IJAREEIE

e-ISSN: 2278-8875
p-ISSN: 2320-3765

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

Volume 11 Issue 4, April 2022

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

Impact Factor: 8.18

9940 572 462 | 6381 907 438 | ijareeie@gmail.com | www.ijareeie.com

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 8.18|

||Volume 11, Issue 4, April 2022||

|DOI:10.15662/IJAREEIE.2022.1104045|

Power Electronics in Renewable Energy Deployment- A Study

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ABSTRACT: This rapid increase in global energy consumption and the impact of greenhouse gas emissions has accelerated the transition towards greener energy sources. For this reason, there is growing attention in the renewable energy around the world. like wind and solar. However, integrating these intermittent energy sources into existing power grids presents significant challenges. In the energy context, power electronics plays a key role in solving these problems, offering innovative solutions for managing, converting, and distributing energy from renewable sources. Power Electronic devices such as High-frequency switching converters, Multi-level converters, Grid-interactive inverters, Energy storage integration, Wide-bandgap semiconductor devices play a vital role in integrating renewable energy sources into modern power grids.

KEYWORDS: Wide-bandgap (WBG), Photovoltaic, Silicon Carbide (SiC) ,Gallium Nitride (GaN)

I. INTRODUCTION

Power electronics are essential for the efficient management of energy produced by alternative energy sources. These systems allow the conversion of energy from direct current, typical of solar sources, to alternating current, used in most power grids. Power converters such as inverters are therefore essential to adapt the energy produced to the needs of existing infrastructures. In addition, power electronics allow the dynamic control of energy flow, ensuring that the energy generated is used in the most efficient way possible. This is particularly important to manage the power fluctuations typical of renewable sources, caused by the variability of wind and solar radiation.

II. ROLE OF POWER ELECTRONICS

During the last thirty years Power electronics has changed rapidly and their applications have been increasing which is mainly due to the developments of the semiconductor devices and the microprocessor technology. For both cases higher performance is steadily given for the same area of silicon as well as they are continuously reducing in price. A typical power electronic system consists of a power converter, a load/source and a control unit as shown in Fig-1

The power converter is an interface between the load/generator and the grid. The power may flow in both directions depending on the topology and applications. These converters, and controllers enable the conversion of variable and intermittent energy outputs into stable and reliable power suitable for distribution and consumption.

Advancements in power electronics have greatly improved the efficiency, reliability, and flexibility of renewable energy systems.

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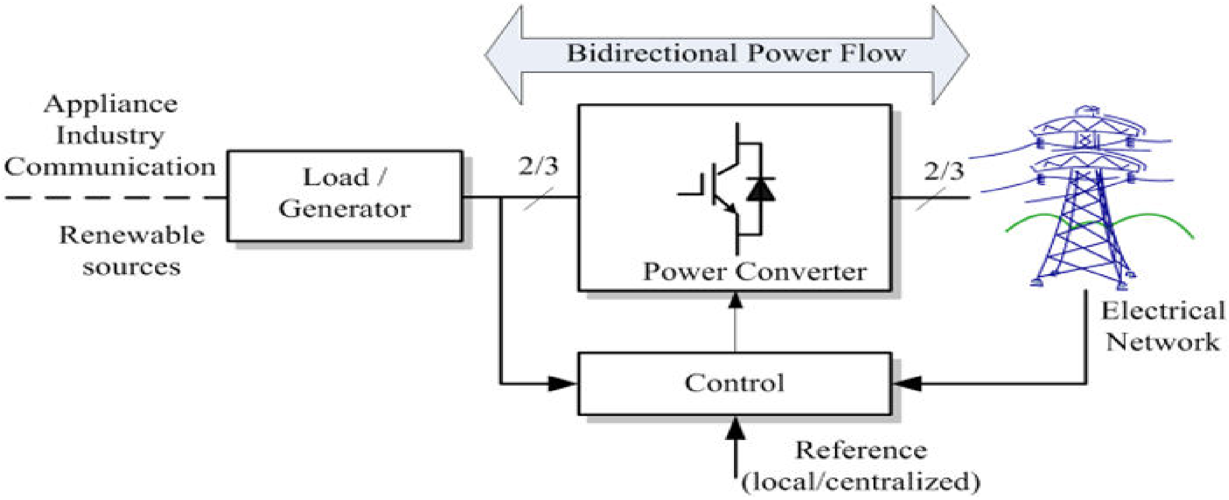

Fig 1. Power electronic system with the grid, load/source, power converter and control [7]

III. TYPES OF POWER ELECTRONICS DEVICES

A. High-frequency switching converters

These are power electronic converters that regulate voltage/current by rapidly switching semiconductor devices (typically tens of kHz to several MHz) , resulting in reduced size, weight, and energy loss. They are especially beneficial in Photo Voltaic (PV) systems and wind turbines, where space and weight constraints are acute. High-frequency converters also enhance grid compatibility by providing a more stable output. They are the backbone of modern power supplies, DC-DC converters, inverters, and chargers.

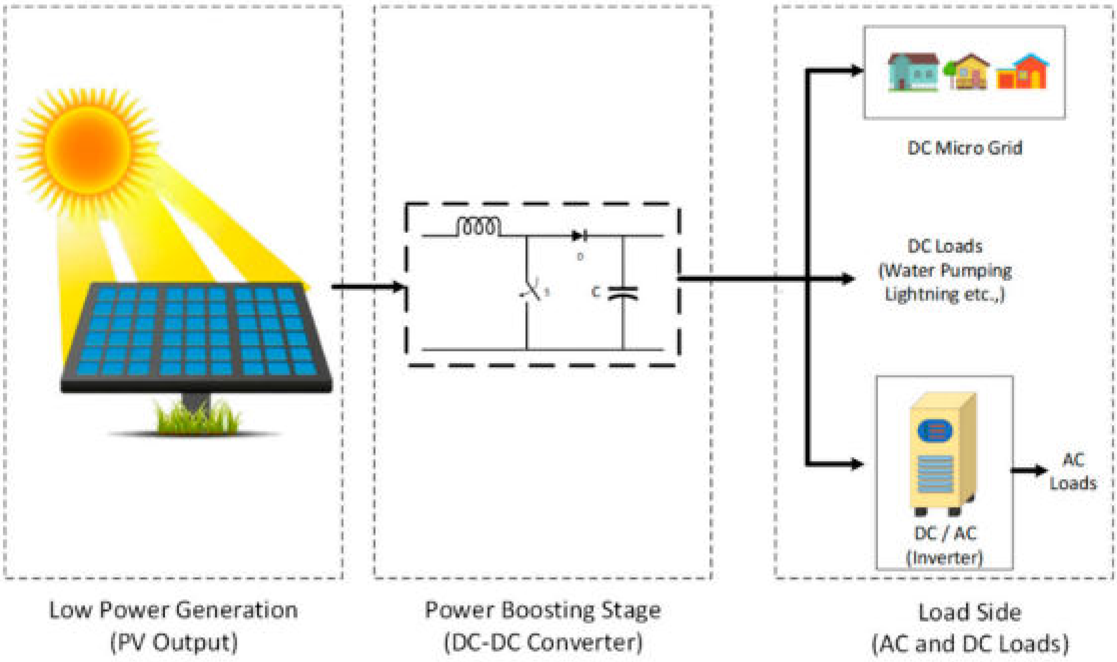

Fig 2.Solar PV integrated system with DC–DC converters fed to the load [1,2]

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B. Multi-level converters

Multi-level converters are key enablers for integrating renewable energy sources into modern power grids because they provide high efficiency, excellent power quality, and scalability to medium- and high-voltage levels. By utilizing multiple voltage levels, these converters minimize harmonic distortions and improve the overall power quality of generated electricity. This advancement ensures smoother integration with the grid, reducing the risk of disturbances.

Multilevel inverters are mostly used in large-scale high-power grid-connected renewable energy systems [5].

Scholars are focusing more on multilevel inverters due to their low switching losses, high voltage operation capability, low Electro-Magnetic Interference (EMI) output, high efficiency, and good power quality performance (low THD output) due to multiple level output waveform [6].

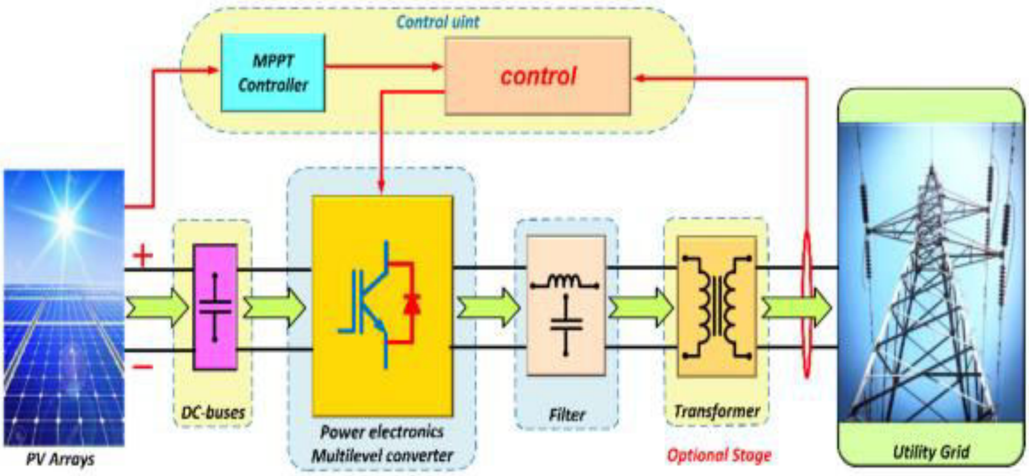

Fig 3. A photovoltaic (PV) system with power electronics and the needed control[3]

C. Grid-interactive inverters

Grid-interactive inverters are *essential interfaces* between renewable energy sources and the utility grid. These provide Efficient DC to synchronized AC conversion, Bi-directional energy flow with the grid, Integration with batteries for hybrid/backup operation and Support for power quality and grid codes, Advanced grid-interactive inverters come equipped with smart control algorithms, enabling features like reactive power control, voltage regulation, and islanding detection, which enhance grid stability.

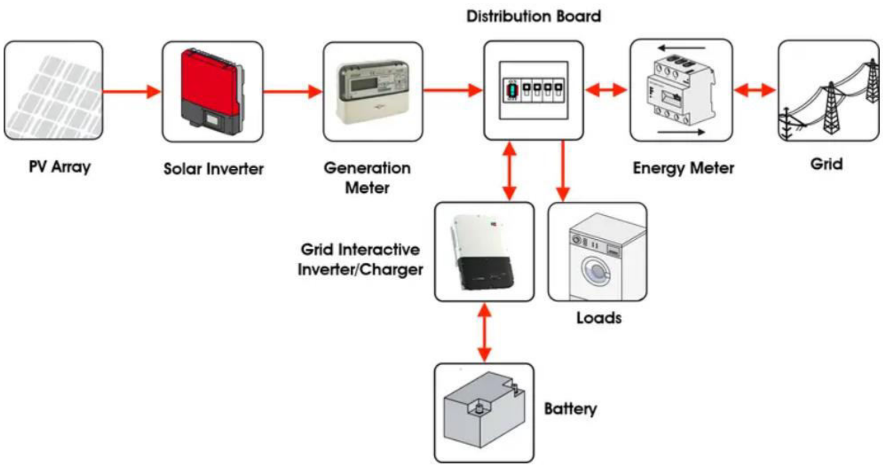

Fig 4 Grid Interactive Battery Inverters

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Grid-interactive battery inverters, can export power to the utility grid, can charge a battery using surplus energy for use in times of low generation and some can also supply backup power to protected loads during a grid outage.

D. Energy storage integration

Energy storage integration connects batteries or other storage technologies with renewable sources (solar, wind) and the grid to improve reliability, flexibility, and power quality. It is a core part of modern grid-interactive inverter systems. Batteries and other energy storage technologies help address the intermittency of renewable sources by storing excess energy during periods of high generation and releasing it when needed. Power electronics facilitate efficient charging and discharging of energy storage systems, optimizing their performance.

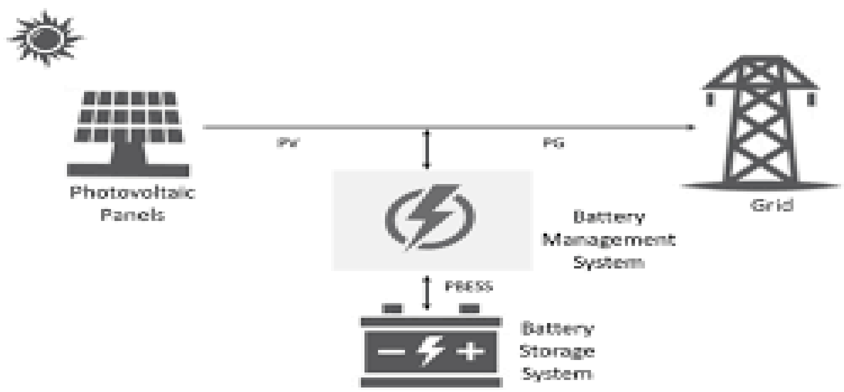

Fig 5 Battery storage systems

E. Wide-bandgap semiconductor devices

Wide-bandgap (WBG) semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN) have larger bandgaps than silicon. This translates to higher breakdown voltages, faster switching, higher operating temperatures, and better efficiency in power electronics — crucial for renewable energy converters. The adoption of wide-bandgap devices in power electronics has led to increased efficiency and reliability in renewable energy systems.

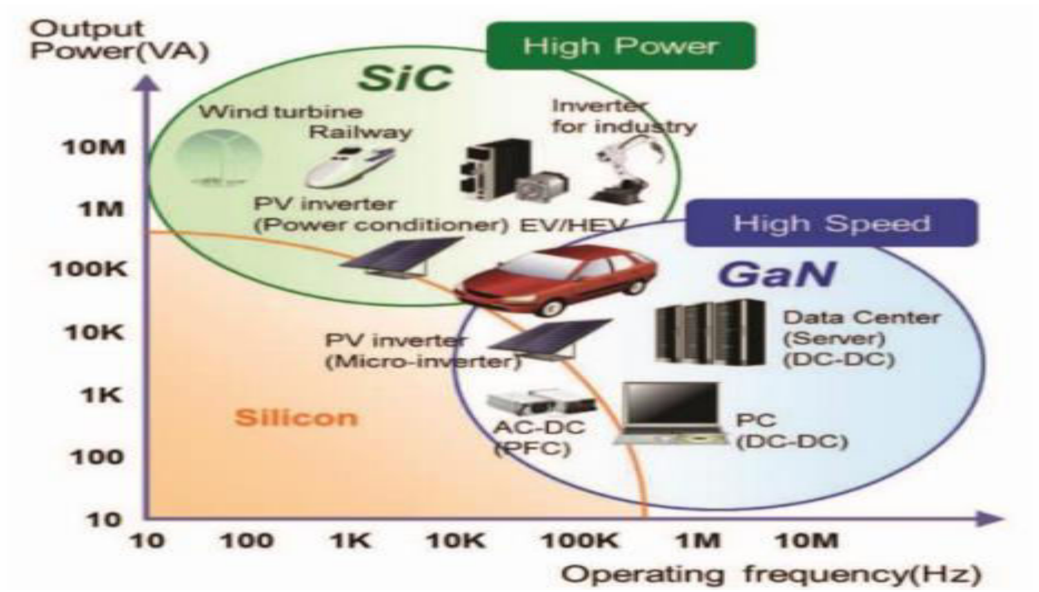

Fig 6. Potential applications of GaN and SiC power switching transistors[4].

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Uses of SiC & GaN in Renewable Systems

Solar PV Inverters

- String and central inverters benefit from SiC/GaN: higher efficiency and smaller size compared to silicon devices.
- GaN excels in lower to medium voltage (e.g., rooftop and 10 kW range); SiC dominates for high-power (>10 kW) central inverters.

Wind Power Converters

SiC devices are increasingly used in wind turbine power converters, enabling higher reliability and increased lifetime under cyclic loads. They reduce switching losses and improve system efficiency, which translates into higher energy yield over the turbine's life.

Battery Storage & Grid Interfaces

WBG devices improve:

- BESS (Battery Energy Storage System,)inverters and bidirectional converters
- Grid support converters (frequency/voltage regulation)
- HVDC links and other large-scale power electronics

by reducing losses and enabling higher voltage and frequency operation.

Electric Vehicle and Energy Storage Integration

Renewable systems paired with EV charging or storage use SiC/GaN in converters for higher efficiency and fast dynamic response from PV or wind side to grid or battery charging systems.

SiC vs GaN: Complementary Roles

Feature	SiC	GaN
Voltage range	Medium to very high (up to multi-kV)	Low to medium (hundreds of volts)
Best for	High-power central inverters, HVDC	High-frequency, compact converters
Switching speed	High	Very high
Efficiency	Excellent	Excellent at high freq.
Renewable use	Wind, large PV, grid interfaces	PV string inverters, high-freq DC–DC converters

In practice, many renewable designs combine both (e.g., GaN for high-frequency front end + SiC for high-power stages).

IV. CONTROL STRATEGIES AND CHALLENGES

A. Advanced Control Strategies

Advancements in control strategies have enhanced the overall performance of power electronics in renewable energy systems. Model Predictive Control (MPC), adaptive control, and Artificial Intelligence (AI)-based algorithms have been applied to optimize the operation of converters and inverters. These advanced control techniques adapt to changing conditions, maximize energy extraction, and minimize system wear and tear.

B. Grid Integration Challenges

Despite the significant progress in power electronics, challenges remain in the seamless integration of renewable energy into the grid. Grid stability, voltage and frequency regulation, and grid protection are issues that require ongoing research and development. Additionally, standardization and grid code compliance are important to ensure the safe and reliable operation of renewable energy systems.

V. CONCLUSION

Advancements in power electronics have played a pivotal role in the integration of renewable energy sources into the grid. High frequency switching converters, multi-level converters, grid interactive inverters, energy storage integration, wide-bandgap semiconductor devices, and advanced control strategies have collectively improved the efficiency, reliability, and grid compatibility of renewable energy systems. Despite the significant progress that has been made,

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ongoing research is required to address the challenges that remain and guarantee a future that is energy-secure and sustainable. In conclusion, power electronics play a crucial role in electrical engineering and electronic technology because they continue to be a driving force behind the global shift toward renewable energy.

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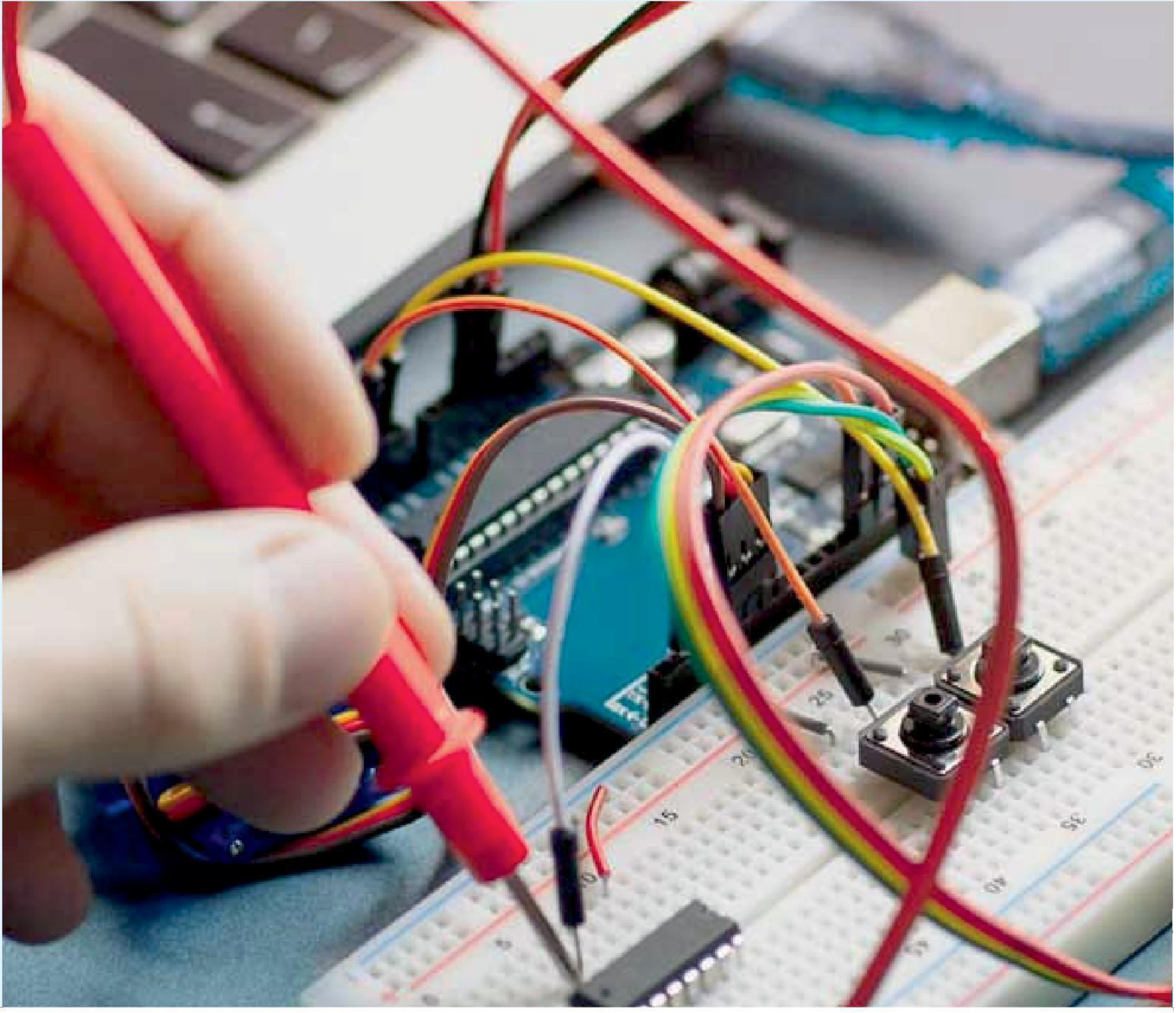

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