via transmission lines. The transfer of power was always one way, from the utilities to the consumers. In the immediate future, renewable energy sources cannot support the entire grid by themselves [1]. They have to be connected to the main grid acting as auxiliary power sources reducing the burden on the primary power generation units. They could also be employed to serve load units isolated from the main grid. A power system employing wind powered turbines, fuel cell based sources, micro generators, and photovoltaic systems augmenting the main power lines will constitute a distributed power generation (DG) system. In a DG system end users need not be passive consumers, they can be active suppliers to the grid. Conventionally, important parameters of power delivered (frequency and voltage) are monitored and controlled by the large power generator units (usually consisting of synchronous generators). In case of DG systems, the power electronic interface has to regulate the voltage, frequency, and power to link the energy source to the grid. The focus will be on high power density, robust dc-ac and ac-ac modules with complex control and safety requirements.

This paper presents some of the requirements of the power electronic interface as applicable with respect to wind, fuel cell, and photovoltaic power generation units and qualitatively examines the existing power electronic topologies that can be employed. Energy storage is also very important for DG, however, this paper focuses solely on the power electronics aspects of DG. Section II presents an overview of wind power generation and the associated challenges. Section III and IV present overviews on power generation based on fuel cells and photovoltaic and its implication on the associated power electronic circuits respectively. Section V presents the conclusion.

II. WIND ENERGY SYSTEMS

Wind energy has the biggest share in the renewable energy sector [1], [3]. Over the past 20 years, grid connected wind capacity has more than doubled and the cost of power generated from wind energy based systems has reduced to one-sixth of the corresponding value in the early 1980s [3]. The important features associated with a wind energy conversion system are:

- Available wind energy
- Type of wind turbine employed
- Type of electric generator and power electronic circuitry employed for interfacing with the grid

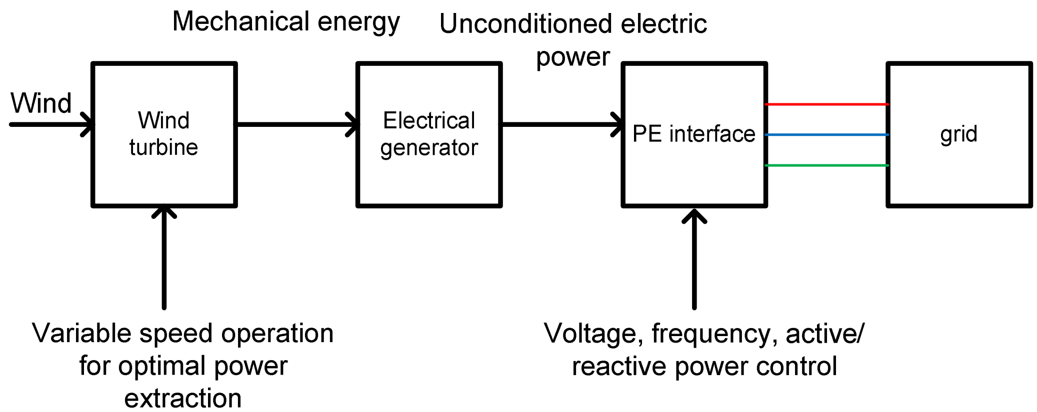


Fig. 1. Variable speed wind energy conversion system.

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]. Detailed explanation of the wind energy resources is beyond the scope of this paper. Based on studies it has been reported that the variation of the mean output power from a 20 year period to the next has a standard deviation of less than 0.1 [4]. It can be concluded with reasonable confidence that wind energy is a dependable source of clean energy. Basics of physics of wind energy can be summarized as below.

The power that can be extracted from the wind is

$$P_w = \frac{1}{2}\pi R^2 \rho v^3 C_p(\lambda), \qquad (1)$$

where R is the blade length, ρ is the density of air, v is the wind velocity, λ is called the tip speed ratio, and C_p is called the power coefficient [4].

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

$$\lambda = \frac{R\Omega}{v}. \qquad (2)$$

It is accepted that the maximum attainable efficiency for wind energy conversion is 0.59 [3]. C_p versus λ characteristics are important indicators of the aerodynamic efficiency of a wind turbine. Based on the aerodynamic blade theory, there is an optimal $\lambda_{(opt)}$ corresponding to $C_{p(opt)}$. The present day variable speed wind turbines follow the $\lambda_{(opt)}$ point to extract the maximum power. This is enabled by variable speed operation and the power electronic module interfacing the turbine and the grid.

Based on the aerodynamic principle utilized, wind turbines are classified into drag based and lift based turbines. Based on the mechanical structure, they are classified into horizontal axis and vertical axis wind turbines. With respect to the rotation of the rotor, wind turbines are classified into fixed speed and variable speed turbines. Presently the focus is on horizontal axis, lift based variable speed wind turbines [2], [3]. Power electronic circuits play a crucial enabling role in variable speed based wind energy conversion systems.

Fixed speed wind turbines are simple to operate, reliable and robust. However the speed of the rotor is fixed by the grid frequency. As result, they cannot follow the optimal aerodynamic efficiency point. In case of varying wind speeds, fixed speed wind turbines cannot trace the optimal power extraction point C_{Pmax}. In variable speed wind turbines, power electronic circuitry partially or completely decouples the rotor mechanical frequency from the grid electrical frequency, enabling the variable speed operation. The type of electric generator employed and the grid conditions dictate the requirements of the power electronic (PE) interface. Fig. 1 depicts a variable speed wind energy conversion system. The electrical generator popularly employed for partially variable speed wind energy conversion systems are doubly-fed-induction-generators [5]. Fig. 2 depicts a doubly-fed-induction-generator where the rotor circuit is controlled by the power converter system via the slip rings and the stator circuit is connected to the grid. This method is advantageous as the power converter has to handle a fraction ~ 25% - 50 % of the total power of the system [5]. The power converter system employs a rotor side ac-dc converter, a dc link capacitor, and a dc-ac inverter connected to the grid as shown in Fig. 2. The power converter enables vector control of the field which facilitates active/reactive power control.

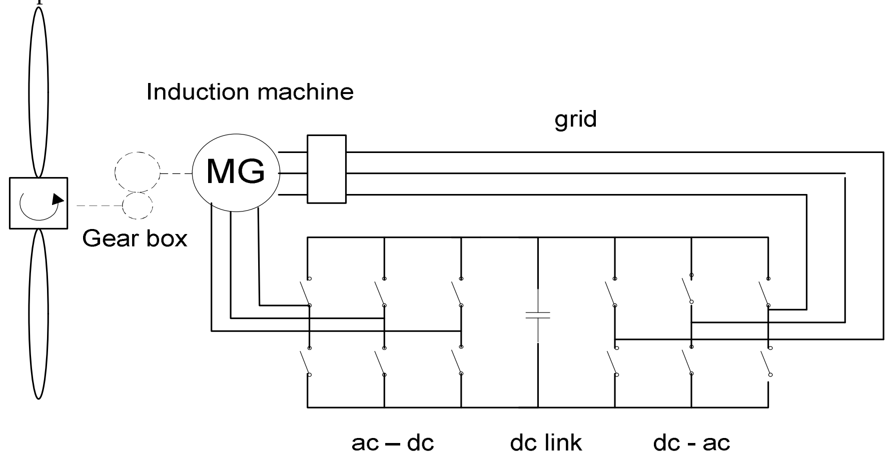


Fig. 2. Limited range, variable wind energy conversion system.

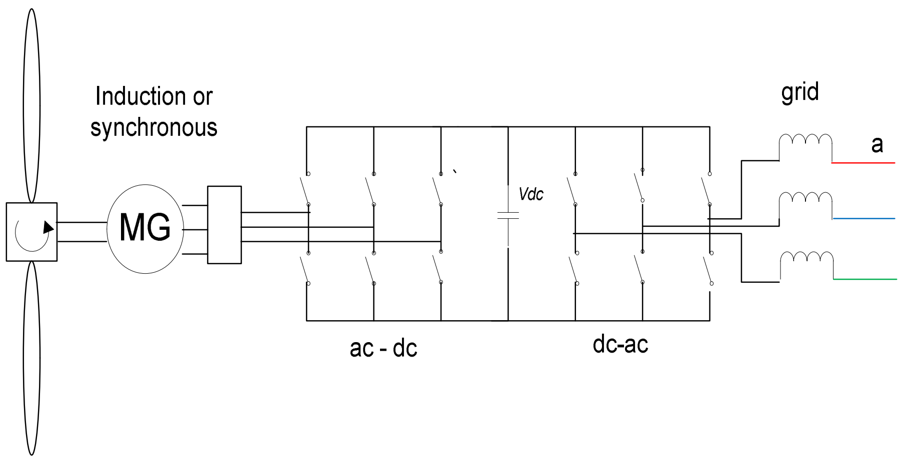


Fig. 3. Fully variable wind energy conversion system.

The rotor side converter controls the speed and torque of the rotor and the stator side convertor maintains a constant voltage across the dc link capacitor, irrespective of the magnitude of the rotor power. This method is more efficient than the fixed speed system; however it does not reflect the possible optimal efficiency.

By employing a full scale ac-ac converter system the wind turbine can be completely decoupled from the grid, enabling a wider range of optimal operation. Such a scheme is depicted in Fig. 3. The variable frequency ac from the turbine is fed to the three phase ac-dc-ac converter. The generator side ac-dc converter is controlled to obtain a predetermined value V_{dc} at the terminal of the dc link capacitor. The dc voltage is then inverted using a six-switch dc-ac inverter. Inversion is inherently buck operation hence the turbine side ac-dc converter has to ensure sufficient voltage level is obtained in order to integrate with the grid. If additional boosting of the voltage is required, an additional dc-dc boost converter can to be employed. This increases the overall cost and complexity. To overcome the shortcomings a Z-source inverter based conversion system can be employed [9]. Z-source inverter is a relatively new topology and has the following advantages over the conventional 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

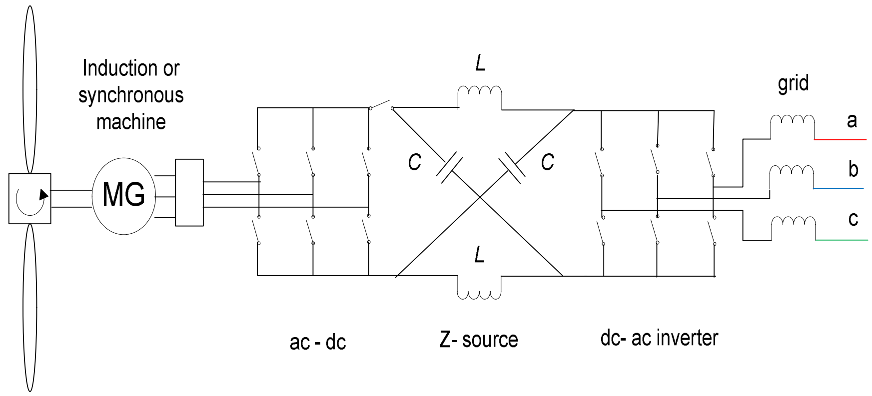


Fig. 4. Z-source based variable speed wind energy conversion system.

Z-source inverter based wind power conversion systems are relatively new, however researches are investigating its applicability. A Z-source converter based wind energy system has been studied and presented in [9]. Fig. 4 shows a Z-source based wind energy conversion system. A single stage three phase ac-ac Z-source converter is presented in [10]. Table I gives 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.

III. FUEL CELL SYSTEMS

Fuel cells offer clean, non-toxic energy at relatively good energy densities (higher than lead-acid battery) and high reliability. Fuel cells cannot store energy as opposed to a battery, However, they can continually produce electricity. Presently the fuel cells being popularly used are:

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

The efficiency of fuel cell systems are ~ 50 %. Along with heat recovery systems the efficiency can be as high as ~ 80 % [2]. Description of the electrochemical process involved in the power generation process of a fuel cell is beyond the scope of this paper. This section briefly describes the electrical characteristics of fuel cells and their implications on the power electronic interface circuitry. Fig. 5 shows the typical V-I characteristics of a fuel cell [11].

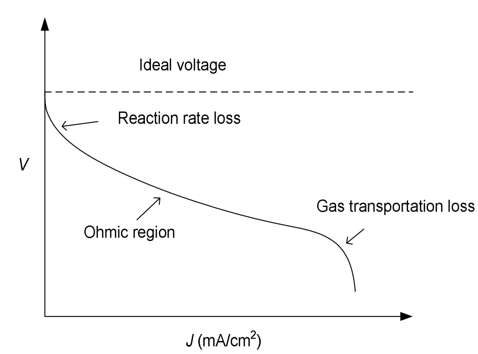
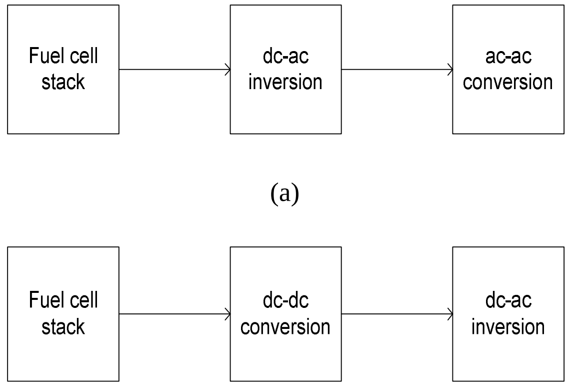


Fig. 5. Typical terminal voltage and current characteristics of a fuel cell [11].



(b)

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

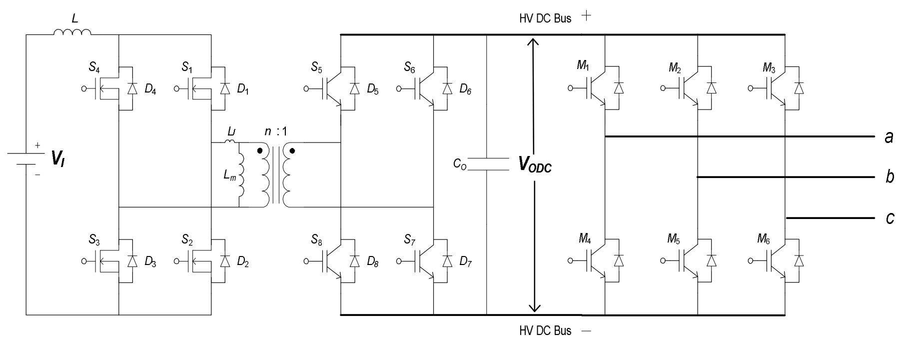


Fig. 7. Energy conversion system with dc-dc converter followed by 3 phase VSI.

The main drawbacks of fuel cells are:

- Inability to store energy - difficult to cold start
- Output voltage is low varies with the load - requires a boost stage with regulation
- Low slew rate - hampers dynamic performance, needs backup energy storage.

Due to the above mentioned reasons, auxiliary energy storage along with PE based power conditioning is essential to realize a practical fuel cell based system. The output voltage is low dc and in many cases line frequency ac is required (grid integration), this requires voltage step up and dc-ac inversion. To meet the dynamic load changes, energy back up (battery or ultra-capacitor) is required. Various dc-dc converter topologies, dc-ac inversion methods have been evaluated for this purpose by researchers in the past [2], [11], and [12].

Due to limited boosting capability of non-isolated boost converters, isolated versions have been preferred (turns ratio can be utilized to enhance the overall boost). This also provides electrical isolation improving the overall reliability. Fig. 6 shows two methods of obtaining usable ac output from the fuel cell. In Fig. 6 (a), the dc output from the fuel cell is first inverted using a conventional voltage source (VSI) inverter or a current source inverter (CSI) and then the ac voltage is stepped up employing a transformer. Inversion from dc to ac employing VSI is inherently a buck operation hence this method invariably requires a step-up transformer. In Fig. 6 (b), the fuel cell output voltage is stepped up employing a dc-dc converter and then the stepped-up dc voltage is inverted to line frequency ac. Conventionally this method has been more popular owing to the absence of transformer and the controllability of the dc-dc converter.

The options for isolated dc-dc converters [15] and their features are discussed below.

- Forward converter – suffers from restrained duty cycle and requires an excitation resetting tertiary winding.
- Push pull – requires center-tap transformer, not ideally suited for high power applications.

- Full bridge converter – suitable for fuel cell applications. Compared to half bridge dc-dc converter it has more components however the device current stresses are lesser.
- Half bridge dc-dc converter – is well suited for fuel cell applications. For improved efficiency H-bridge based soft switching series resonant converter is more suited. The other advantages of this topology include inherent short circuit protection and no saturation problem of the transformer.

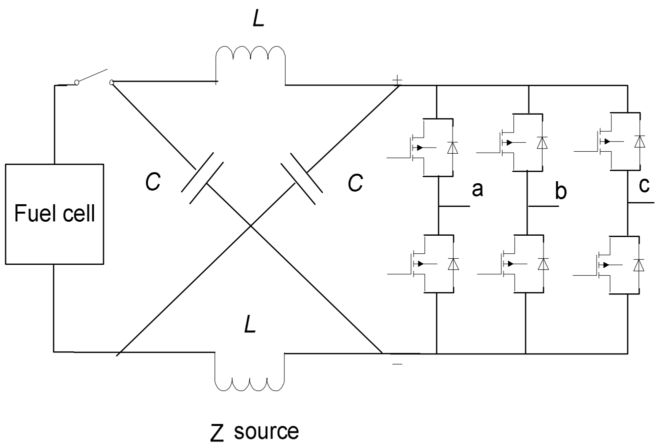


Fig. 8. Fuel cell energy conversion system employing a Z-source converter.

Traditionally for dc-ac conversion three phase, six-switch VSI have been used extensively. This technique is well established and the control strategies are well developed too. The main drawback of VSI is that its operation is inherently a step down operation. Z-source inverter presented in [8] incorporates the boost feature into the VSI without altering the inherent features of the VSI. This topology appears to be very useful for fuel cell and other renewable energy applications. Fig. 7 shows fuel cell energy conversion with a current-fed full-bridge dc-dc full bridge converter and a conventional dc-ac VSI. Fig. 8 shows a fuel cell energy conversion system employing a Z-source dc-ac inverter.

Most of the real time power-electronic enabled energy systems have energy backup in the form of a capacitor bank, ultra-capacitor, or a battery to augment the primary energy source like during dynamic loads. In dc-ac grid connected inverter based systems, since the grid voltage level and frequency are fixed the control variable is limited to being the current. The real and the apparent power being injected into or drawn from the grid have to monitored and controlled using complex control strategies.

IV. PHOTOVOLTAIC ENERGY CONVERSION SYSTEMS

Photovoltaic energy systems consist of arrays of solar cells which create electricity from irradiated light. The yield of the photovoltaic systems (PV) is primarily dependent on the intensity and duration of illumination. PV offers clean, emission-less, noise-free energy conversion, without involving any active mechanical system. Since it is all electric it has a high life time (> 20 years) [2]. A lot of work is being done to enhance the efficiency of the solar cell which is the building block of PV. In this regard the focus is mainly on electro-physics and materials domain. Some of the existing PVs and their efficiencies 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 formed by connecting a certain number of solar cells in series. Since the cells are connected in series to build up the terminal voltage, the current flowing is decided by the weakest solar cell [2], [13]. Parallel connection of the cells would solve the low current issue but the ensuing voltage is very low (< 5 V). These panels are further connected in series to enhance the power handling ability. The entire PV system can be seen as a network of small dc energy sources with PE power conditioning interfaces employed to improve the efficiency and reliability of the system.

The role of PE is mainly two-fold:

I. To interconnect the individual solar panels – two solar panels cannot be identical hence a dc-dc converter interfacing the two will help maintain the required current and voltage, and with regulation improve the overall efficiency.
   Several non-isolated dc-dc converters have been employed for this purpose. Buck, buck-boost, boost, and Cuk topologies with suitable modifications can be employed for this purpose [13].
   Fig. 9 shows a PV system with dc- dc module used to interface the PV panels.
II. To interface the dc output of the PV system to the grid or the load - This includes the previously discussed topics of dc-dc-ac and dc-ac-ac conversion. The topologies considered for fuel-cell system grid interconnection correlates to the grid interconnection of PV based system as well including the usage of the Z-source inverter.

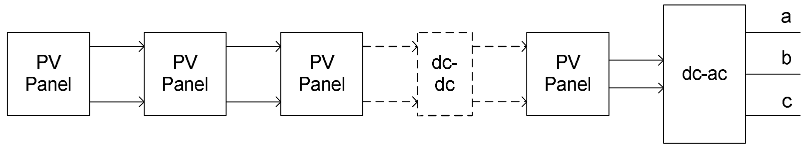


Fig. 9. PV system with dc-dc module.

V. CONCLUSION

The importance of renewable energy, renewable energy based energy conversion systems, and distributed power generation has been reiterated. A brief overview of the wind energy basics and the existing PE interface requirements and techniques have been addressed qualitatively. The basic electrical characteristics of fuel cell and photovoltaic based systems have been presented. The different methods of integrating these systems to the grid have been briefly described. The advantage of employing a Z-source inverter over a conventional dc-ac VSI has been emphasized. It can be concluded that with the advancements being made in the area of renewable energy and distributed power generation power electronics has a demanding and critical role in the future of efficient power generation and distribution.

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