Advanced Power Converters in Robotics

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The effectiveness and performance of the robot's manipulative actions in any field of operation primarily depend on the dynamic response of its internal drive system. Power converters play a pivotal role in robotics by facilitating efficient energy conversion and management.

Keywords: robotics ; power converters ; energy management

1. Introduction

Industrial robots have a wide range of applications across various industries, including tasks like handling, painting, assembly, welding and more [1][2][3]. In fields like autonomous vehicles, machine-learning algorithms process sensor data to make real-time decisions, enabling vehicles to navigate and respond intelligently to complex environments [4][5][6]. In healthcare, robots equipped with AI can assist in surgeries, diagnose illnesses and even provide emotional support to patients [7][8][9]. Manufacturing processes are streamlined through AI-driven robotics that optimize production lines and adapt to changing demands [10][11].

The integration of AI and machine learning with robotics also enhance the development of human–robot collaboration. Robots can understand and adapt to human behavior, making them safer and more intuitive to work alongside. The effectiveness and performance of the robot's manipulative actions in any field of operation primarily depend on the dynamic response of its internal drive system [12][13]. This internal drive system has several impacts on the environment, depending on its design, efficiency and energy source. This concept encompasses the idea of robots being able to adapt, improve and learn from their interactions with their environment, tasks and humans.The control and conversion of electrical energy is responsible for highly efficient robotic systems such as when a robot performs a mix of high-energy and low-energy tasks; learning-based control can allocate energy resources dynamically [14][15][16]. It can optimize power distribution to different actuators based on the priority of tasks. They aim to optimize the efficiency of energy transfer from the power source to the actuators. This is particularly important in robotics, where energy efficiency translates to longer battery life, reduced heat generation and overall better performance [17][18].

2. Advanced Power Converters in Robotics

Power converters play a pivotal role in robotics by facilitating efficient energy conversion and management [16][19]. In this section, the significance of power converters in robotics is discussed, as well as the various types utilized, recent technological advancements and case studies, highlighting their influence on robotic performance and energy efficiency. **Figure 1** illustrates the schematic representation of the robotic system's partitioning, shedding light on the essential components that collectively enable the robot's operation.

2.1. Role of Power Converters in Robotics

In the dynamic landscape of robotics, where energy-efficient operation is predominant, power converters serve as the bridge between energy sources and the electrical demands of robotic subsystems [14][20]. The role of power converters encompasses several key aspects:

- **Voltage Regulation:** Robotic systems incorporate components with diverse voltage requirements. Power converters provide efficient voltage regulation, ensuring that sensors, microcontrollers and other components receive the appropriate voltage levels. This not only prevents potential damage due to overvoltage but also maximizes the efficiency of these components [19][21].

- **Current Management:** Motors and actuators, crucial for robotic motion and manipulation, often require varying current levels [22]. Power converters enable precise current control, allowing dynamic adjustment to match the specific demands of each task. This adaptability results in optimized motor performance and enhanced control accuracy [23].

- **Waveform Shaping:** Certain robotic components require specific waveform characteristics, such as sinusoidal signals for AC motors. Power converters facilitate waveform shaping, converting DC power to AC with the desired frequency and amplitude, thereby enabling precise control over motor behavior [24][25].

- **Energy Efficiency:** By minimizing energy losses during conversion and distribution, power converters contribute significantly to overall energy efficiency in robotic systems. Efficient power conversion reduces wasted energy as heat, leading to prolonged operational times and reduced battery replacements [14][19].

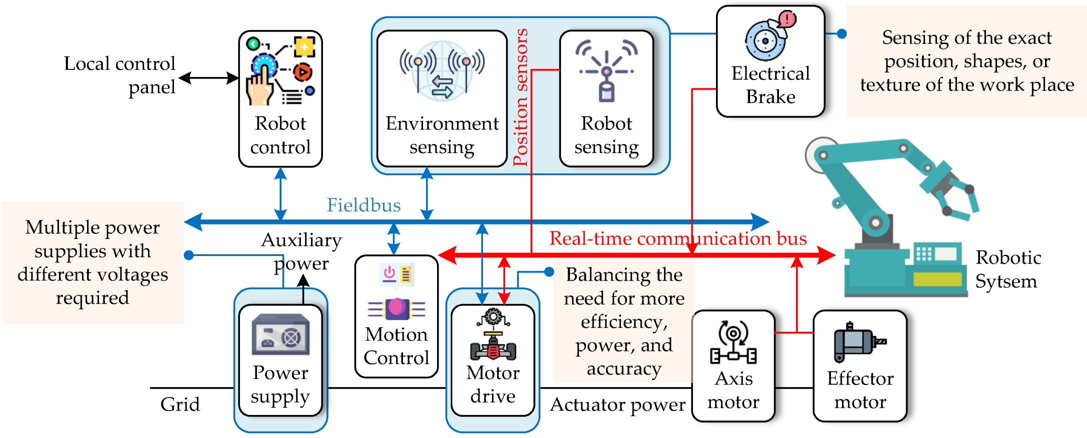

Figure 1. Schematic Representation of Robotic System Partitioning, highlighting the integration of Power Supplies, Converters, Control Box and Sensing Systems for the Robot's Operation.

2.2. Types of Power Converters in Robotics

The complex landscape of robotic applications necessitates a spectrum of power-converter types tailored to specific demands. **Figure 2** presents an overview of the power-converter technologies that find applications across various robotic systems.

2.2.1. DC–DC Converters

DC–DC converters are pivotal in robotics, providing voltage step-up or step-down capabilities. For instance, in battery-powered robots, where the available voltage decreases as the battery discharges, DC–DC converters maintain stable voltage levels for critical components. Additionally, as robots integrate sensors and actuators with distinct voltage requirements, these converters ensure compatibility across the system [26].

2.2.2. DC–AC Converters

In robotics, DC–AC converters or inverters play a central role in converting DC power from batteries to AC power for motor-driven systems [27]. Advanced inverter technologies, including advanced modulation schemes like sinusoidal pulse width modulation (SPWM), enable precise control over AC motor characteristics, such as torque, speed and position. This level of control enhances robotic locomotion, manipulation and even aerial operations [28].

2.2.3. AC–DC Converters

AC–DC converters or rectifiers are essential for robotic systems that require power input from alternating current (AC) sources [29]. These converters not only rectify AC power to DC for internal use but also allow robots to draw power directly from AC grids. Charging stations for electric robots, as well as industrial robots operating in environments with readily available AC power, benefit from AC–DC converters.

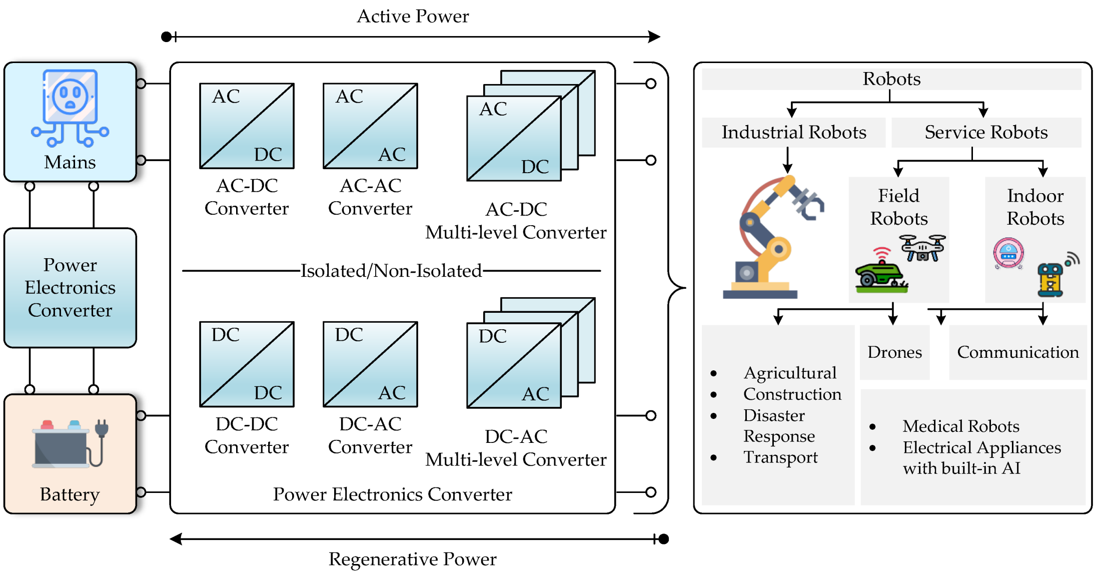

Figure 2. Power Converters for Diverse Robotic Applications.

2.2.4. Resonant Converters

Resonant converters utilize resonant components to achieve efficient power conversion with reduced switching losses. This feature makes them valuable for wireless power-transfer applications within robotics, enabling energy delivery without physical connections [30]. Resonant converters are employed in scenarios like charging robotic devices over short distances or even wirelessly powering sensors in remote locations [31][32].

2.2.5. Multi-Level Converters

Robotic systems often demand power converters that can handle high voltages while minimizing harmonic distortion. Multi-level converters achieve this by generating stepped voltage waveforms, reducing stress on components and improving overall system efficiency [33][34]. Applications include high-power robotic arms, where precise motion control requires efficient and high-voltage power conversion.

2.2.6. Soft-Switching Converters

Soft-switching converters focus on reducing switching losses during power conversion. These converters utilize techniques like Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) to minimize stress on semiconductor devices, leading to improved efficiency and reduced electromagnetic interference (EMI) [35]. In robotics, soft-switching converters find use in high-frequency motor drives and precision robotics that demand minimal energy loss and EMI [36].

2.2.7. Matrix Converters

Matrix converters perform direct AC–AC conversion without intermediate DC links [37]. This feature offers advantages in terms of efficiency, size and reduced components. In robotics, matrix converters can be applied to variable-speed motor drives and actuators [38], facilitating fine-tuned control and efficient power management.

2.2.8. Dual Active Bridge Converters

Dual Active Bridge (DAB) converters provide bidirectional AC–DC conversion, enabling power flow in both directions. This characteristic suits applications where energy regeneration and grid connection are important, such as grid-tied robotics or robots operating in dynamic environments where power needs fluctuate [39].

By understanding and harnessing the capabilities of these advanced power converters, robotics can achieve higher levels of performance, efficiency and adaptability across a wide range of applications. **Table 1** provides a comprehensive overview of the key advancements in power-converter technologies for robotics, highlighting the benefits they offer and the specific applications where they find utility. These advancements represent critical milestones in the evolution of robotic systems, enabling enhanced performance, efficiency and adaptability.

Table 1. Key Advancements in Power-Converter Technologies for Robotics, along with their Benefits and Applications.

Power Converter	Key Features	Voltage Regulation Range	Efficiency Range	Switching Frequency	Robotics Applications
Buck Converter [40]	**Step-down voltage conversion**	**Narrow to Moderate**	**High**	**Medium to High**	**Battery-powered robots, sensor nodes**
Boost Converter [41]	**Step-up voltage conversion**	**Moderate**	**High**	**Medium to High**	**Energy harvesting, charging mobile robots**
Buck-Boost Converter [42]	**Bidirectional voltage conversion**	**Wide**	**High**	**Medium to High**	**Battery management, variable power demands**
Resonant Converter [31][32]	**Zero-voltage switching, reduced EMI**	**Wide**	**Moderate to High**	**Medium to High**	**Wireless power transfer, contactless charging**
Multi-level Converter [33][34]	**Reduced harmonics, high voltage capability**	**Wide**	**High**	**Medium to High**	**High-power robotic arms, electric vehicles**
Matrix Converter [37][38]	**Bi-directional AC–AC conversion**	**Wide**	**High**	**Medium to High**	**Variable-speed motor drives, robotic actuators**
Soft-Switching Converters [35][36]	**Minimal switching losses**	**Moderate to Wide**	**High**	**High**	**High-frequency motor drives, precision robotics**
Dual Active Bridge Converter [39]	**Bidirectional AC–DC conversion**	**Moderate**	**High**	**Medium to High**	**Grid-tied robotics, energy-efficient actuators**

2.3. Advancements in Power-Converter Technologies for Robotics

Robotic systems are witnessing transformative impacts due to advancements in power-converter technologies. **Table 2** highlights several significant advancements in power-converter technologies for robotics. These advancements are tailored to address the unique challenges and opportunities in robotics.

2.3.1. Integration of Wide-Bandgap Semiconductors

Wide-bandgap materials, notably silicon carbide (SiC) and gallium nitride (GaN), have revolutionized power-converter design. The unique material properties of SiC and GaN enable higher operating temperatures, reduced conduction and switching losses and faster switching speeds [43][44]. In robotics, this translates to increased power-converter efficiency, reduced cooling requirements and improved power density. These benefits are particularly relevant for robots operating in extreme environments, such as industrial automation, space exploration and search-and-rescue missions [45][46].

2.3.2. Enhanced High-Frequency Operation

Robotics often demands compactness and agility. Advancements in high-frequency operation have enabled power converters to operate at frequencies beyond conventional limits [47]. Higher switching frequencies allow for the miniaturization of passive components like inductors and capacitors, resulting in more compact converter designs. This is pivotal in creating lightweight robots that exhibit improved agility, responsiveness and energy efficiency [48][49].

Table 2. Advancements in Power-Converter Technologies for Robotics.

Advancement	Description	Benefits	Applications
GaN Transistors [50][51]	**High-efficiency, fast-switching transistors enabling compact power converters.**	**Reduced power losses, smaller form factors, improved thermal management.**	**Industrial robots, drones, electric vehicles.**
SiC Devices [52]	**High-temperature, high-power devices for efficient and reliable converters.**	**Higher power handling, reduced cooling requirements, better performance in harsh environments.**	**Electric propulsion, extreme environment robotics.**
Digital Power Management [53][54]	**Real-time parameter adjustment for adaptable and efficient converters.**	**Improved adaptability, energy efficiency, remote monitoring.**	**Mobile robots, medical robots, automation.**
Resonant Converter Topologies [55][56][57]	**Reduced switching losses, high efficiency, low electromagnetic interference.**	**Improved efficiency, reduced heat, less EMI.**	**Renewable energy, wireless charging.**

Advancement	Description	Benefits	Applications
Hybrid and Multilevel Converters [58][59]	**Combined topologies for efficiency and voltage control.**	**Enhanced efficiency, reduced distortion, improved voltage control.**	**Electric grids, robotic vehicles, renewables.**
Advanced Cooling Techniques [60][61][62]	**Innovative cooling for efficient operation in confined spaces.**	**Improved thermal management, higher power handling, compact designs.**	**High Performance Computing (HPC) clusters, motor drives, confined spaces.**
Advanced Control Algorithms [63][64][65]	**Precise regulation for changing conditions and loads.**	**Enhanced accuracy, better response, improved stability.**	**Prosthetics, haptics, precision control.**
Wireless Power Transfer [50][66][67]	**Wireless charging for convenience and seamless integration.**	**Convenience, reduced wear, seamless integration.**	**Mobile robotics, drones, underwater robots.**

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