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A Survey on Power-Electronics Interface for Renewable Energy Sources

Venkata Ramireddy Y(MTech)
Dept. of Electrical Engineering
RGUKT-RK Valley,
Kadapa(AP)

Mahesh P (MTech)
Dept. of Electrical Engineering
RGUKT-RK Valley, Kadapa(AP)

Sreedhar D (MTech)
Dept. of ECE,
RGUKT-RK Valley,
Kadapa(AP)

***Abstract*---The global electrical energy consumption is steadily rising and consequently there is a demand to increase the power generation capacity. Deregulation of energy has in the past lowered the investment in large power plants, which means the need for new electrical power sources may be very high in the near future. Two major technologies will play important roles to solve the future problems. One is to change the electrical power production sources from the conventional, fossil (and short term) based energy sources to renewable energy resources. Another is to use high efficient power electronics in transmission, power transmission/distribution, and end-user application. The PE plays a vital role in the Grid integration. Therefore, PE based converters are also widely used in renewable energy systems. The specification of a power electronic interface is subject to requirements related not only to the renewable energy source itself but also to its effects on the power-system operation. The paper focuses on the power electronics used in renewable energy systems and especially in wind, photovoltaic (PV), and fuel cell applications. Discussions about common and future trends in renewable energy systems based on reliability and maturity of each technology are presented in this paper.**

***Index Terms—*Doubly fed induction generator (DFIG), Z-source converter, buck-boost converter, maximum power point tracker (MPPT) controller, and voltage source converter (VSI).**

I. INTRODUCTION

The energy consumption is steadily increasing and the deregulation of electricity has caused that the amount of installed production capacity of classical high power stations cannot follow the demand. A method to fill out the gap is to make incentives to invest in alternative energy sources like wind turbines, photovoltaic systems, micro turbines and also fuel cell systems. The wind turbine technology is one of the most promising alternative energy technology [1], [3], [4].

Electricity generation using wind energy has been well recognized as environmentally friendly, socially beneficial, and economically competitive for many applications. For research into wind energy conversion systems, especially innovative wind turbine generators, power-electronic converters, maximum power extraction algorithms, and advanced controls, the provision of a controlled test environment with steady-state characteristics of wind turbines is significant [1], [2]. The figure 1 gives an outlook of the RES (renewable energy sources) industry, looking into how the different renewable energy technologies can contribute to a fully sustainable energy supply by 2050

provided there is strong political, public and economic support for all renewable energy technologies [11].

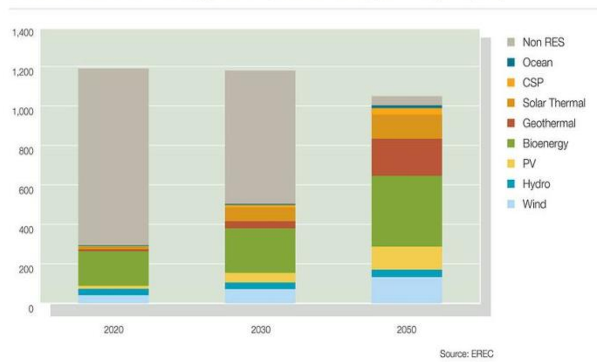

Fig. 1. A vision on future integration needs of renewable energies for Europe

There are two main trends in development of power systems. First is a wide utilization of renewable power sources. The second is decentralization of power generation. Hence, small power sources, very often RES sources, called dissipated power generators are developed. They are usually in range of megawatts starting from kilowatts. They operate automatically and are remotely controlled. In fact the sources are electronic devices. Microprocessor control units are used to control power production and perform remote control and power electronic converters are used to control power flow. So, many different kinds of power electronic devices are required.

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

II. WIND TURBINE SYSTEMS

Wind power is the conversion of wind energy into a useful form of energy, such as using wind turbines to make electric power, windmills for mechanical power, wind pumps for water pumping or drainage, or sails to propel ships. Families living in rural areas who do not have access to the national grid may have to travel long distances and wait long times for their batteries to be recharged at commercial centers. Practical Action has developed reliable and cost effective wind energy systems for charging batteries to help meet the electrical energy needs of these people. Wind energy has the biggest share in the renewable energy sector. 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. Figure 2 depicts the wind energy conversion system. Wind speeds, air pressure, atmospheric temperature, earth surface temperature etc., are highly inter-linked parameters. The wind speed is the most important factor influencing the amount of energy a wind turbine can produce. Increasing wind velocity increases the amount of air passing the rotor, which increases the output of the wind system as shown in Table1. Most popular power electronics and machines in large wind turbines are:

- Synchronous generator along with a rectifier and power inverter for grid interconnects. Both rectifier and inverter need to be sized the same power level as the generator.
- Doubly fed induction generator with an ac-to-ac power converter for rotor frequency and power control. The converter is only required up to 30% of the generator power [7].

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 = blade length
ρ = density of air
v = wind velocity
λ = tip speed ratio
C_p = power coefficient

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

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

Currently the focus is on the variable speed, horizontal wind turbines [5], [6]. Power electronic circuits play a crucial enabling role in variable speed based wind energy conversion systems. Fixed speed wind turbines are reliable, simple and robust by maintaining the grid frequency is to be constant with respect to rotor. It is accepted that the maximum attainable efficiency for wind energy conversion is 0.59 [5]. As a result of this we cannot obtain the optimal aerodynamic efficiency point C_{Pmax} . 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 difference between fixed speed and variable speed operation characteristics is as shown in figure 3. The grid connected wind turbine(WT) are connected to the utility grid either directly or through power electronics, feeding the produced energy to the grid. On this type of WT all manufacturers are trying to increase the size and efficiency of the machines. Many studies have been made on the speed control part and on ways to reduce the cost of the unit.

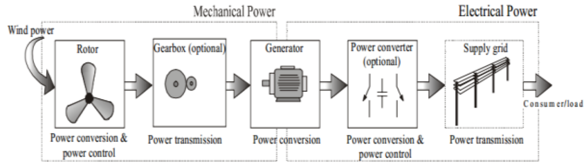

Fig. 2.Basic Power Conversion Principle in Wind Energy System

There are several types of inverters which are used on wind turbine installations, such as PWM – VSI converters and matrix converters. However the matrix converter is not widely used. The back – to back PWM VSI is a bi-directional power converter consisting of two PWM – VSI inverters [10].A solid-stateAC-AC converter converts an AC waveform to another AC waveform, where the output voltage and frequency can be set arbitrarily. 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 Figure 4 [9]. An AC-AC converter with approximately sinusoidal input currents and bidirectional power flow can be realized by coupling a pulse-width modulation(PWM) rectifier and a PWM inverter to the DC-link. The DC-link quantity is then impressed by an energy storage element that is common to both stages, which is a capacitor C for the voltage DC-link or an inductor L for the current DC-link. The PWM rectifier is controlled in a way that a sinusoidal AC line current is drawn, which is in phase or anti-phase (for energy feedback) with the corresponding AC line phase voltage.

Due to the DC-link storage element, there is the advantage that both converter stages are to a large extent decoupled for control purposes. Furthermore, a constant, AC line independent input quantity exists for the PWM inverter stage, which results in high utilization of the converter's power capability. On the other hand, the DC-link energy storage element has a relatively large physical volume, and when electrolytic capacitors are used, in the case of a voltage DC-link, there is potentially a reduced system lifetime. Major research and development efforts in wind power control can be found in the following areas.

TABLE I
Wind speed versus Power output

Average Wind Speed Km/h(mph)	Suitability
Up to 15(9.5)	No good
18(11.25)	Poor
22(13.75)	Moderate
25(15.5)	Good
29(18)	Excellent

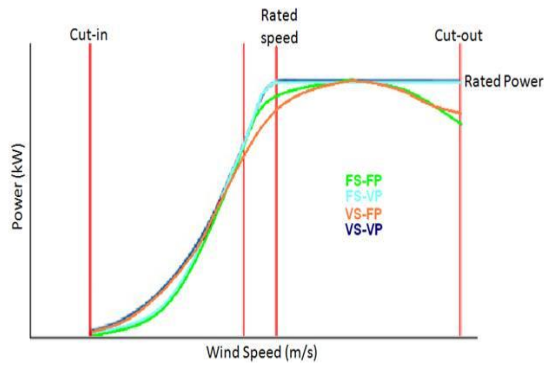

Fig. 3.Fixed Speed and Variable Speed Operation Characteristics

- Blade design optimization to increase power production
- Drive train optimization to eliminate gears
- Rotor speed control for maximum power tracking
- Energy management with multiple energy sources
- Large size permanent magnet (PM) generator

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 as shown in figure 5 [8]. Table 2 gives a qualitative summary of the wind energy conversion systems. WEC (wind energy conversion). 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

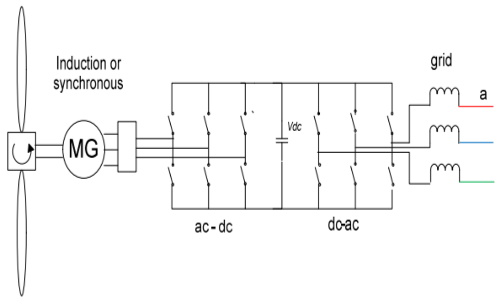

Fig. 4.Fully Variable Wind Energy Conversion System

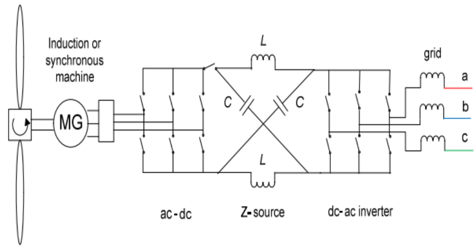

Fig. 5.Z-source Based Variable Speed Wind Energy Conversion System.

TABLE II
Wind Energy Conversion Systems Summary

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.PHOTOVOLTAIC SYSTEMS

Solar Photovoltaic (SPV) technology is one of the most matured renewable energy (RE) technologies and there is an increasing demand of SPV installation both in grid-connected as well as off-grid stand-alone modes. Although in recent years, the penetration of solar PV installation has increased substantially due to several initiatives, it is yet to be considered as one of the mainstream renewable energy technologies. The main drawbacks of solar PV system is its high cost of installation for producing desired power level of electricity which is due to the high manufacturing cost of solar modules compounded with its low conversion efficiency. To make the solar PV system commercially viable, the cost of unit generation of electricity from solar PV system needs to be reduced which, in turn, calls for the development of a low cost, high efficient power conversion systems or schemes for delivering required electrical power. Hence it is always critical to design the most appropriate power converters and to assess their performance to ensure maximum power capture from solar modules along with impeccable power quality, reliability and efficiency.

Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photo voltaic effect. Photovoltaic power generation employs solar panels composed of a number of cells containing a photo voltaic material. Materials presently used for photovoltaic include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium sulfide. Solar photovoltaic is now, after hydro and wind power, the third most important renewable energy source in terms of globally installed capacity. 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 [12-16]. The PV system consists of three main blocks the PV array, DC/DC converter and DC/AC inverter [12], [17].

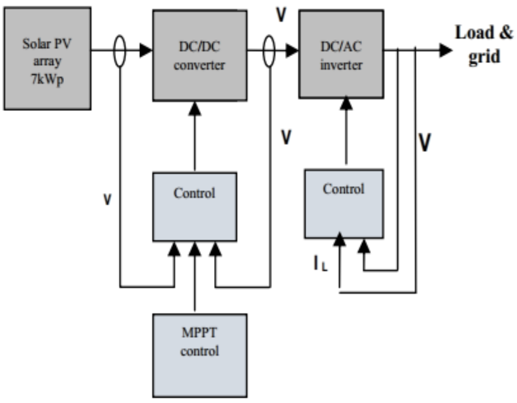

Fig. 6.Experimental setup of the 7kW solar PV system

The conversion of the output voltage from solar module to a useful DC power (using a DC-DC converter) and then, to the required AC power (using a DC-AC inverter) for operating most of the conventional appliances makes the conversion scheme complicated. A major challenge that needs to be addressed by the DC-DC converters is to take the non-linear output characteristic of the solar PV sources which varies with solar insolation and temperature and convert it in to appropriate level of voltage. Similarly the main challenge for the DC-AC inverter is to shape the current and voltage into a sinusoidal waveform and to maintain the maximum power factor, ensuring the galvanic isolation between input and output side. In order to maximize the performance of the panel, a maximum power point tracker (MPPT) controller is used in SPV system as shown in figure 6 [12]. The MPPT applies heuristic algorithms to track array voltage which results in maximum power, given a solar irradiance level as shown in figure 7. The efficiency of modern MPPTs is between 92-97%.The input resistance of the converter is same as the output resistance of the PV cell/module [15]. The relationship between the output resistance of the PV cell/module and the actual load for maximum power transfer using buck-boost converter can be derived as

$$R_{OUT\,(Module\,)} = R_{O(Load\,)}.\frac{\left(1 - D_{mp}\right)^2}{{D_{mp}}^2} \qquad -(3)$$

Here,

$R_{OUT\,(Module\,)}$ = PV cell resistance

$R_{O(Load\,)}$ = Load resistance

D_{mp} = Duty cycle at MPPT

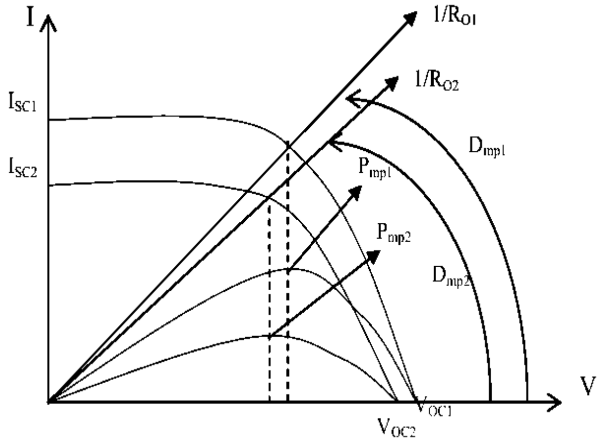

Fig. 7.Maximum Power Point Tracking

Maximum power point tracking system tracks the maximum power point of the PV cell/module and adjusts D_{mp} from the feedback network based on the voltage and current of the PV module to match the load. Maximum power point tracking can be achieved in a number of ways. The first step is to define K = $\frac{V_{mp}}{V_{oc}}$ where 0<K<1. In the block diagram, reference cell is supposed to be an identical cell that is being used in an application. The V_{mp} of this cell is used to compare the voltage of the actual cell. The V_{mp} of the reference cell is obtained by multiplying V_{oc} with K. When V_{module} matches with V_{mp} , there will be zero error and the module is delivering maximum power. If error is not zero, then the error signal is fed into a controller that would create a rectangular pulse of appropriate duty cycle which is fed to the power conditioner circuit (here it is a DC-DC converter).

IV. FUEL CELL SYSTEMS

Fuel cells that are currently being developed can be used as possible substitutes for the internal combustion engine in vehicles as well as in stationary applications for power generation [19-20]. A fuel cell is an electro-chemical device which produces electricity without any intermediate power conversion stage. The most significant advantages of fuel cells are low emission of greenhouse gases and high power density. The energy density of a typical fuel cell is 200 Wh/l, which is nearly ten times that of a battery. The efficiency of a fuel cell is also high, in the range of 40% to 60%. If the waste heat generated by the fuel cell is used for cogeneration, the overall efficiency of such a system could be as high as 80%. Presently the fuel cells being popularly used are:

- Solid Oxide(SOFC)
- Molten Carbonate(MCFC)
- Proton Exchange Membrane(PEMFC)
- Phosphoric Acid(PAFC)
- Alkaline(AFC)

In these kinds of fuel cells, PEMFCs are being rapidly developed as the primary power source in movable power supplies and distributed generation (DG), because of their high energy density, low working temperature, and firm and simple structure [18]. Table 3 provides a summary of various fuel cell types and corresponding characteristics. Fuel cells are similar to PV systems in that they produce DC power. Power conditioning systems, including inverters and DC-DC converters, are often required in order to supply normal customer load demand or send electricity into the grid. The power electronics topologies for fuel cell systems are varied and are based on the number and types of cascaded stages in the conversion systems. Two such topologies that can be used with fuel cells for supplying consumer loads and for utility connection include cascaded DC-DC and DC-AC converters (DC-link) [6, 21-22] and cascaded DC-AC and AC-AC converters (high-frequency link). There are also many recently developed and/or proposed circuit configurations for fuel cell applications, including a Z-source converter that combines functionality of DC-DC boost andVoltage-Source Inverter (VSI).

TABLE III
Summary of typical fuel cell characteristics for DE applications

Electrolyte Material	Operating Temp (Warm-up Time)	Anticipated Applications	Comments
Solid Oxide (SOFC)	1000^0c (long)	Stationary	High temperature create material problems, steam generation could increase efficiency by cogeneration
Molten Carbonate (MCFC)	600^0c (long)	Stationary	Same as SOFC
Proton Exchange Membrane (PEMFC)	80^0c (relatively short)	Stationary and vehicle	Minimum contamination and material problem Fully variable system
Phosphoric Acid (PAFC)	Approx. 100 (medium)	Stationary	Higher temperature and longer warm up time makes unsuitable for vehicles
Alkaline (AFC)	Approx. 100 (relatively short)	Space program	Susceptible to contamination, very expensive

The simplest form of fuel system configuration, as shown in figure 8, consists of a fuel system stack followed by the DC-AC converter. If the isolation or a high ratio of the voltage conversion is required, a transformer is usually integrated into the system. The main drawback for this configuration is that the low-frequency transformer placed at the output of the inverter makes the system very bulky and expensive.

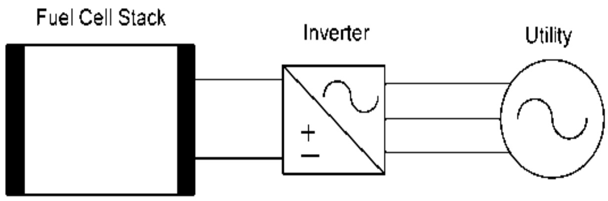

Fig. 8.Fuel cell system configuration with a single inverter

A DC-DC converter is usually put between the fuel cell and the inverter. The DC-DC converter performs two functions: 1) it acts as the DC isolation for the inverter; and 2) it produces sufficient voltage for the inverter input so that the required magnitude of the AC voltage can beproduced. The inverter can be single-phase or three-phase depending on the utility connection. An example of a fuel cell system with power electronics interfacing into a three-phase utility system, where an isolated DC-DC bridge converter and a three-phase hard switching voltage-source inverter (VSI) are used. 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 [23] 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.

The high-frequency link power conversion technique is attractive for this application because a high-frequency link direct DCAC converter which consists of a high- frequency inverter, a cycloconverter, and a high frequency transformer between them provides a possible way to build a compact direct DC-to-AC converter without the DC-link capacitor. The advantage of thisapproach provides a high power conversion efficiency due to the reduced number of conversion steps. High-frequency-based PE topologies are mainly used in single-phase systems. Three-phase cycloconverter require alarge number of devices, which results in higher costs, more switching losses, andincreased system complexity.

The conventional cascade topology, as described, is a DC-DC forward converter with a DC-AC inverter. This configuration actually has three stages of power conversion: DC-AC in the forward converter primary, DC in the rectification for the DC bus, and then DC-AC in the inverter. The cascaded conversion would appear to have redundancy, especially since the topology adds a DC bus that must be filtered. A few topologies exist for cascaded DC-AC and AC-AC cycloconverter for the fuel cell applications. In the future, the possibility of using matrix converters as the AC frequency changer will probably introduce more high-frequency link topologies for the fuel cell systems. One high-frequency topology for the fuel cell system. In this circuit, the forward converter is replaced with a simple square-wave inverter that produces a high-frequency link at the transformer. The internal rectifiers and DC bus filtering have been eliminated; the output inverter is replaced with an AC–AC converter that processes the high-frequency link and delivers the AC at utility frequency. The PWM cycloconverter concept is used for the control of an AC-AC converter which reduces some of the complexities of cycloconverter control.

V. CONCLUSION

The importance of renewable energy, renewable energy based energy conversion systems, and distributed power generation has been reiterated. This paper illustrated and highlighted the role of Power Electronics (PE) in the research and development of renewable energy systems. It should be possible to develop the power-electronic interface for the highest projected turbine rating, to optimize the energy conversion and transmission and control reactive power, to minimize harmonic distortion, to achieve at a low cost a high efficiency over a wide power range, and to have a high reliability and tolerance to the failure of a subsystem component.

This papers dealt only with the wind, solar-PV and fuel systems as they are the most promising renewable energy sources for generation of electricity. The configurations of integrating DFIG wind system, photovoltaic system using MPPT controller and fuel system using two inverters (VSI and Z-source) to the grid have been briefly described. Based on which, it can be concluded that PE plays crucial role in the research and development of renewable energy systems, especially, wind, photovoltaic and fuel systems.

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