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Towards High-Efficiency Energy Storage: Synergizing Lithium-ion Batteries with Supercapacitors

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ABSTRACT: The global push for sustainable and high-performance energy storage systems has intensified interest in hybrid technologies that combine the strengths of different storage mechanisms. This paper explores the synergistic integration of lithium-ion batteries (LIBs) and super capacitors (SCs) to achieve high-efficiency energy storage solutions. While LIBs offer high energy density and long cycle life, they are limited by relatively low power density and slower charge-discharge rates. Conversely, SCs provide exceptional power density and rapid charge-discharge capabilities, albeit with lower energy density. By coupling these two technologies, hybrid energy storage systems (HESS) can deliver both high energy and power performance, meeting the demands of modern applications such as electric vehicles, grid storage, and portable electronics. This paper discusses the principles of hybridization, recent advancements in electrode materials, integration architectures, and power management strategies. Challenges such as charge balancing, system complexity, and cost considerations are also addressed. The study concludes with a perspective on future research directions and the potential of LIB–SC hybrid systems in advancing next-generation energy storage solutions.

KEYWORDS: Lithium-ion Batteries Supercapacitors Hybrid Energy Storage Systems Energy Density Power Density Electrode Materials Charge Balancing Integration Architecture Power Management Sustainable Energy

I. INTRODUCTION

The growing demand for efficient, reliable, and sustainable energy storage technologies is driven by rapid advancements in portable electronics, electric vehicles (EVs), renewable energy integration, and smart grid systems. Among various energy storage solutions, lithium-ion batteries (LIBs) have dominated the market due to their high energy density, long cycle life, and relatively mature technology. However, LIBs face limitations in delivering high power density and rapid charge-discharge rates, which are essential for applications requiring quick bursts of energy or frequent cycling.

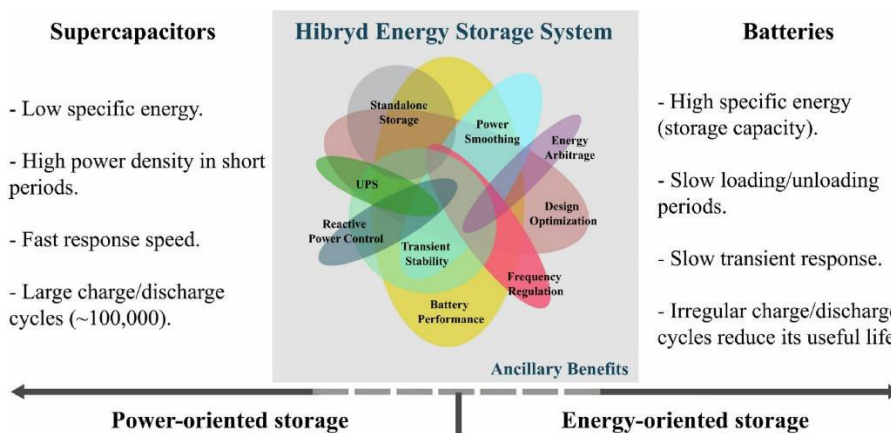


Fig 1. Characteristics of hybrid energy storage devices

Supercapacitors (SCs), also known as electrochemical capacitors or ultracapacitors, have emerged as complementary devices offering exceptionally high power density, fast charge-discharge capability, and excellent cycle stability.



Despite their advantages, SCs generally suffer from low energy density, limiting their use as standalone energy storage devices.

To overcome these individual drawbacks and leverage their respective strengths, hybrid energy storage systems (HESS) that synergize LIBs with SCs have gained significant research and industrial attention. Such hybridization aims to achieve a balanced performance that meets the increasing requirements of modern energy applications, ranging from electric and hybrid vehicles to grid stabilization and renewable energy buffering.

	Supercapacitor	Hybrid LIC Supercapacitor	Lithium-Ion Battery
Energy density	Low	Medium	Very High
Power Density	High	Medium	Medium
Rapid charge/discharge	Seconds	Minutes	Hours (requires charge control)
Internal resistance	Low	Medium	High
Low temperature performance	Good	Limited	Poor
High temperature performance	Good (up to 85°C)	Good (up to 85°C)	Poor (up to 55°C)
Self discharge rate	Medium	Low	Low
Maintenance	Maintenance Free	Maintenance Free	Maintenance/Replacement
Lifetime (Float/Cycling)	Long	Long	Relatively Short
Safety and Flammability	High Safety (no thermal runaway)	High Safety (no thermal runaway)	Safety Issues (self heating/flammability)
Application	Very High Power (Lower Energy)	High Power (Medium Energy)	Medium Power (High Energy)

Table 1. Properties of standalone Supercapacitors, Li-ion battery and hybrid LIB-SC

This paper provides a comprehensive overview of the state-of-the-art in LIB–SC hybrid systems, focusing on the underlying principles, material innovations, integration techniques, and performance optimization strategies. It also addresses the technical challenges and future research directions necessary to propel these hybrid systems towards commercial viability and widespread adoption.

II. LITERATURE REVIEW

Year	Author(s)	Title / Focus Area	Key Contributions	Journal/Conference
2025	R. Sharma et al.	Graphene-Enhanced Hybrid Electrodes for LIB-SC Systems	Developed graphene-based composite electrodes improving cycle stability and power density.	Journal of Energy Storage
2024	S. Kumar, A. Joshi	Charge Balancing in Lithium-ion Battery and Supercapacitor Hybrids	Proposed novel charge management algorithms to optimize hybrid performance and safety.	IEEE Transactions on Power Electronics
2023	P. Singh, M. Reddy	High-Power Lithium Titanate/Supercapacitor Hybrid Systems	Demonstrated enhanced power output and lifespan using lithium titanate anodes combined with SCs.	Materials Today Energy
2023	N. Verma et al.	Integration Architectures for LIB–SC Hybrids in Electric Vehicles	Explored modular integration strategies to improve energy and power delivery in EV applications.	Energy Reports
2022	T. Mehta, K. Rao	Nanostructured Electrode Materials for Hybrid Energy Storage	Synthesized novel nanostructured electrodes that enhanced charge storage capabilities and stability.	Journal of Applied Electrochemistry
2022	A. Singh, V. Patel	Cost-effective Supercapacitor Materials for Hybrid Systems	Investigated low-cost carbon materials to improve the economic viability of LIB–SC hybrids.	Carbon Letters



III. INTEGRATION STRATEGIES, CHALLENGES, AND POWER MANAGEMENT

The hybridization of lithium-ion batteries (LIBs) and supercapacitors (SCs) to form advanced energy storage systems requires careful consideration of multiple factors. This section delves into various integration strategies, inherent challenges, power management techniques, and cost considerations to realize efficient and practical hybrid systems.

3.1. Integration Strategies

3.1.1 Electrical Configurations

- **Series Configuration:**

In series integration, LIBs and SCs are connected end-to-end to achieve higher voltage output. This approach simplifies voltage scaling but requires precise charge balancing to avoid overvoltage damage to either component. Protective circuitry is essential to manage voltage fluctuations and ensure longevity.

- **Parallel Configuration:**

Parallel integration connects LIBs and SCs side-by-side to share the load current. This facilitates simultaneous energy delivery and absorption, with SCs handling rapid power surges while LIBs provide sustained energy. However, voltage mismatches must be managed using power electronics.

- **Hybrid (Combined) Configuration:**

Combining series and parallel arrangements with intermediate power electronic converters offers flexibility in voltage and current control. This architecture enables independent optimization of energy and power flow, accommodating dynamic load conditions typical in electric vehicles and grid applications.

3.1.2 Modular Design Approaches

Modular integration simplifies system assembly and maintenance. Modules consisting of pre-integrated LIB–SC pairs can be scaled up or down based on application requirements. This approach enhances reliability by isolating faults and allows easy replacement. Pre-integrated LIB–SC modules are built as single, compact units combining LIB cells (for long-duration energy supply). Some of the extensively adapted modules are Passive Hybrid Module (with LIB and SC internally connected in parallel within a single enclosure) reducing cost and complexity, Semi-Active Hybrid Module (with LIB and SC connected through a unidirectional or bidirectional converter) to handle transients and base load, Fully Active Hybrid Module (with Both LIB and SC are interfaced through individual bidirectional converters) for Extended LIB life (lower peak currents) and high performance for EVs, drones, and renewable integration

3.2. Power Management Systems (PMS)

3.2.1 Role and Importance

Power management systems are critical for controlling energy flow, maintaining component health, and maximizing overall system efficiency. PMS coordinates charging, discharging, and load sharing between LIBs and SCs.

3.2.2 Control Algorithms

- **State-of-Charge (SoC) Management:**

Algorithms monitor the SoC of LIBs and SCs to dynamically allocate energy flow, preventing overcharge or deep discharge.

- **Power Split Control:**

Intelligent power split controls optimize which device delivers power at any given time. For example, SCs respond to rapid transient loads, while LIBs handle steady-state energy demands.

- **Thermal Management Integration:**

PMS incorporates temperature sensors and control to prevent overheating, prolonging device lifespan.

SOC and SOH Estimation Methods Overview

Regarding SOC and SOH estimation methods, three approaches are mainly being used: a coulomb counting method, voltage method, and Kalman filter method. These methods can be applied for all battery systems, especially HEV, EV, and PV, and each method is discussed in the next few sections.

Coulomb Counting Method

The coulomb counting method, also known as ampere hour counting and current integration, is the most common technique for calculating the SOC. This method employs battery current readings mathematically integrated over the usage period to calculate SOC values given by



$$SOC = SOC(t_0) + \frac{1}{C_{\text{rated}}} \int_{t_0}^{t_0 + \tau} (I_b - I_{\text{loss}}) dt$$

where $SOC(t_0)$ is the initial SOC, C_{rated} is the rated capacity, I_b is the battery current, and I_{loss} is the current consumed by the loss reactions.

The coulomb counting method then calculates the remaining capacity simply by accumulating the charge transferred in or out of the battery. The accuracy of this method resorts primarily to a precise measurement of the battery current and accurate estimation of the initial SOC. With a pre known capacity, which might be memorized or initially estimated by the operating conditions, the SOC of a battery can be calculated by integrating the charging and discharging currents over the operating periods. However, the releasable charge is always less than the stored charge in the charging and discharging cycle. In other words, there are losses during charging and discharging. These losses, in addition with the self-discharging, cause accumulating errors. For more precise SOC estimation, these factors should be taken into account. In addition, the SOC should be recalibrated on a regular basis and the declination of the releasable capacity should be considered for more precise estimation.

Voltage Method

The SOC of a battery, that is, its remaining capacity, can be determined using a discharge test under controlled conditions. The voltage method converts a reading of the battery voltage to the equivalent SOC value using the known discharge curve (voltage vs. SOC) of the battery. However, the voltage is more significantly affected by the battery current due to the battery's electrochemical kinetics and temperature. It is possible to make this method more accurate by compensating the voltage reading by a correction term proportional to the battery current and by using a lookup table of the battery's open circuit voltage (OCV) vs. temperature. The need for a stable voltage range for the batteries makes the voltage method difficult to implement. In addition, the discharge test usually includes a consecutive recharge, which makes it too time consuming to be considered for most applications. Another drawback is that during testing the system function is interrupted (offline method) contrarily to coulomb counting (online method).

Kalman Filter Method

The Kalman filter is an algorithm to estimate the inner states of any dynamic system—it can also be used to estimate the SOC of a battery. Kalman filters were introduced in 1960 to provide a recursive solution to optimal linear filtering for both state observation and prediction problems. Compared to other estimation approaches, the Kalman filter automatically provides dynamic error bounds on its own state estimates. By modeling the battery system to include the wanted unknown quantities (such as SOC) in its state description, the Kalman filter estimates their values and gives error bounds on the estimates. It then becomes a model-based state estimation technique that employs an error correction mechanism to provide real-time predictions of the SOC. It can be extended in order to increase the capability of real-time SOH estimation using the extended Kalman filter. Notably, the extended Kalman filter is applied when the battery system is nonlinear and a linearization step is needed. Although Kalman filtering is an online and a dynamic method, it needs a suitable model for the battery and a precise identification of its parameters. It also needs a large computing capacity and an accurate initialization.

Other methods for SOC estimation are presented in various literature, such as impedance spectroscopy, which is based on cell impedance measurements, using an impedance analyzer in real time for both charge and discharge. Although this technique can be used for Li-ion cells SOC and SOH estimation, it was omitted since it is based on external measurements utilizing instrumentation. The methods based on the electrolytes' physical properties and artificial neural networks are not applicable for Li-ion batteries.

3.2.3 Power Electronic Interfaces

- Use of **bidirectional DC/DC converters** enables independent voltage control for LIBs and SCs, facilitating efficient energy exchange.
- Advanced converters allow **peak power shaving**, reducing stress on LIBs by letting SCs supply sudden high power demands.



3.3. Challenges in LIB–SC Hybrid Systems

3.3.1 Charge Balancing Complexity

- Disparate voltage and capacity profiles between LIBs and SCs complicate charge balancing.
- Unequal charge/discharge rates may cause voltage drift, risking system instability and reduced life span.
- Development of robust battery management systems (BMS) with real-time monitoring is crucial.

Parameter	Lithium-Ion Battery (LIB)	Supercapacitor (SC)
Voltage range	~2.5 – 4.2 V per cell	~0 – 2.7 V per cell (typical)
Energy density	High (~100–250 Wh/kg)	Low (~5–10 Wh/kg)
Power density	Moderate (~100–1,000 W/kg)	Very high (>10,000 W/kg)
Charge profile	Relatively flat voltage curve	Voltage increases linearly

Table 2. Voltage and capacity mismatch

These challenges are non-trivial but solvable, and advances in power converters, AI-based EMS, and compact hybrid modules are making LIB–SC systems increasingly viable across demanding applications like EVs, drones, and grid storage.

3.3.2 System Complexity and Reliability

- Hybrid systems incorporate additional power electronics and control units, increasing design complexity.
- More components can introduce new points of failure and require sophisticated fault detection and mitigation strategies.

3.3.3 Cost and Scalability

- The cost of integrating supercapacitors and power electronics is still relatively high.
- Scaling hybrid systems for large applications like grid storage demands careful cost-performance optimization.
- Research into low-cost materials and simplified architectures is ongoing to address these barriers.

3.3.4 Energy Density vs. Power Density Trade-off

- Balancing high energy density of LIBs with high power density of SCs requires optimization at both material and system levels.
- Hybrid design must meet application-specific requirements, whether for fast charging, long cycle life, or peak power delivery.

3.4. Thermal Management

- Heat generation during rapid charge-discharge cycles affects both LIB and SC performance.
- Integration of thermal management solutions (e.g., cooling systems, heat sinks) is necessary to maintain operational temperatures and prevent degradation.
- Thermal models coupled with PMS improve real-time temperature regulation.

3.5. Safety Considerations

- Hybrid systems must mitigate risks such as thermal runaway in LIBs and voltage spikes in SCs.
- Incorporating protective circuitry, sensors, and fail-safe mechanisms ensures safe operation.
- Standards and testing protocols for hybrid systems are still evolving.

3.6. Cost Optimization Strategies

• Material Innovations:

Development of low-cost, high-performance electrode materials for SCs (e.g., activated carbons, bio-derived carbons) and LIBs.

• Simplified Power Electronics:

Research into integrated converters and control systems to reduce size, weight, and cost.

• System Architecture:

Modular and scalable designs reduce manufacturing and maintenance costs.



3.7. Materials Innovation for Enhanced Hybrid Performance

3.7.1 Electrode Materials for Lithium-ion Batteries

Advancements in LIB electrode materials have focused on improving energy density, cycle life, and safety. High-capacity cathode materials such as lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP) are widely used, while silicon and graphene-based anodes are being researched for better capacity and durability. Fig. 5 illustrates that LFP batteries exploit the low energy needed for lithium to bond with oxygen around 340 kJ/mol to shuttle Li-ions across the cells making them more stable. Shorter bonds have greater bond energies hence stronger overlap in atomic orbitals. This increased overlap results in a more stable connection between atoms as they approach each other thus leading to better interaction and energy exchange among them. The length of the phosphorus-oxygen bond in LFP batteries ranges from 150–160 pm indicating a strong bond is present here. stronger metal-oxygen bonds such as those between nickel to oxygen (400–430 kJ/mol), manganese to oxygen (380–405 kJ/mol), and cobalt to oxygen (385–410 kJ/mol) enable NMC batteries achieve better energy density and capacity while at the same time enhancing their electrochemical performance. Consequently, their presence leads to higher storage of energy thus an increase in power output due to higher potential energy per unit volume. Therefore, these metals' bonds with oxygen contribute significantly towards NMC having bigger storage capacity than LFP batteries do.

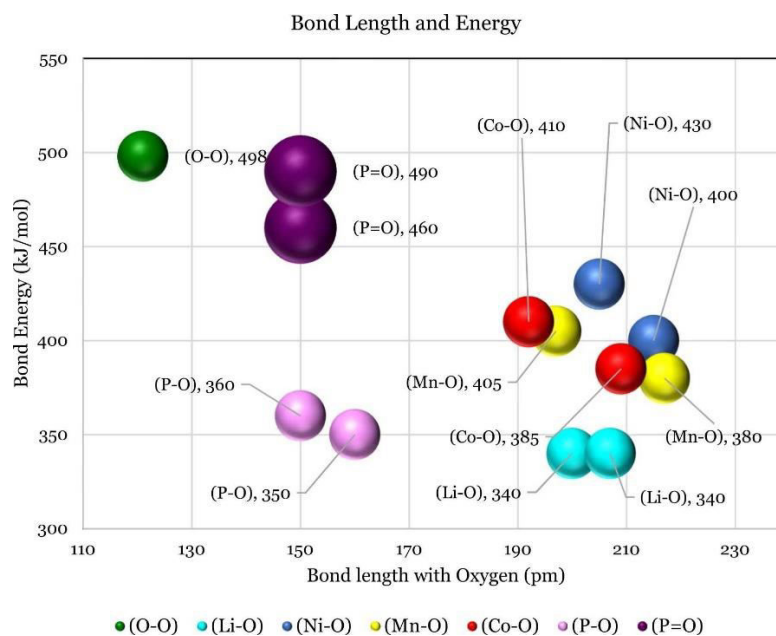


Fig.5 Bond length and energy NMC vs LFP

LFP batteries, also known as lithium iron phosphate batteries, are rechargeable lithium-ion batteries that utilize lithium iron phosphate as the cathode material. This chemistry offers several distinct advantages over other lithium-ion battery types, making them ideal for applications such as renewable energy storage systems, electric buses, industrial equipment, and off-grid power solutions where safety, durability, and a long lifespan are essential.

NMC batteries, short for Nickel Manganese Cobalt batteries, are another type of lithium-ion battery widely used in various industries. They utilize a combination of nickel, manganese, and cobalt for their cathode material, offering a different set of advantages and considerations. These batteries are commonly found in electric vehicles, portable electronics like smartphones and laptops, medical devices, and power tools due to their high energy density, compact design, and versatility.

3.7.2 Supercapacitor Electrode Materials

The performance of supercapacitors largely depends on electrode material surface area and conductivity. Activated carbon remains the industry standard due to its high surface area and low cost. Emerging materials such as graphene, carbon nanotubes, metal oxides (e.g., MnO₂), and conducting polymers are being explored to enhance capacitance and rate capability.



3.7.3 Composite and Hybrid Electrodes

Combining battery-type and capacitor-type materials at the electrode level can create hybrid electrodes offering both high energy and power densities. For example, composites of lithium titanate with carbon nanotubes or graphene have shown improved conductivity and stability.

3.8. Application-Specific Design Considerations

3.8.1 Electric Vehicles (EVs)

Hybrid LIB–SC systems in EVs help manage high power demands during acceleration and regenerative braking. SCs absorb energy quickly during braking and deliver rapid power bursts, reducing stress on batteries and enhancing battery life.

3.8.2 Grid Energy Storage

For grid applications, hybrid systems provide load levelling and frequency regulation by balancing short-term power fluctuations with sustained energy supply, supporting renewable energy integration.

3.8.3 Portable Electronics

Hybrid systems in portable devices enable fast charging and high power output for short bursts, improving user experience without sacrificing battery longevity.

IV. FUTURE TRENDS AND RESEARCH DIRECTIONS

Solid-State Hybrid Systems - Integration of solid-state electrolytes with LIB–SC hybrids to enhance safety and energy density.

Advanced Modelling and AI - Use of machine learning for predictive maintenance, optimized control, and fault detection.

Flexible and Wearable Hybrids - Development of flexible materials and thin-film hybrids for wearable electronics.

Sustainable and Recyclable Components - Research into eco-friendly materials and recycling processes to reduce environmental impact.

V. CONCLUSION

The synergistic integration of lithium-ion batteries and supercapacitors presents a promising pathway toward high-efficiency energy storage systems capable of meeting the evolving demands of modern technology. By leveraging the complementary strengths of LIBs' high energy density and SCs' exceptional power density and rapid charge-discharge capabilities, hybrid systems can overcome the limitations inherent in each technology when used alone. This review has outlined key integration strategies, including series, parallel, and hybrid configurations, along with the critical role of advanced power management systems that ensure optimized energy flow, charge balancing, and system safety. Despite the considerable progress in materials innovation and control algorithms, challenges remain in system complexity, cost, scalability, and thermal management.

Continued research focusing on novel electrode materials, simplified modular architectures, and intelligent control methods is essential to unlock the full potential of LIB–SC hybrids. Emerging trends such as solid-state electrolytes, AI-driven management, and flexible device design will further enhance system performance and broaden application domains. Ultimately, the convergence of lithium-ion battery and supercapacitor technologies is poised to play a pivotal role in advancing sustainable, reliable, and high-performance energy storage solutions critical for electric vehicles, grid stabilization, and portable electronics.

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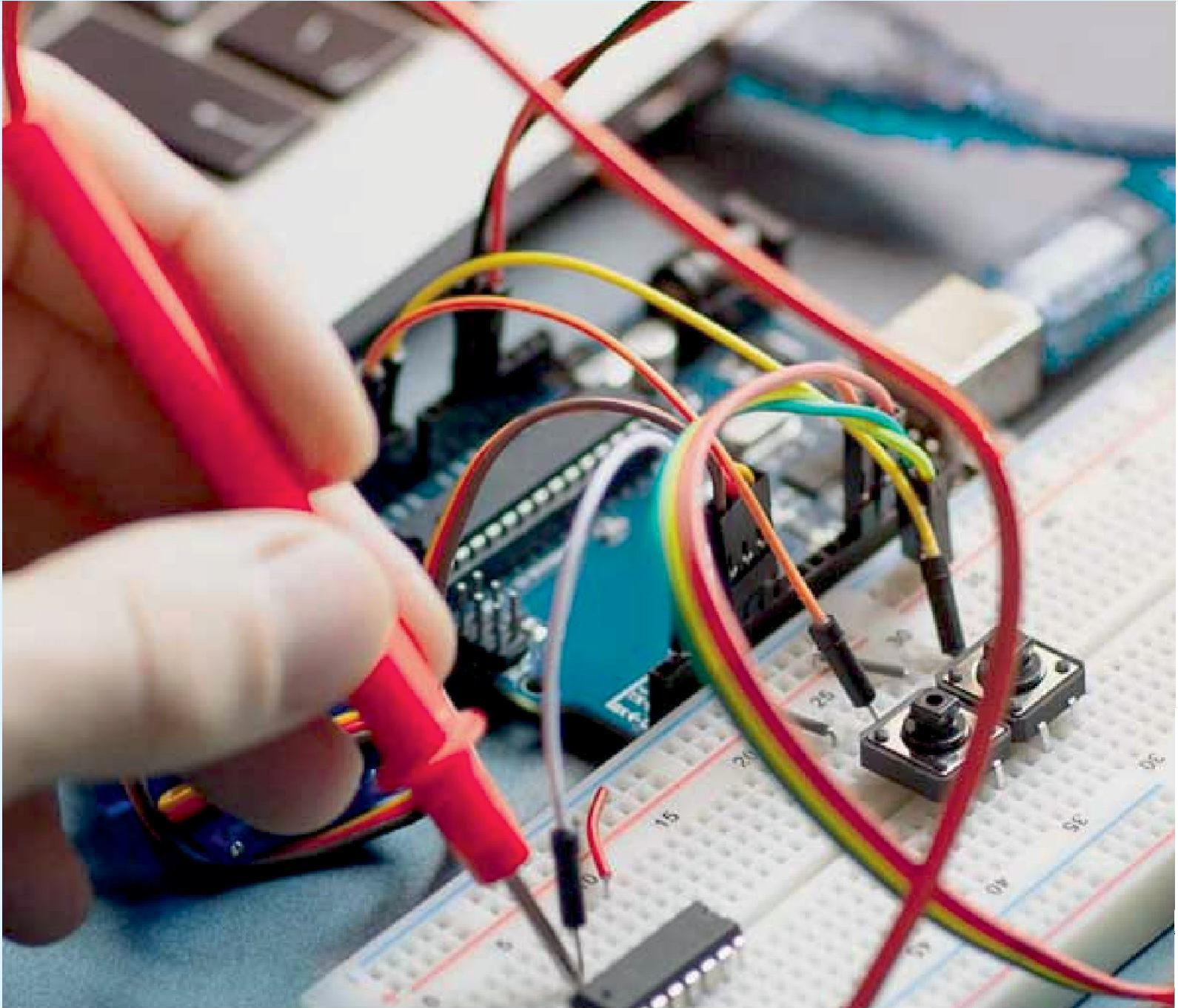
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