A Review of the Application of Electromagnetic Induction in Energy Systems

Mengqi Yu

Electrical Engineering, Lappeenranta–Lahti University of Technology (LUT), Lappeenranta 53850, Finland  
  
Mengqi.Yu@student.lut.fi

**Abstract.** Electromagnetic induction, originally discovered by Faraday, remains a foundational phenomenon in modern electrical and energy systems. It serves as the basis for a wide range of advanced applications, including wireless power transfer, smart grid infrastructure, and renewable energy technologies. This review systematically presents the fundamental principles governing electromagnetic induction, with particular emphasis on Faraday’s law, the concept of inductance, and high-frequency induction mechanisms. Current applications of induction technologies are examined in detail, focusing on wireless charging systems for electric vehicles, biomedical implantable devices, and consumer electronics. Furthermore, the role of inductive components within smart grids is explored, highlighting developments such as inductively powered sensors and solid-state transformers. In the context of renewable energy, electromagnetic induction is critically involved in the optimization of photovoltaic systems and the implementation of inductive energy storage technologies, notably superconducting magnetic energy storage (SMES). The review also identifies key directions for future research. Priorities include enhancing transmission efficiency, developing cost-effective and high-performance materials, addressing electromagnetic compatibility challenges, and integrating inductive methods with emerging energy storage systems. Continued innovation in electromagnetic induction is expected to drive significant advancements in sustainable energy development and the evolution of smart infrastructures.

# introduction

Discovered by Michael Faraday in 1831, electromagnetic induction is the phenomenon in which a changing magnetic field induces an electric potential (EMF) or voltage in a nearby conductor. Faraday's Law of Electromagnetic Induction quantified this effect and laid the foundation for modern electrical engineering, making technologies such as generators, transformers and induction motors possible.

Until today, electromagnetic induction remains the core principle of smart grids, new energy systems and wireless charging. Many devices, from mobile phones to electric cars, rely on it for contactless charging. Electromagnetic induction has also been used in the medical field, allowing implantable devices to be powered wirelessly, improving safety and longevity. This technology has become an important underpinning of smart infrastructure and sustainable energy development.

This review outlines the basic concepts of electromagnetic induction and its role in modern applications. It begins with the fundamental principles that form the foundation of advanced technologies: Faraday’s Law, inductance, and high-frequency induction techniques. This paper examines the applications of electromagnetic induction across several key domains. It first investigates wireless power transfer technologies, including their use in electric vehicle charging, biomedical implants, and the charging of electronic devices. It then explores applications in smart grid systems, such as wireless sensing and inductive power conversion. In the field of renewable energy, the paper highlights the role of electromagnetic induction in optimizing photovoltaic systems and enabling inductive energy storage. Finally, it outlines future research directions and technical challenges, including enhancing transmission efficiency, developing low-cost and high-performance materials, ensuring electromagnetic compatibility, and integrating inductive techniques with emerging energy storage technologies.

# Applications in Wireless Power Transfer

Wireless Power Transfer (WPT) is the transfer of electrical energy from a power source to a load without the need for a physical connector, usually through an electromagnetic field. Inductive coupling based on Faraday's law is the most widely used method for near-field wireless power transmission. In an inductive WPT, a primary coil driven by an AC power source generates a time-varying magnetic field, which induces a current in the approaching secondary coil. WPT has gained momentum due to its convenience and new capabilities, and many practical applications already exist–for example, smartphone charging pads, implantable biomedical devices, electric vehicle chargers, and various consumer and industrial electronics [1].

## Inductive Charging for Electric Vehicles

One of the most influential modern applications of electromagnetic induction is wireless charging for electric vehicles (EVs). This technology uses a ground-based charging pad to generate an alternating magnetic field, which induces a current in a receiver coil located at the bottom of the vehicle—enabling high-power charging (3–11 kW) without physical plugs, even with an air gap of 10–25 centimeters. It offers users a convenient charging experience and supports dynamic charging and automated energy replenishment for autonomous vehicles, making it a key application of wireless power transfer.

Modern EV inductive charging systems utilize resonant magnetic coupling and advanced power electronics to maximize efficiency. With carefully designed coils—typically circular or double-D shapes with ferrite backings to guide magnetic flux—and impedance compensation networks, these systems can maintain high efficiency even across air gaps. In fact, recent industry developments show that the overall efficiency of wireless EV charging can reach 90% or higher, comparable to wired charging. For example, one industry provider reports their wireless chargers operate at roughly 90–93% efficiency—on par with typical plug-in chargers in the 92–95% range [2]. This level of performance represents a significant improvement over early experiments with wireless charging for electric vehicles, thanks to enhanced coil coupling (using larger coil areas, ferrite magnetic cores, and alignment mechanisms) and optimized operating frequencies.

This technology is rapidly maturing. Some automakers already offer factory-installed wireless charging options—for example, BMW introduced an inductive charging pad for one of its plug-in hybrid models—and pilot projects are underway to wirelessly charge buses at bus stops. Ongoing research includes improving coil designs for higher efficiency with larger gaps or misalignment, embedding charging systems into roads for dynamic highway charging, and enabling bidirectional wireless charging. In summary, inductive charging for electric vehicles is a prime example of Faraday’s law applied to sustainable transportation, illustrating a future of seamless and ubiquitous charging. Indeed, analysts conclude that WPT for EVs will play an essential role in advancing EV adoption in coming years [3].

## Wireless Powering of Implantable Medical Devices

Electromagnetic induction enables implantable medical devices such as pacemakers, cochlear implants, and brain-computer interfaces to be wirelessly powered through inductive coupling, eliminating the surgical risks and costs associated with frequent battery replacements. This technology not only extends the lifespan of the devices but also improves patient safety and quality of life.

The inductive link for medical implants typically consists of an external transmitting coil and a much smaller receiving coil embedded within the implant. The system operates in the near-field (non-radiative) region, with frequencies typically ranging from several hundred kilohertz to a few megahertz. At these frequencies, human tissue is largely transparent to magnetic fields. Inductive coupling is favored for implants because it is a straightforward and safe power transmission method for biomedical applications, achieving relatively high power transfer efficiency with lower tissue absorption than far-field radio-wave methods [4]. In other words, magnetically coupled coils can transfer energy while minimizing tissue heating, unlike high-frequency electromagnetic waves, which deposit more energy within the body. This is a key safety advantage and a primary reason why inductive coupling remains the dominant method for powering implantable devices. Indeed, inductive coupling is commonly and efficiently used to transfer power (and often data) to implantable medical instruments, including pacemakers, implantable defibrillators, neurostimulators, and cochlear implants [5].

Designing the inductive link for implantable devices presents unique challenges. One major issue is the mismatch in size and coupling: the implant’s receiving coil must be very small to fit inside the body, while the external transmitting coil can be much larger. The coupling coefficient k between a very small and a large coil is typically low, especially when separated by even a small tissue gap. To address this, designers use resonance techniques—both coils are tuned with capacitors to form a resonant pair, significantly boosting voltage and power transfer at the operating frequency. Even so, delivering sufficient power to deeper implants remains difficult; most commercial systems target devices located subcutaneously or only a few centimeters beneath the skin. Some innovative research is exploring the use of external coil arrays or higher operating frequencies to improve coupling with implants located deeper inside the body. For example, Lyu et al. (2020) demonstrated a microstimulator implant powered inductively at 198 MHz, achieving a tiny implant size (~5 mm × 7.5 mm) and a 14 cm transmission distance in an animal model – though such high-frequency approaches are uncommon due to concerns about tissue absorption at tens of MHz. In general, hundreds of kHz to a few MHz is the frequency range used for most implants, as a compromise that allows reasonable coil dimensions, adequate coupling, and acceptable tissue penetration [6].

Numerous real-world applications have demonstrated the success of inductive power transfer for medical devices. According to a recent review, contemporary inductive WPT designs for implants can deliver on the order of a few milliwatts up to a few hundred milliwatts to implants, at efficiencies that, while modest, are sufficient for low-power electronics [4]. Future advancements aim to further expand the range and efficiency of inductive links while ensuring patient safety.

## Charging Consumer Electronics

Inductive wireless charging has also advanced in both industrial and consumer electronics. In consumer products, the most common example is wireless charging pads for smartphones and other devices. The Qi standard, developed by the Wireless Power Consortium, has been widely adopted for phones, earbuds, smartwatches, electric toothbrushes, and other small gadgets. These chargers typically operate around 100–205 kHz, with tightly coupled coils—devices must be placed directly on the charging pad, usually only a few millimeters apart.

While the power levels are moderate (about 5–15 W for smartphones, and higher for some tablets or laptops), the convenience is significant: users simply place their device on the pad, without the hassle of plugging in a cable. Some pads use multiple coils or resonance techniques to charge multiple devices at once.

Thanks to the short distance and strong coupling, Qi chargers are highly efficient—typically achieving 70–85% end-to-end efficiency. This high efficiency is a direct result of strong mutual inductance over a short range. Inductive charging has become so common that many users now see it as an everyday necessity. The widespread adoption of wireless charging for personal devices underscores the reliability and practicality of near-field inductive technology.

# Applications in Smart Grid Systems

The “smart grid” refers to an enhanced electrical grid that leverages sensing, communication, and control technologies to improve efficiency, reliability, and the integration of distributed energy resources. Electromagnetic induction plays a vital role in the smart grid—ranging from the fundamental operation of components like transformers and inductors to innovative applications such as wireless sensors and power flow control devices.

## Inductively Powered Wireless Sensor Networks

The smart grid requires comprehensive monitoring of parameters such as current, voltage, and temperature, with many sensors deployed in hard-to-reach locations where wiring or frequent battery replacement is impractical. Inductively powered wireless sensor nodes harvest electromagnetic energy from the grid itself, enabling self-sustained power and wireless communication—an important application of electromagnetic induction in energy harvesting.

One approach is to use the grid’s own current to generate power for the sensors. A current transformer clamped onto a live power line produces an induced current proportional to the line current (based on the principle of mutual induction). By tapping a small portion of this induced current, the sensor node can continuously power itself without significantly affecting the line. A research prototype of such an inductive harvester (a coil on a steel core around a conductor) was able to scavenge on the order of 0.9 V (rms) from a 155 A AC line, which was sufficient (after rectification and energy storage) to run a low-power sensor and radio transmitter [7].

In many power grid applications, electromagnetic induction is also the basis of the sensors themselves. Traditional current sensors (current transformers, CTs) and voltage transformers (PTs), used for metering and protection, are inductive devices. They reduce line values to measurable levels. Although new optical and electronic sensors are emerging, inductive CTs are still widely used because of their simplicity and reliability. In smart grids, there is a trend toward making each sensor energy-autonomous. By combining inductive energy harvesters with low-power sensors and wireless transmitters (using protocols such as Zigbee or LoRa), a large number of sensors can be deployed for grid monitoring without increasing maintenance needs. A comprehensive review of energy harvesting for wireless sensor networks noted that harvesting from power line magnetic fields is among the most feasible methods for grid sensors, given the high currents available and the maturity of inductive pick-up techniques [7].

## Inductive Power Converters and Solid-State Transformers

Power electronic interfaces in smart grids often rely on inductive components. In this context, inductive power converters refer to devices that use transformers or inductors as key elements to change voltage levels, control power flow, or provide electrical isolation between parts of the grid. A typical example is the solid-state transformer (SST), sometimes called a “smart transformer.” Unlike traditional power transformers, which consist of two inductively coupled coils on a shared magnetic core and operate at 50/60 Hz—SSTs use high-power electronic switches and high-frequency transformers for voltage conversion. They also offer additional functions such as DC output, fast voltage regulation, and communication or control capabilities.

Traditional inductive devices still play a vital role in the grid. Line-frequency transformers, commonly found in substations, provide large voltage step-down and isolation through electromagnetic induction. In distribution networks, step voltage regulators are essentially autotransformers with on-load tap changers. These changers adjust the inductive coupling between windings to regulate voltage dynamically. In smart grids, such devices may include sensors or actuators, but their core operation is still based on electromagnetic induction.

Inductors are also widely used to control power flow in power systems. By inserting inductors (to limit current) or capacitors (to boost current) in transmission lines, it is possible to regulate power. FACTS controllers, such as Thyristor-Controlled Reactors (TCR), use phase control to adjust inductance and thereby manage reactive power and voltage. While power electronics enhance speed and controllability, the core principle still relies on using inductance or capacitance to influence current. Even modern FACTS devices, like STATCOMs and SVCs, typically include inductors as key reactive components or interfaces.

In conclusion, inductive power converters in smart grids include SSTs, traditional voltage regulators, and FACTS elements. All of them use electromagnetic induction to transfer energy or regulate current and voltage between circuits. Modern designs combine power electronics and control technologies, making them more suitable for the flexible and intelligent needs of smart grids. This reflects a fusion of traditional inductive methods with advanced technology.

# Applications in Renewable Energy Systems

Renewable energy generation (such as wind and solar power) and their associated energy storage systems have become central to modern electricity supply. Electromagnetic induction plays a key role in these technologies, both in the primary energy conversion process and in supporting systems that enhance efficiency and stability. In this section, we will explore three areas: magnetically coupled wind turbines, electromagnetic considerations in solar photovoltaic (PV) systems, and inductive components in renewable energy storage, particularly Superconducting Magnetic Energy Storage (SMES).

## Electromagnetic Optimization in Solar Photovoltaic (PV) Systems

Solar photovoltaic (PV) systems use the photovoltaic effect in semiconductor cells to directly convert sunlight into direct current (DC) electricity. In the process of integrating PV power into the grid or improving system performance, inductors play key roles in two main areas. First, they are used in inverters and converters that connect PV power to the grid. Second, they help manage electromagnetic interference (EMI) within the PV system and ensure safe operation. In microinverters (which serve individual solar panels), the operating frequency of the high-frequency transformer can range from several tens of kilohertz to over 100 kHz. Using these HF transformers gives isolation that reduces leakage currents and improves power quality by preventing unwanted paths for current [8]. In transformerless PV inverters, leakage current and electromagnetic interference (EMI) can occur due to the parasitic capacitance between the PV array and the ground. As a result, many PV inverters still include either line-frequency or high-frequency transformers, or they use complex filtering networks to reduce these effects.

In PV power conversion, boost inductors or coils are essential components. Many common PV inverters use a DC-DC boost stage to increase the PV voltage before converting it to AC. The boost process relies on the inductor to store and release energy. The voltage is increased by controlling the charging and discharging of the inductor through switching devices.

Although the electricity generation in solar cells is a quantum or photoelectric process, the balance-of-system components involve important principles of electromagnetic induction. Well-designed inductors can improve efficiency (by reducing energy losses as heat), enhance power quality (by producing a cleaner sine wave with lower total harmonic distortion), and increase safety (by providing isolation and reducing leakage current). As one energy review noted, ongoing research in materials and engineering for magnetic components aims to address efficiency and loss challenges, potentially leading to more efficient and sustainable energy solutions (Pasupuleti, 2025). In fact, the continuous improvement of magnetic materials and circuit topologies in PV inverters—though gradual—is a crucial part of making solar energy a reliable pillar of our power grid.

## Inductive Elements in Renewable Energy Storage (SMES and Hybrids)

Energy storage is essential for balancing the variability of renewable energy. Among various storage technologies, Superconducting Magnetic Energy Storage (SMES) systems store energy in the magnetic field of a coil made from superconducting wire. When a direct current flows through the superconducting coil, it can circulate without resistance loss—because superconductors have nearly zero resistance below their critical temperature. As a result, energy is stored in the magnetic field. Since there is no resistive dissipation, the energy can be stored indefinitely in the form of circulating current and later released through power converters.

Studies have shown that SMES offers very quick response (on the order of milliseconds), high power density, and high round-trip efficiency for short bursts [9]. These characteristics make SMES systems well-suited for applications such as smoothing short-term fluctuations in wind or solar power output, as well as providing stability services like voltage support or frequency regulation. For instance, simulation studies of hybrid solar-wind power systems have demonstrated that adding an SMES can significantly reduce output fluctuations and improve reliability compared to having no SMES [9]. The main limitation of SMES is that, unless scaled to a very large size, it cannot sustain long-duration discharge. Therefore, hybrid systems often combine SMES with other storage technologies that have higher energy capacity. A common setup is a battery-SMES hybrid system. In this configuration, the battery handles energy needs lasting from several minutes to a few hours, while the SMES manages short-term transients lasting seconds or less. This protects the battery from high-frequency cycling and improves the overall stability and lifespan of the system. Such combinations have been shown to improve microgrid stability during events like sudden PV output drops or wind gusts by quickly injecting or absorbing power [10]. Essentially, SMES smooths out fast fluctuations, while batteries meet sustained energy demands. The control system assigns the high-frequency components of power variation to the SMES and the low-frequency components to the battery.

In addition to SMES, inductors are essential components in power electronics used to connect energy storage systems to the grid. For example, battery storage systems use bidirectional inverters or converters with inductors, or high-frequency transformers, to achieve current control and electrical isolation. However, when it comes to inductive energy storage, SMES is the main technology. Another example of inductive coupling for storage is wireless charging of mobile storage units—such as in vehicle-to-grid (V2G) applications—though this falls under the category of wireless power transfer.

SMES is essentially a large inductor, storing energy in a magnetic field with very low loss. It is a practical application of electromagnetic induction for energy storage. The existence of SMES highlights the versatility of inductors—they can function not only as circuit components but, in a superconducting state, also serve as energy storage devices. In the future, combining inductive storage (like SMES) with other emerging storage technologies and power electronic controls may play a key role in stabilizing grids with a very high share of renewable energy.

# Future Research Directions and Challenges

With the wide use of electromagnetic induction technology, improving efficiency, reducing cost, and optimizing compatibility have become key concerns for researchers. Future research will focus on several important areas:

## Improving Wireless Power Transfer Efficiency

Currently, transformers and near-field wireless chargers can reach over 90% efficiency. However, when the distance increases or there is a position offset, efficiency drops sharply. To maintain high efficiency under non-ideal conditions, researchers are exploring resonance and adaptive control technologies. By adjusting frequency and matching impedance dynamically, systems can respond to changes in coupling conditions and stay in optimal working states. Relay coil arrays and metamaterial-based magnetic field guidance are also under study. These methods aim to extend the effective transmission distance.

High-frequency power electronic devices have also become an important direction for improving wireless charging efficiency. Using advanced semiconductors like GaN and SiC, together with specialized inverter topologies such as Class-E inverters and zero-voltage switching circuits, can effectively reduce switching losses. However, operating in the MHz range brings challenges related to electromagnetic interference (EMI), which still need to be addressed. Future research will focus on innovative coil designs. One example is phased array coils, which can dynamically adjust magnetic field focus to improve transmission efficiency.

## Developing Low-Cost, High-Performance Materials

Materials are a key foundation of inductive technology. Currently, high-performance magnetic materials such as ferrites, amorphous alloys, and rare-earth permanent magnets are expensive and have certain performance limits. Future material research aims to develop cheaper magnetic materials with better performance. For example, nanocrystalline and amorphous alloy cores show lower losses and higher saturation flux at high frequencies. These materials are suitable replacements for traditional ferrite cores. At the same time, emerging polymer-based magnetic composites allow the use of 3D printing to create complex core structures. This opens new paths to reduce cost and improve design flexibility.

## Electromagnetic Compatibility (EMC) and Safety

The wide use of inductive technology has led to electromagnetic interference (EMI) issues, especially in wireless power transfer. Future research needs to focus on magnetic shielding, filtering techniques, and spectrum control to ensure that inductive systems do not affect nearby devices. Standardized frequency allocation and intelligent communication coordination can also support efficient coexistence of different systems. Health and safety are key concerns in the EMC field. Inductive devices must follow magnetic field exposure limits. Advanced detection methods, such as foreign object detection, are needed to prevent safety risks from accidental contact. In addition, high-power inductive systems connected to the grid must meet harmonic and power quality standards. Active power electronic compensation strategies are a promising future research direction.

## Integration with Emerging Energy Storage Technologies and Smart Grids

Future power grids will integrate distributed energy storage, smart loads, and dynamic charging systems. Wireless bidirectional charging technologies, such as vehicle-to-grid (V2G), are typical examples of this trend. More forward-looking research includes combining electromagnetic induction with high-performance storage technologies like superconducting magnetic energy storage (SMES). In the field of miniaturized devices, inductive energy harvesting combined with micro-energy storage can enable continuous, self-powered sensing systems. These have wide applications in industrial and environmental monitoring.

Overall, the future development of inductive technologies will focus on improving wireless energy transfer efficiency, developing cost-effective and high-performance magnetic materials, ensuring electromagnetic compatibility and safety, and integrating with advanced energy storage and smart grid technologies. These directions not only improve technical performance but also support the creation of a more efficient, safe, and sustainable smart power infrastructure.

# Conclusion

Electromagnetic induction has made great progress since Faraday’s simple experiments with coils and magnets. Today, its principles empower many advanced technologies in the growing fields of renewable, smart, and wireless energy systems.

The ongoing research and future developments aim to overcome current limitations—improving efficiency, reducing dependence on expensive materials, lowering interference, and ensuring seamless integration. If these efforts succeed, electromagnetic induction will continue to be a foundation of innovation in electrical engineering.

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