IJAREEIE

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

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

Volume 14, Issue 11, November 2025

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

Impact Factor: 8.807

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 8.807 | A Monthly Peer Reviewed & Refereed Journal |

|| Volume 14, Issue 11, November 2025 ||

| DOI:10.15662/IJAREEIE.2025.1411010|

Reconfigurable Three-Switch Leg Multi-Port Boost Inverters with Novel Modulation Schemes for Hybrid Dc/Ac Microgrid Systems

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ABSTRACT: The current state of system technologies, research, and application of conventional and novel control methods is presented in a review of multiport converters technologies. This review paper provides information regarding multiport converters, with the goal of guiding academics, designers, and application engineers toward a better understanding of technical characteristics, operation principles, and a selection process for these types of converters. The paper is focused not only on the multiport converters' classification, which is based on the isolation characteristics, but also takes into consideration other important aspects inherent in this type of power electronic devices. Among other major characteristics are the multiport converter's structure, power flow direction and gain coefficients. In recent review papers dedicated to multiport converter technologies, the focus is on multiport converters designed for renewable energy sources applications. The current review includes research works from the fields of renewable energy sources, electrical vehicles, energy storage systems, and micro-grids where multiport converters are also quite important. That are dedicated to the investigation of multiport converters' operation and performance. The up-to-date information regarding these technologies can help the readers to find the most important concepts and efficient ways of utilizing these concepts in the field of multiport converters.

KEYWORDS: AC voltage gain, Boost inverter, DC-link voltage utilization, DC voltage gain, modulation scheme, multi-port DC/AC converter

I. INTRODUCTION

The demand for renewable energy sources (RES) has been steadily rising in recent years. A dependable solution to the current global energy problem brought on by unstable political and economic conditions can be found in the production of electricity using diverse renewable energy sources, such as solar, hydro, wind, tidal, and biomass. Given the limited availability and high CO2 emissions of conventional fossil fuels such as coal, natural gas, and oil, the importance of renewable energy sources is growing. Over the following decades, renewable energy sources will become the most important and fundamental components in achieving energy efficiency, energy savings, and environmental protection.
The unpredictable zero-power periods brought on by different renewable energy sources, such as photovoltaics (PV) and wind turbines, can be reduced with the help of the hybridization of the system. As a result, the use of PV modules, energy storage (ES) batteries, and wind power production systems have a larger potential to provide continuous electrical energy than the use of only one renewable energy source.

Although there have been great advancements in the use of renewable energy sources, there are still some substantial limitations. These limitations are a result of issues with voltage and frequency variance, grid protection, safety, and solidity of the system, as well as power quality.

The concept of microgrids (MG) is being developed as a solution to these problems in order to meet local energy demands while also enabling the connection of diverse renewable energy sources to the main distribution grid via nearby substations. Because they can interface renewable energy sources, DC loads, and the majority of energy storage systems, MGs are able to reduce the number of times when direct current (DC) is converted to alternate current (AC) and vice versa, thus increasing the system's overall efficiency. The additional stages of energy conversion make the system more complex, increase energy losses, and reduce system efficiency in general.

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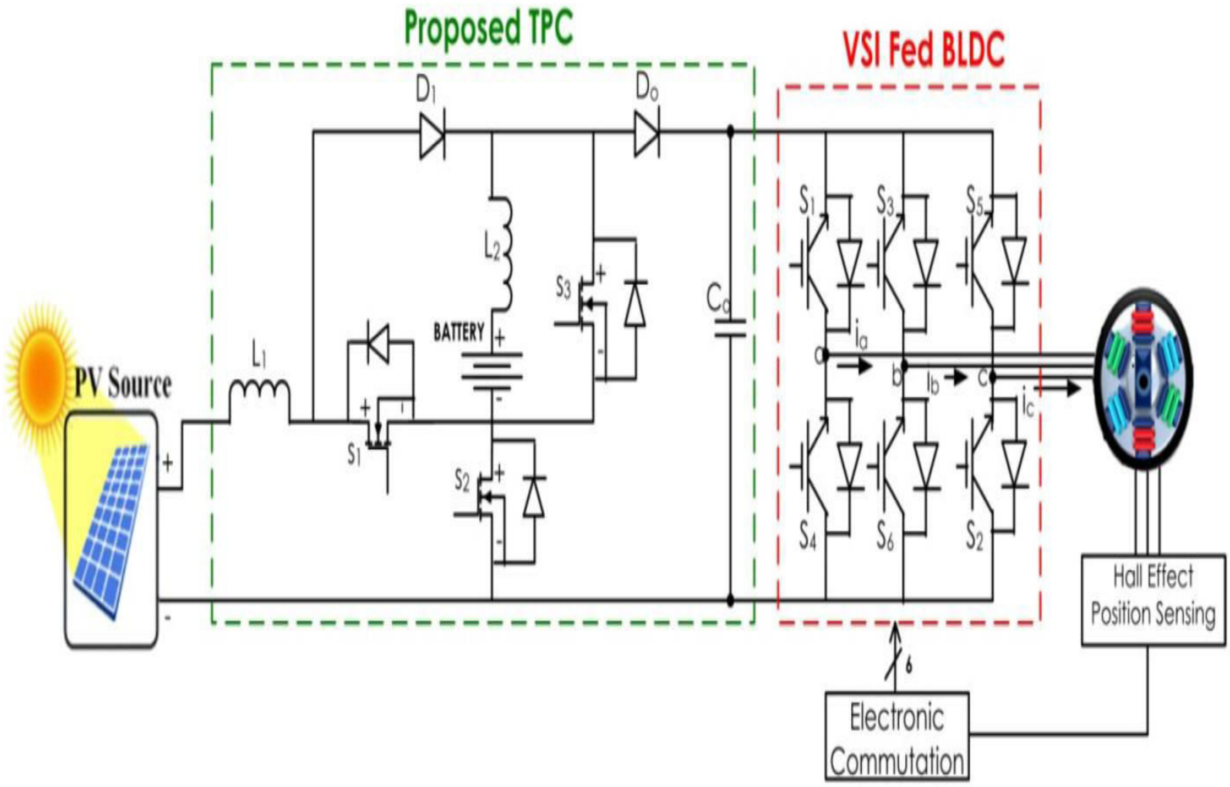

Fig 1: Three-Port Bi-Directional DC–DC Converter

It is required to use separate conversion stages for the load, energy storage systems, and renewable energy sources in order to allow power transfer between them, due to the fact that energy storage devices often have standard outputs that are different from the output of renewable energy sources based on their voltage-current characteristics. According to recent statistics, static power electronic converters are used to transport over 70% of electrical energy produced to the grid. Classical DC-DC converters such as the Boost, Buck, Buck-Boost, CUK, SEPIC, and ZETA require a significant number of components to provide adequate output voltages and integrate renewable energy sources into the microgrid. It causes the end product to be expensive and the equipment to be complex. Therefore, integrating numerous ports using separate power converters is not an effective approach.

A different strategy was suggested as an alternative to creating a power converter with integrated numerous ports, or multiport converter (MPC). The multiport converter's major objective is to connect several power sources with inputs and outputs through a single power converter to enable power flow between each port. These multiport converters are designed to remove redundant and superfluous power conversion stages and excessive semiconductor switching devices that would often be present in classical topologies. When compared with the benefits offered by multiport converters, using numerous conventional converters becomes less appealing, especially in hybrid systems that combine renewable energy sources, energy storage, the grid, and a variety of loads or consumers. In some cases, the multiport converters perform other important control functions in addition to regulating the low-level direct current voltages of the renewable energy sources to the proper level for supplying the inverter. Therefore, there are currently two main approaches, including the use of an individual converter for connecting each energy source to the grid or a multiport converter for connecting several sources that can be used to link various renewable energy sources, including the battery, to supply load or the grid.

II. BACKGROUND OF WORK

There are many review papers dedicated to different aspects of multiport converter technologies. In, the authors describe several topologies (more than 30) and indicate that the implementation of wide band gap (WBG) semiconductors and particularly silicon carbide and gallium nitride technologies will establish future trends. For energy

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storage management, a novel implementation of multiport zero-current switching switched-capacitor converters is described in. The suggested switched capacitor converters allow individual control of the charging or discharging current of the series-connected energy storage modules, such as the battery or super-capacitor cells, in addition to the auto-balancing function provided by the switched capacitor approach. Circuit analysis and derivation of the corresponding analytical representation are discussed along with various configurations, such as the single-input multi-output, multi-input single-output, and altered circuits for string-to-cells, cells-to-string, and cells-to-cells equalizers. The authors indicate that the simulation analysis and experimental findings showed that the presence of a battery management system and closed-loop management of cell currents significantly increased the balancing speed. In, multiple input-single output DC-DC converters with isolated and non-isolated outputs are compared. Pulsed voltage source cells (PVSC) serve as the foundation for the examination of DC-DC converters. The analysis focuses on efficiency, non-ideal output properties, and size considerations. According to the results, the multi-input single-output Buck converter's output voltage has a linear relationship with the duty cycle control signal and is more efficient than the Flyback converter.

In, multiport converters for the combination of solar energy with energy storage systems are systematically reviewed. Along with a comparison of converter architectures and features such as operating conditions, classification of isolated and non-isolated topologies is offered. Based on its architectural design, each set of multiport converters is classified into several smaller groups. Important topologies are described with detailed specifications. A performance comparison that highlights the benefits and drawbacks of the various topologies results in recommendations for the next research perspective. A review of current developments in multiport DC-DC converters using hybrid renewable energy sources (HRES) for various applications is found in [20]. Numerous cutting-edge single-stage multiport topologies are shown in the paper .

In the literature, multiport converters are divided into two basic categories: isolated and non-isolated. These types of isolated and non-isolated multiport converters have only lately started to appear in the literature. The following sections cover the general operating principles of multiport converts, their historical background, and main fields of application of these devices. The typical topologies of non-isolated, partially isolated, and completely isolated multiport converts are covered with some of the presented examples. The main focus is on analyzing multiport converters' operation and characteristics in a RES system and for EVs.

III. METHODS

To clearly highlight the advantages of the proposed method, a detailed comparison between the proposed singlestage three-switch-leg multi-port boost inverter (TSLMPBI) and state-of-the-art multi-port DC-AC converters is provided in Table 4. This comparison evaluates critical parameters, including boost and buck voltage gains, device count, the number of DC and AC ports, voltage stress across switches, modulation schemes, and DC-link utilization. Additionally, Table 4 presents the number of inductors and capacitors, including AC-side LC filters. As evident from the comparison, the proposed topology, in conjunction with its novel modulation schemes, demonstrates superior performance by minimizing component count while achieving higher AC voltage gains, enhanced DC-link utilization, and both boost and buck voltage gains. These advantages establish the proposed TSLMPBI as a highly efficient and compact alternative to existing state-of-the-art multi-port inverters.

Based on the steady-state equations discussed in section II. C, the design specifications and the ratings of the designed passive components, switches, and diodes are summarized in Table 3. The influence of the DC offset (Doft) on the voltage gains of the DC and AC ports has been analyzed. Fig. 8 illustrates the theoretical (T), simulated (S), and experimental (E) voltage gains at the DC and AC ports as functions of Doft , maximum modulation index (MU), and (ML). As shown in Fig. 8, the simulated,experimental voltage gains slightly deviate from the theoretical values due to non-idealities, including the internal resistances of the components used in the single-stage TSLMPBIs.The experimental DC gain and AC gain tested up to the DC offset of 0.5, i.e, DC gain 4 times and AC gain 3 times to the input voltage. Fig. 8, along with equations (6), (17), and (18), demonstrate that the proposed converter achieves significantly higher voltage gains at its AC ports compared to state-of-the-art topologies with similar functionality.

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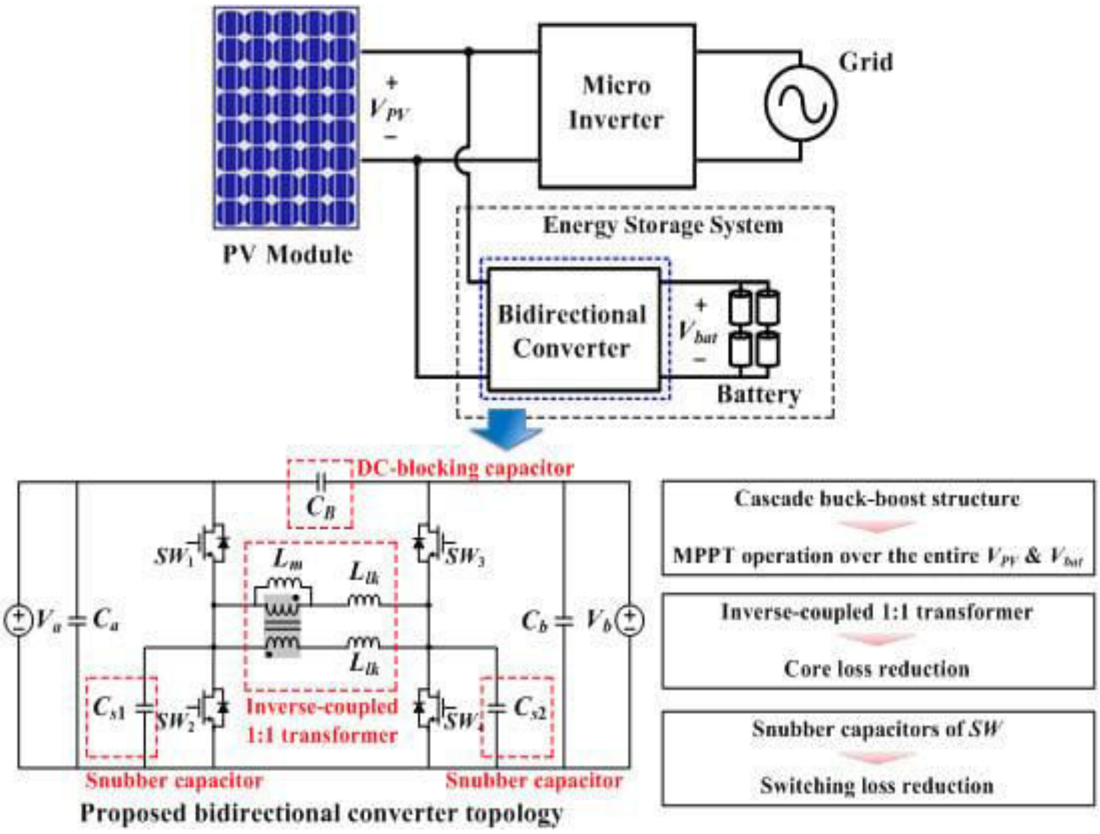

Fig 2: High-efficiency Bidirectional Buck–Boost Converter

For the three-switch multiport boost inverter configuration 3 (C3), as shown in Fig. 3(c), the two low-voltage DC ports are connected between the middle and bottom switches of the two legs separately, while AC port 1 is connected between the top and middle switches. To achieve boost and buck operation, separate two constant pulse-width signals are required. For inversion at the AC ports, unipolar sinusoidal reference modulation signals are necessary. Directly applying these two constant PWM signals and unipolar modulation signals results in over-modulation and crossover issues, making it difficult to achieve both boost, buck, and dual inversion operations efficiently.

Both the constant PWM and unipolar sinusoidal modulation signals are combined to enable simultaneous boost and inversion at the DC port and AC port 2. Additionally, an independent unipolar sinusoidal reference modulation signal is used for AC port 1. However, directly applying these modulation signals results in over-modulation and crossover issues, affecting the efficiency of boost and dual inversion operations. To overcome these challenges and ensure maximum AC voltage gain and DC-link utilization, the modulation signals are transformed into two hybrid categories: rectified inverse sinusoidal modulation signals (Vm1, Vm2) and phase-shifted rectified level-shifted sinusoidal modulation signals (Vm1, Vm2). These hybrid modulation signals, illustrated in 5(a), facilitate seamless integration of boost and dual-inversion operations.

IV. RESULT ANALYSIS

To further enhance the practical relevance of the topology and address fault scenarios, we have implemented overcurrent and overvoltage protection mechanisms within the hardware control logic using voltage and current sensors. If the measured switch voltage or current exceeds predefined reference values, the control system automatically disables the PWM pulses of the switches, preventing excessive stress on the components. Additionally, a fault indication is displayed on the monitor control screen for real-time diagnostics, facilitating quick intervention. Moreover, we have incorporated an isolator at the input source, serving as an additional layer of protection. If the current surpasses the isolator rated limit, it transitions into an open-circuit state, effectively disconnecting the source and preventing further damage. These protective mechanisms significantly enhance system reliability and operational

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safety, reinforcing the robustness of the proposed topology under dynamic conditions, including potential fault scenarios.

Based on the topology configurations (C1, C2, and C3), operating principles, modulation schemes, and experimental investigations, it is evident that the proposed single-stage three-switch-leg multi-port boost inverter topologies, combined with the novel modulation strategies, are highly versatile and well-suited for a wide range of applications. These include integrating renewable energy sources such as solar PV and fuel cells into AC and DC stand-alone or grid-connected systems (hybrid DC/AC microgrids), AC and DC electric vehicle (EV) charging systems, aircraft power distribution systems, and two-phase applications.

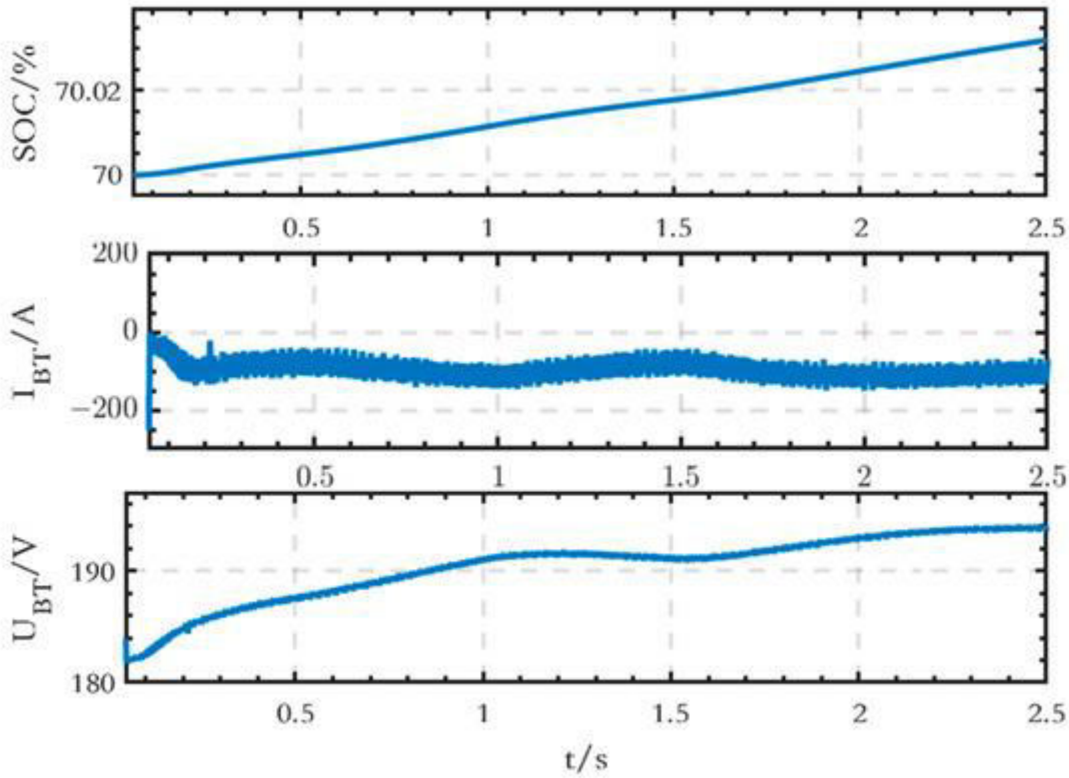

Fig 3: Design and Feasibility Verification of Novel AC/DC Hybrid Microgrid Structures

The results presented in Fig. 3 validate the effectiveness of the proposed hybrid control modulation scheme for C1 of the single-stage TSLMPBI, which provides significantly improved DC and AC voltage gains. This enhancement reduces the required DC-link voltage magnitude to achieve the desired AC output voltage levels at the AC ports, offering a distinct advantage over comparable topologies. Moreover, the proposed modulation scheme enables maximum power transfer to the AC ports by facilitating higher AC output voltage levels. Configuration C1 is particularly well-suited for integrating unidirectional low-voltage DC sources, such as solar PV systems and fuel cells, into DC and AC standalone or grid-connected systems using a single converter. Its capability to operate with different AC port frequencies, including high frequencies (e.g., 400 Hz), also makes it highly suitable for aircraft power systems and two-phase applications, owing to its ability to produce a leading phase angle between AC output voltages.

V. CONCLUSION

The effectiveness of the proposed topologies and hybrid modulation schemes was validated using a 500 W laboratory prototype. Experimental results demonstrate that the TSLMPBIs achieve up to 3.9 times boost, capability to step down DC voltage by 4.8 times, and AC voltage gains of 2.8 and 3.8 times at AC ports 1 and 2, respectively, relative to the low input source voltage. Additionally, DC bus voltage utilization was enhanced. The AC ports operated at variable voltages, frequencies, and phases, highlighting the flexibility of the TSLMPBI topologies. Furthermore, all

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configurations facilitated maximum power transfer to the AC ports. Overall, the proposed TSLMPBIs offer broad applicability, reduced cost, and a reduced switch count while delivering versatile multi-port functionality. These attributes establish the proposed topologies as a highly efficient, cost-effective, and flexible solution for advanced hybrid DC/AC microgrid systems, making them ideal for emerging applications such as renewable energy systems, electric vehicles, and modern power systems.

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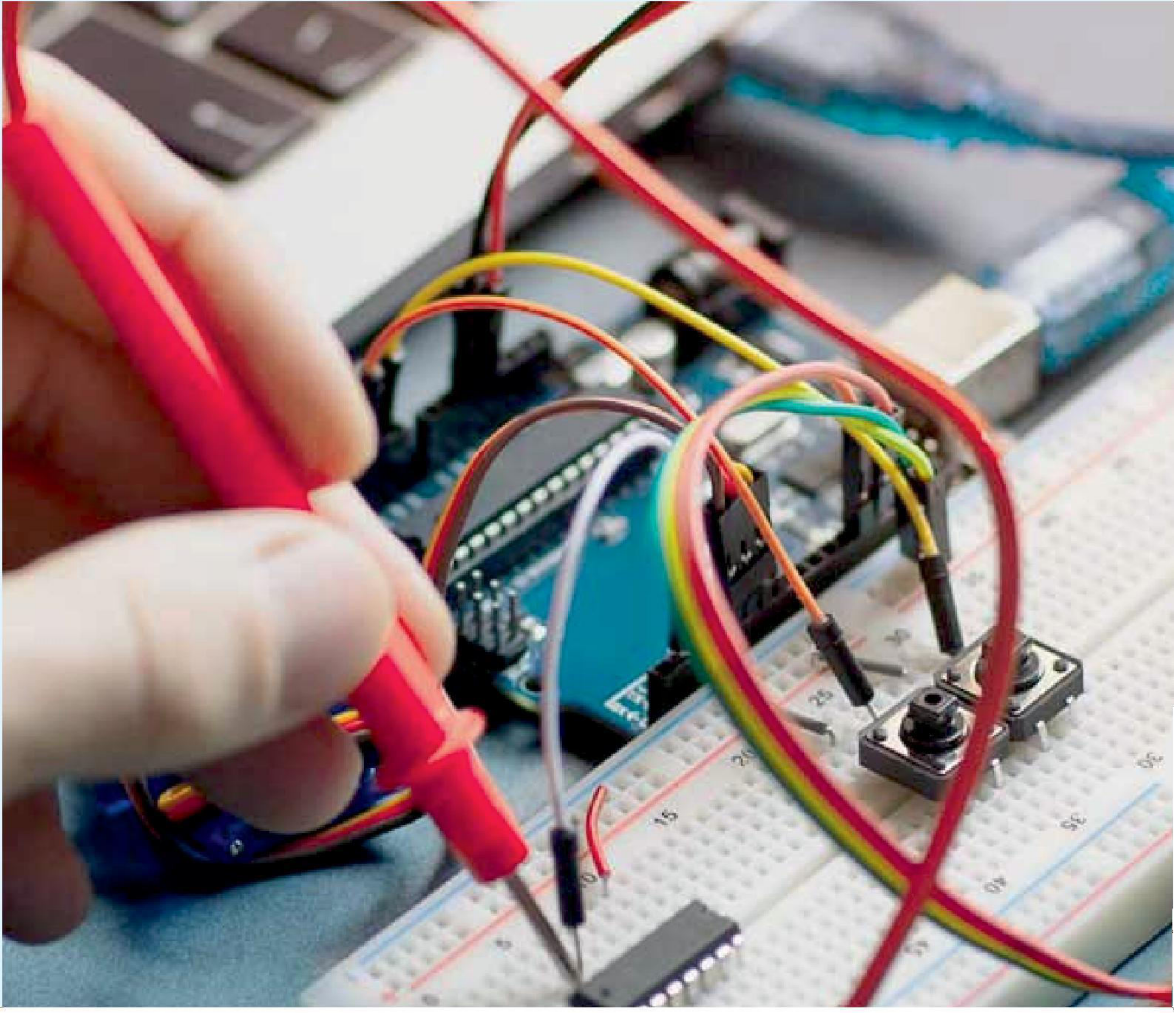

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