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Semiconductor Devices in Renewable Energy Systems

Department of Physics
Atul Kumar Pandey
Assistant Professor, Department of Physics
Government Degree College Sehmo, Basti

Abstract: A lot of new technology in solar energy, wind energy and other types of clean energy is based on advances in semiconductors. This review looks at some important semiconductors such as p-n junction diodes, power MOSFETs, insulated gate bipolar transistors (IGBTs) and thyristors, and how these devices are used in photovoltaic, wind turbine and other renewable energy systems. We will discuss the operation and performance of each device, as well as their converter topology (the circuit that connects the device to the renewable energy system), as described in the numerous publications on these topics. For each type of semiconductor device, we have also identified several common challenges, including switching losses, thermal management issues, and efficiency optimization. Finally, we conclude that the further development of wide-bandgap semiconductor materials holds significant potential for powering next-generation renewable energy systems.

Keywords: *semiconductor devices, renewable energy, photovoltaics, power electronics, MOSFET, IGBT, thyristor*

1. Introduction

An increased interest in renewable energy sources (especially solar PV and wind) has resulted from a greater need for clean, sustainable energy globally. Semiconductors serve as the core component of contemporary power electronics and, therefore, are fundamental to the effective transformation and distribution of energy produced from renewable sources (e.g., p-n junction diodes used in solar energy systems or power switching devices such as MOSFETs and IGBTs, which allow for precise control of electrical energy with reduced losses on device performance). Because semiconductors play a critical role in energy conversion (e.g., DC-DC conversion), inverter operation, and maximum power point tracking (MPPT), this review will provide an overview of the major types of devices and circuits, as well as potential new materials.

2. P-N Junction Devices and Photovoltaic Cells

The p-n junction serves as the basic building block of energy conversion using semiconductors. An illuminated photon with energy greater than the bandgap will create electron-hole pairs, which are separated by the built-in electric field of the depletion region to create a current [5]. The open circuit voltage (Voc) and short-circuit current (Isc) are used to determine performance; power conversion efficiency (PCE) is determined from the maximum electrical power output as a ratio of total incident optical power [6].

Monocrystalline silicon (c-Si), the most widely used commercially, achieves efficiencies of 15-20%, whereas polycrystalline silicon cells are the least expensive and range from 13 to 16 % in efficiency. CdTe and CIGS thin film technologies are less efficient but provide flexibility for deposition [7]. Bypass diodes within PV arrays help prevent damage from reverse bias to shaded cells, while blocking diodes prevent reverse current flow into the PV array during periods of low irradiance [3, 8].

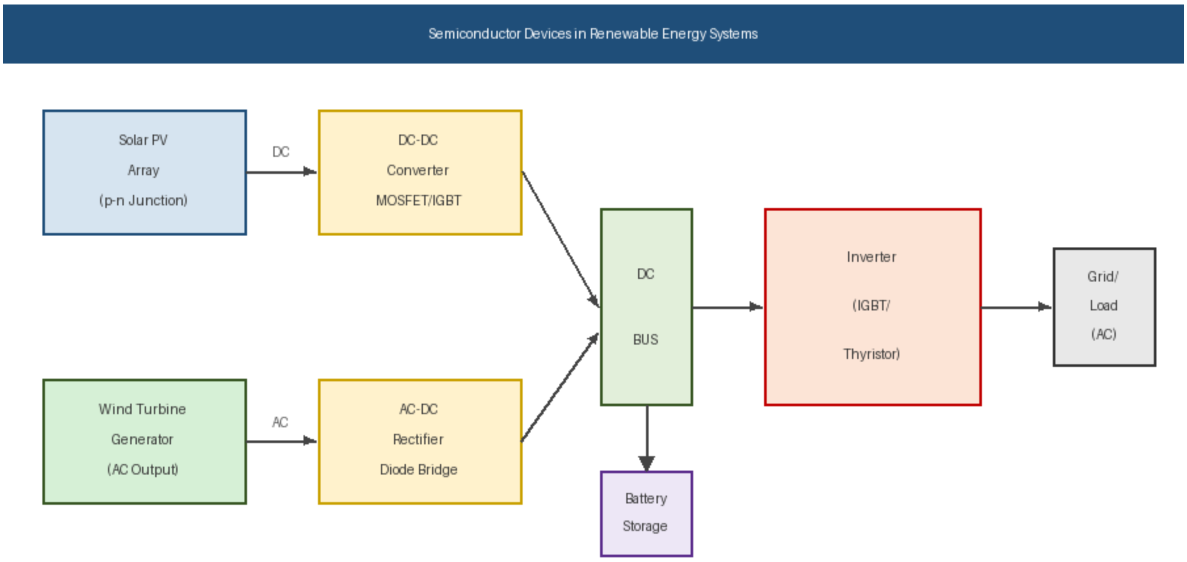
Semiconductor Devices in Renewable Energy Systems

Fig. 1: Block diagram of semiconductor roles in a hybrid renewable energy system

Figure 1: Block diagram of semiconductor device roles in a hybrid renewable energy system.

3. Power Switching Devices

Power MOSFETs

Power MOSFETs predominate in terrestrial ground or commercial-sized DC-to-DC conversion levels; their extremely high speed, low I g, low parasitic capacitance (C g) at the gate, and RDS(on) values combine to support high frequency operation (20-200 kHz), which results in large reductions in overall physical size of passive components, while providing significantly higher MPPT dynamic performance [9]. Power MOSFETs (Si) have voltage ratings from approximately 600 - 900 V and can cover the majority of global market needs with respect to PV-based commercial usage [11].

Insulated Gate Bipolar Transistors (IGBTs)

The Insulated Gate Bipolar Transistor (IGBT) combines the advantages of the gate structure of a MOSFET and the low on-state voltage (V ce(sat)) of a bipolar transistor, thus providing an efficient means of operation at medium to high voltages (600 V to multiple kilovolts) for applications such as grid tied PV inverters and wind turbine converters [12]. Grid-connected inverters typically use (6) IGBT's configured in a 3-phase full bridge to provide a PWM output of AC voltage. At the grid scale, multi-level inverter designs are now capable of using IGBT modules rated in excess of 1 kA and 3.3-6.5 kV, which significantly reduce harmonic distortion and device-level switching losses [12, 13].

Thyristors

SCRs and GTOs continue to play an important role in large-scale HVDC (High Voltage Direct Current) transmission connections to the electrical grid powered by distant offshore wind farms. Both have kilovolt ratings that help improve reliability. Unfortunately, SCRs/GTOs have slow switching speeds and limited gate triggering capabilities, making them difficult to implement in higher frequency converters [1].

4. Converter Topologies and Control

In photovoltaic (PV) systems, the most common type of DC-DC converter is the boost converter, which uses MOSFETs, inductors, and diodes to transform the voltage from the PV array to match that required by the DC link. To find the maximum power point, whatever changes occur in irradiance, maximum power point tracking (MPPT) algorithms such as perturb-and-observe (P&O) and incremental conductance are used to adjust the duty cycle of the boost converter.

Voltage source inverters (VSIs) using a full bridge topology based on insulated gate bipolar transistors (IGBTs) are standard for connecting to electrical grids in both single- and three-phase forms. Multi-level topologies such as neutral-point clamped (NPC) or cascaded H-bridge topologies are often used to minimise the harmonic content of the voltage produced and to reduce the dv/dt stress placed on the devices themselves.

Variable speed (VS) wind turbines that use permanent magnet synchronous generators (PMSGs) employ full-power back-to-back converters to provide an interface between the generator and the grid, as well as voltage-source inverters (VSIs). Wind turbines that use doubly fed induction generators (DFIGs) use a partially rated converter for the rotor circuit at approximately 25–30% of the generator's rated power. This allows for operation at both sub-synchronous and super-synchronous speeds with a significant reduction in semiconductor ratings.

Space vector pulse width modulation (SVPWM) provides the benefit of reducing the output harmonic distortion when compared to sinusoidal pulse width modulation (SPWM), while also decreasing the switching losses associated with the resultant PWM signal.

Thermal management through heat sink design, thermal interface materials, and innovative packagings helps ensure that semiconductors are kept within their safe operating area (SOA)

5. Wide-Bandgap Semiconductors and Future Directions

The properties of silicon carbide (SiC) and gallium nitride (GaN) for power electronics are significantly superior than silicon (Si) and gallium nitride. The bandgap for SiC is 3.26 eV, while the bandgap of silicon is 1.12 eV. The properties of SiC allow for an overall higher breakdown voltage, operation at elevated temperatures, and lower switching losses [19]. In addition, the electron mobility of GaN HEMTs allows for switching frequencies in excess of 1 MHz, with low RDS(on). Studies have been conducted that demonstrate using SiC devices in place of silicon IGBTs, in a 10 kW three-phase inverter, will produce approximately a 1-2 per cent increase in efficiency at partial load, which is important because the majority of an inverter's operating time is at partial load [19]. Although multi-junction III-V solar cells (gallium indium phosphide (GaInP), gallium arsenide (GaAs), and germanium (Ge)) have reached efficiencies greater than 40 per cent under concentrated sunlight, the cost of producing these cells limits their use to concentrated photovoltaic (CPV) systems [7].

6. Conclusion

This review has assessed the main semiconductor components of renewable energy systems. In photovoltaics, the primary semiconductor is the p-n junction, and for power transmission, MOSFETs provide very efficient, high-frequency DC-DC Converter capabilities; for high-medium power applications, IGBTs are the primary inverter semiconductor device type; and Thyristors provide the hardware for high-power applications in high-voltage DC systems. Multi-level converter topologies will enable the application of IGBTs to MW installations and improve power quality concerning medium/high power levels. Wide Bandgap materials (Silicon Carbide(SiC) and Gallium Nitride (GaN)) are expected to play a significant role in power electronics for next-generation renewable energy power systems as their manufacturing processes mature, and costs decrease because they overcome silicon's inherent drawbacks.

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