Advances in medical power electronics: applications and challenges

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ABSTRACT

Power electronics plays a crucial role in modern medical applications by providing efficient power management, conversion, and regulation across a wide range of devices. In high-power systems, such as medical imaging equipment, power electronics ensure precise control, stable operation, and optimal performance, which are essential for accurate diagnostic imaging. On the other hand, in low-power devices such as wearable health monitors and implantable medical devices, power electronics focus on enhancing energy efficiency and miniaturization. This is vital for extending battery life, reducing the need for frequent recharging or replacement, and improving patient comfort and mobility. This review examines the role of power electronics in diverse medical applications, highlighting its importance in enabling stable performance in critical life-support systems, therapeutic devices, and portable health monitors. Key technologies and power management integrated circuits are explored for their contribution to improving the efficiency, reliability, and longevity of medical devices. The review also addresses significant challenges, including miniaturization, energy efficiency, and regulatory compliance. Future trends such as the development of advanced semiconductor materials, innovations in energy harvesting techniques, and wireless power transfer technologies are also discussed. These advancements are expected to revolutionize the field, driving the next generation of medical devices and shaping the future of healthcare technology.

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1. INTRODUCTION

Power electronics is a critical field within electrical engineering that focuses on converting, controlling, and conditioning electrical power. It plays a vital role in managing power distribution, optimizing energy efficiency, and ensuring a stable power supply across various applications. In healthcare, the importance of power electronics has grown significantly, driven by the rising need for portable, efficient, and reliable medical devices. These devices range from large-scale systems like magnetic resonance imaging (MRI) and computed tomography (CT) scanners to smaller, low-power devices like wearable health monitors and implantable pacemakers. Power electronics ensures that these devices operate smoothly, with precise control over power levels to enhance performance and safety. Moreover, advancements in power electronics are enabling energy-efficient designs, extending battery life in portable devices, and minimizing heat generation, which is crucial for patient comfort and safety in wearable and implantable technologies. The ongoing integration of power electronics into healthcare technologies is shaping the future of medical devices, promoting innovation in diagnostics and treatment solutions [1]-[3]. Figure 1 shows the block diagram of power electronics.

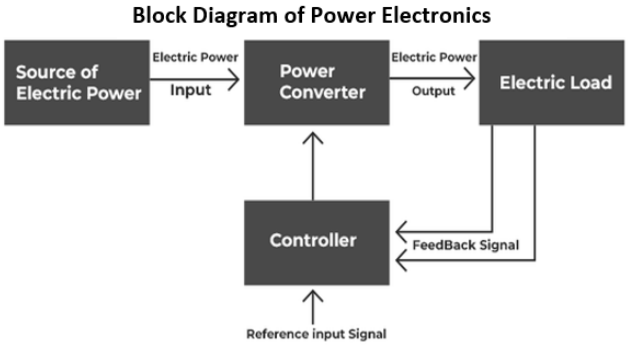

Figure 1. Block diagram of power electronics

In the medical field, power electronics enables a variety of critical functions, such as ensuring stable power supplies for sensitive imaging systems, enhancing battery life in portable and wearable devices, and facilitating wireless power transfer in implantable medical devices. The importance of power electronics in healthcare stems from the need for high precision, energy efficiency, and reliability in medical applications, where even minor malfunctions can have serious consequences for patient safety [4]-[6]. Medical devices have stringent requirements for power management, making power electronics a vital component of their design. These devices range from low-power wearables, such as fitness trackers and glucose monitors, to high-power equipment. The ability to provide stable, reliable, and efficient power is critical for these systems to operate correctly [5], [6].

In addition to efficiency, power electronics in medical devices also need to address size constraints. Miniaturization of power electronics components has become essential, particularly for portable and implantable medical devices. This has led to advancements in semiconductor materials, power management circuits, and battery technology, which allow for smaller, more efficient, and longer-lasting medical devices [7], [8].

Direct current (DC) converters are widely used in medical devices to manage power at different voltage levels. These converters are essential for battery-powered devices, such as pacemakers and wearable monitors, where power management is crucial for extending battery life and ensuring consistent performance. High-efficiency DC-DC converters allow for optimal power distribution without excessive heat generation or power loss [9], [10]. In low-power medical devices, such as hearing aids and glucose monitors, buck converters (which step down voltage) and boost converters (which step up voltage) are used to ensure that the devices receive the correct voltage levels for their operation [11]. These converters are designed to minimize power loss and heat generation, improving the overall efficiency of the device [12].

Power management integrated circuits (PMICs) are essential for the precise control of power in medical devices. These integrated circuits regulate the distribution of power, ensuring that various components receive the correct voltage and current levels. In implantable devices and portable medical equipment, PMICs are used to optimize power usage, reduce noise, and improve overall efficiency. PMICs also play a crucial role in battery management, ensuring that the device’s battery is charged and discharged efficiently [13], [14]. This helps extend battery life and reduce the need for frequent recharging, which is particularly important in implantable devices where battery replacement requires medical applications [15].

Energy harvesting techniques are becoming increasingly relevant for medical devices, particularly wearables and implantable. Technologies such as thermoelectric energy harvesting and piezoelectric materials enable devices to generate power from body heat or movement. Advanced battery technologies, including lithium-ion and solid-state batteries, are used in conjunction with power electronics to provide longer-lasting power sources for medical applications [16], [17]. In wearable devices, energy harvesting can be used to supplement battery power, reducing the need for frequent recharging. Power electronics ensure that the harvested energy is efficiently converted and stored, enabling the device to operate for longer periods without external power sources [18].

Wireless power transfer (WPT) is an emerging area in medical applications, enabling devices to be powered or charged without the need for invasive procedures. Power electronics ensures the efficient transmission of power through electromagnetic fields, which can be used to recharge batteries in implantable devices or power external medical equipment [19]. WPT reduces the risk of infection and discomfort associated with traditional charging or battery replacement methods. WPT is particularly useful in implantable devices, where battery replacement surgeries can be avoided. Power electronics is used to manage the wireless transfer of power, ensuring that it is delivered efficiently and safely to the device [20].

This comprehensive review explores the current state of power electronics in the medical field, detailing its critical role in various medical applications, the key technologies involved, design challenges, and the latest innovations. Additionally, future trends in power electronics, such as miniaturization, energy harvesting, and advanced semiconductor materials, are discussed in the context of their potential impact on medical device development. The review concludes with an outlook on how power electronics will continue to shape the future of healthcare technology.

2. MEDICAL APPLICATIONS UTILIZING POWER ELECTRONICS

Implantable medical devices (IMDs), such as pacemakers, defibrillators, cochlear implants, and neurostimulators, require highly reliable and efficient power electronics to ensure continuous operation over extended periods (6). These devices are often powered by batteries that must last several years without replacement, necessitating the use of low-power DC-DC converters and advanced power management techniques to optimize energy consumption [8]. A study on far-field radio-frequency powering for IMDs demonstrated that an access point should be equipped with a minimum transmit power of 0.4 W to maintain an outage probability for energy harvesting below 10-1. The research also established that the optimal distance between the access point and the body surface should not exceed 0.5 m for effective power transfer [21]. Figure 2 demonstrates a system model illustrating the wireless power transfer during the downlink phase and information transmission during the uplink phase.

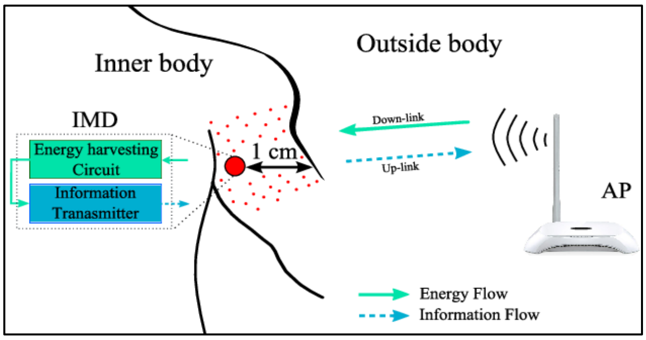

Figure 2. System model illustrating the wireless power transfer during the down-link phase and information transmission during the up-link phase

Another innovative approach explored the use of microbial fuel cells (MFCs) placed in the human large intestine to power IMDs. This study achieved stable power generation with an open circuit voltage of 552.2 mV and a maximum power density of 73.3 mW/m^2. The research suggested that MFCs located in the large intestine could generate 7-10 mW of power, which is sufficient for many IMDs [22].

In the realm of WPT systems, a single-loop WPT system with an adjustable compensation network was proposed. This system demonstrated the ability to provide a constant voltage supply without the need for a regulating circuit in the receiver. The prototype showed effective performance across various load resistances (100 Ω to 500 Ω) and coupling coefficients, maintaining a constant voltage of 3.4 V [23]. A study presented a microcontroller unit (MCU) with remotely programmable features, optimized for IMDs using techniques such as clock gating, power gating, and instruction set improvement. This MCU was fabricated with a scale of 79.1 K equivalent gates in standard 0.18 µm complementary metal-oxide-semiconductor (CMOS) technology, demonstrating progress in energy-efficient and flexible IMD designs [24].

Wearable health devices, such as heart rate monitors, blood pressure sensors, and glucose monitors, have become increasingly popular in healthcare. These devices require power electronics to manage power consumption and ensure that they can operate for long periods without frequent recharging [25]. PMICs are used to regulate power consumption and optimize energy efficiency in these devices [26]. Energy harvesting technologies, such as thermoelectric generators (TEGs) and piezoelectric materials, are also being integrated into wearables to capture energy from body heat or movement. Power electronics plays a crucial role in managing and converting this harvested energy into usable power for the device, reducing the need for external power sources or frequent charging [25].

A study focused on RF energy harvesting demonstrated a rectifier circuit capable of powering wearable medical devices with high efficiency. The researchers achieved a maximum RF-DC conversion efficiency of 84.63% at 10 dBm input power, with a simulated DC output voltage of 3.563 V, sufficient to energize low-power medical devices [27]. In another study, researchers developed a wearable smart bracelet using flexible photovoltaic panels as an energy source. The solar energy harvesting subsystem achieved up to 90% energy conversion efficiency, enabling a self-sustainable wireless wearable system. In-field experiments showed that a single flexible solar panel could harvest up to 16 mW of power outdoors and 0.21 mW indoors, demonstrating the potential for long-term patient monitoring in healthcare [28].

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Robotic surgical systems are increasingly being used in minimally invasive surgeries, where precision and control are paramount. These systems rely on advanced power electronics to regulate the power supplied to motors, actuators, and sensors, enabling precise movements and control during surgery [30]. Power electronics also help minimize energy consumption, ensuring that the robotic systems can operate for extended periods without overheating or power failure [31].

In the field of urology, robotic technology has shown promising results in overcoming difficulties associated with pure laparoscopy. Robot-assisted surgery has been successfully applied to treat genitourinary diseases such as bladder cancer and ureteropelvic junction obstruction, building on the success of robot-assisted prostatectomy and partial nephrectomy [32]. A study in head and neck surgery evaluated the feasibility and efficacy of robot-assisted surgery via a transoral approach. The research, involving 141 patients, reported successful completion of all surgeries with a mean robotic operative time of 69.3 minutes and an average blood loss of 29.6 ml. Patients expressed satisfaction with both cosmetic results and treatment outcomes, demonstrating the potential of robotic systems in this complex surgical area [33].

The study found that robotic systems reduced surgery time (MD -86.2447 minutes), lowered mortality rates (OR 0.3652), and improved neurological outcomes as measured by modified Rankin Scale and Glasgow Outcome Scale scores. Additionally, complications such as rebleeding and infections were significantly reduced [34]. Research on haptic feedback in robotic surgery has shown promising results. A study incorporating force feedback capabilities into robotic surgical systems demonstrated that the addition of force feedback leads to better tissue characterization compared to using only visual feedback. Furthermore, the integration of force feedback in a teleoperation platform resulted in lower peak forces during surgical knot-tying tasks, potentially improving surgical precision and safety [35].

3. CHALLENGES IN POWER ELECTRONICS FOR MEDICAL APPLICATIONS

Medical devices must meet stringent safety and reliability standards, as malfunctions can have serious consequences. Power electronics must ensure stable operation, even in the face of electrical disturbances or component failures. Robust design and testing procedures are required to meet regulatory requirements and ensure patient safety. In addition, medical devices often operate in critical environments, where the consequences of failure are life-threatening, such as in life-support systems and implantable medical devices. The design of power electronics systems for these applications must be fault-tolerant, ensuring continuous operation despite potential power interruptions or component malfunctions [36].

The reliability of power electronics in medical devices is critical, particularly in life-support systems and implantable devices, where failure can be life-threatening. Power electronics components must be designed to withstand harsh conditions, such as exposure to body fluids, high levels of electromagnetic interference, and temperature variations that may be encountered inside or outside the human body. Durability and long-term stability are key concerns, as any breakdown in power delivery could compromise the performance of a medical device and jeopardize patient safety [37]. As medical devices become smaller and more portable, the challenge of miniaturizing power electronics components becomes more significant. In wearable devices, such as fitness trackers or health monitors, and implantable devices, like pacemakers and neural stimulators, compact designs are essential to fit within the constrained spaces available. Power electronics must provide high power density while ensuring minimal heat generation to prevent discomfort or tissue damage. Thermal management and efficient packaging solutions are critical in preventing overheating in these miniature systems. The continued trend toward miniaturization has driven research into integrating components, such as compact voltage regulators and energy-efficient power converters, while maintaining the same or even greater levels of performance [38], [39].

Recent advancements in semiconductor materials and manufacturing techniques have enabled the development of smaller, more efficient power electronics components. These innovations, such as wide-bandgap semiconductor materials, have allowed for higher power density and more efficient power conversion in smaller packages. Gallium nitride (GaN) and silicon carbide (SiC) devices, for instance, are playing an increasingly important role in improving energy efficiency and power density in modern medical devices. However, further research is needed to continue improving the power density and efficiency of these components for use in next-generation medical devices, particularly in the realm of ultra-low-power implantable systems where power budgets are extremely constrained [40]. Energy efficiency is a critical concern in medical devices, particularly those powered by batteries or energy-harvesting systems. For wearable and implantable devices, reducing energy consumption ensures that devices can operate for extended periods without frequent recharging or battery replacement, which is essential for patient comfort and compliance. Battery longevity is especially crucial in implantable devices, where replacing the battery may require surgery. Power electronics must optimize energy usage, ensuring that devices can operate for long periods without frequent recharging or battery replacement. For high-power devices, such as imaging equipment, energy efficiency reduces operational costs and environmental impact [41].

Power electronics plays a key role in improving the energy efficiency of medical devices by optimizing power conversion, reducing energy loss, and ensuring that devices operate within their optimal power ranges. Advances in power semiconductor technology, such as the use of GaN and SiC devices, have further improved the energy efficiency of power electronics in medical applications. These materials offer lower switching losses, higher efficiency, and better thermal performance, making them well-suited for use in energy-critical medical devices. By reducing energy consumption, these innovations contribute to the development of sustainable, longer-lasting medical devices [42]. Medical devices must operate in environments with other electronic equipment, where electromagnetic interference (EMI) and noise can affect performance. Power electronics systems are responsible for managing power delivery, but they can also be sources of EMI, particularly in high-frequency switching circuits. Minimizing EMI is critical in ensuring that medical devices can function properly without being affected by or causing interference to other devices in proximity. For instance, in a hospital setting, medical equipment such as diagnostic imaging machines, monitors, and therapeutic devices must operate reliably without causing interference with each other [43].

To address this challenge, power electronics in medical devices must include shielding, filtering, and grounding techniques to reduce EMI. Proper filtering circuits and shielding materials are integrated to block or divert EMI, ensuring that power electronics can operate in electromagnetically noisy environments without disruptions. Additionally, power electronics components must be designed to operate at high frequencies without generating excessive noise, which could interfere with the operation of other medical equipment. By adopting advanced design techniques and incorporating noise-reduction strategies, power electronics systems in medical devices can operate safely and efficiently in complex healthcare environments [44]. The continuous evolution of power electronics in medical applications, driven by advancements in semiconductor technologies, miniaturization techniques, and energy efficiency improvements, is essential to meet the demands of modern healthcare [45]-[50]. As the industry progresses, innovative power electronics solutions will play a crucial role in enabling the development of more advanced, reliable, and efficient medical devices capable of improving patient care and enhancing medical outcomes [51]-[53].

4. CONCLUSION

Power electronics is a critical technology in the design and operation of medical devices, providing the energy efficiency, reliability, and safety required for a wide range of applications. From high-power imaging systems to low-power wearable and implantable devices, power electronics enable the efficient conversion, control, and distribution of electrical power. As medical devices continue to evolve, the demand for smaller, more efficient, and biocompatible power solutions will increase. Innovations in semiconductor materials, energy-harvesting techniques, and wireless power transfer will drive the future of power electronics in medical applications, enabling the development of more advanced, reliable, and patient-friendly devices. With continued research and development, power electronics will play a central role in shaping the future of healthcare technology, improving patient care, and enhancing the capabilities of medical devices.

The future trends in medical technology are heavily influenced by advancements in several key areas. The development of flexible and stretchable power electronics opens new possibilities for wearable medical devices. These systems can conform to the body's shape, providing more comfortable and seamless monitoring solutions. Flexible power electronics are also more durable, withstanding the stresses of daily use while maintaining high performance. Advances in WPT technologies are expected to have a significant impact on the development of implantable and wearable medical devices. WPT allows devices to be powered or charged without the need for invasive procedures, improving patient comfort and reducing the risk of infection.

The integration of artificial intelligence (AI) into power electronics systems is expected to revolutionize the design and operation of medical devices. AI-driven power management systems can optimize energy usage, predict power needs, and reduce energy consumption in real time. This enables medical devices to operate more efficiently, extending battery life and improving overall performance. In addition to optimizing power management, AI can also be used to predict device failures and alert healthcare providers before a malfunction occurs. This predictive maintenance approach improves the reliability of medical devices and reduces the risk of unexpected downtime. Biocompatible power sources are particularly important for next-generation implantable devices, such as neural interfaces and bioelectronic medicine systems, where long-term reliability and safety are paramount. The development of biocompatible materials and energy-harvesting systems is expected to drive the growth of implantable medical devices in the coming years.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that supports the findings of this study are available from the corresponding author, [HAO], upon reasonable request.

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