

Smart Cities

Power Electronics, Renewable Energy,
and Internet of Things



Edited by

**Ahteshamul Haque, Akhtar Kalam and
Himanshu Sharma**

Smart Cities

This book discusses the integration of power electronics, renewable energy, and the Internet of Things (IoT) from the perspective of smart cities in a single volume. The text will be helpful for senior undergraduate, graduate students, and academic researchers in diverse engineering fields including electrical, electronics and communication, and computers. The book:

- Covers the integration of power electronics, energy harvesting, and the IoT for smart city applications.
- Discusses concepts of power electronics and the IoT in electric vehicles for smart cities.
- Examines the integration of power electronics in renewable energy for smart cities.
- Discusses important concepts of energy harvesting, including solar energy harvesting, maximum power point tracking (MPPT) controllers, and switch-mode power supplies (SMPS).
- Explores IoT connectivity technologies such as long-term evolution (LTE), narrow band NB-IoT, long-range (LoRa), Bluetooth, and ZigBee (IEEE Standard 802.15.4) for low data rate wireless personal communication applications.

The text provides knowledge about applications, technologies, and standards of power electronics, renewable energy, and IoT for smart cities. It will serve as an ideal reference text for senior undergraduate, graduate students, and academic researchers in the fields of electrical engineering, electronics and communication engineering, computer engineering, civil engineering, and environmental engineering.



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I am thankful to Almighty Allah (SWT) for allowing us to complete this book.

This book is dedicated to last Prophet of Humanity Prophet Mohammad ﷺ, who has introduced Almighty Allah (SWT) to all of us.

Ahteshamul Haque

This book is dedicated to all my engineering students, all of whom are dedicated, conscientious, diligent and are giving their best to make this world sustainable, energy efficient and free of pollution.

Akhtar Kalam

I am thankful to almighty God and my teachers and parents who motivated me to contribute in this book.

Himanshu Sharma



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Preface

Welcome to the world of smart cities – where technology, sustainability, and innovation converge to transform urban living into a seamless, intelligent experience. As we delve into the pages of this book, we embark on a journey to explore the fascinating realm of smart cities, focusing on the pivotal role of renewable energy, power electronics, and the Internet of Things (IoT).

The concept of smart cities has emerged as a response to the ever-growing challenges faced by urban areas around the globe. Rapid urbanization, increased energy demands, environmental concerns, and the desire for improved living standards have necessitated the integration of cutting-edge technologies into city infrastructures. This book aims to shed light on how renewable energy sources, harnessed through advanced power electronics systems, are shaping the sustainable future of urban landscapes, while the Internet of Things acts as the connective tissue that binds it all together.

OUR PURPOSE

The purpose of this book is to provide a comprehensive and insightful overview of the interplay between renewable energy, power electronics, and the Internet of Things in the context of smart cities. By delving into the fundamentals of each domain and showcasing real-world applications and case studies, we hope to equip readers with a deeper understanding of the profound impact these technologies have on urban development.

WHO SHOULD READ THIS BOOK

This book is intended for a wide audience, including students, researchers, urban planners, engineers, policymakers, and technology enthusiasts interested in exploring the dynamic landscape of smart cities and the key elements driving its transformation. Whether you are a seasoned professional in the field or a curious mind eager to learn about the future of urban living, this book offers valuable insights and knowledge.

WHAT TO EXPECT

Throughout the chapters of *Smart Cities – Renewable Energy, Power Electronics, and Internet of Things (IoT)*, we will navigate through the essential concepts, advancements, and challenges that define smart cities. From the utilization of renewable energy sources like solar, wind, and hydroelectric power to the sophisticated control and conversion mechanisms provided by power electronics, we will explore how these technologies are paving the way for a sustainable, energy-efficient urban landscape.

Furthermore, we will delve into the transformative impact of the Internet of Things, which enables seamless communication, data exchange, and automation within smart cities. Through a series of case studies and examples, we will witness how IoT-driven solutions are enhancing various aspects of urban life, including energy management, transportation, healthcare, waste management, and more.

CONCLUSION

As we embark on this enlightening journey into the world of smart cities, we invite you to join us in envisioning a future where sustainable, intelligent, and connected urban environments create a better tomorrow for generations to come. The convergence of renewable energy, power electronics, and the Internet of Things opens the door to endless possibilities, and it is our hope that this book will inspire you to be an active participant in shaping the Smart Cities of the future.

Let's begin this transformative expedition together!



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Fundamentals of power electronics in smart cities

Ahteshamul Haque, Naila Shah, Junaid Ahmad Malik, and Azra Malik

Jamia Millia Islamia, New Delhi, India

1.1 INTRODUCTION

The idea of a “smart city” refers to the application of technology, data driven systems, and intelligent solutions to increase sustainability, improve the standard of life for its citizens, and optimize resource management. One of the major developments in today’s technology is the smart city. The need for a “smart” and sustainable metropolis has arisen from the increase in the global population. The word “smart city” was first coined in 1990. At that time the main focus was given to infrastructure based on ICT (Information and Communication Technologies). Later on, this shifted to the concept of designing smart cities based on smart communities presented by California Institute [1]. There were many definitions given by authors regarding smart city. One definition given by Casio in [2] emphasizes the importance of ICTs by defining them as scalable systems to improve standards of life, minimize costs, and enhance efficiency. Another definition given by Chourabi stated that a smart city is a city that aims to achieve smartness by making itself more productive, democratic, enjoyable, and sustainable [3]. A city that is functioning well in terms of mobility, government, economics, population, and living standard of people can be summarized as smart city [4]. The main characteristics of smart cities include theme, quality, and structure, with theme being the prime support of smart cities. These attributes are dependent on four features that include quality of life, urbanization, sustainability, and smartness as shown in Figure 1.1. The quality of life aims to achieve welfare of citizens. Urbanization and smartness attributes include changing the infrastructure from rural to urban conditions. In sustainability the focus is given to ecosystems, pollution, energy, and climate change.

Smart cities employ optimization of resources, reduced operational costs, and improved overall efficiency through various techniques like data analytics, IOT (Internet of Things), and automation [5]. Integration of solutions is essential for a better and more regulated utilization of the resources due to their scarcity and high cost. Smart cities also focus on enhancing sustainability, governance, and control infrastructure and aim to reduce carbon footprint. Smart cities offer improved services to all of inhabitants using effective methods that minimize time and resource waste [6]. Smart cities

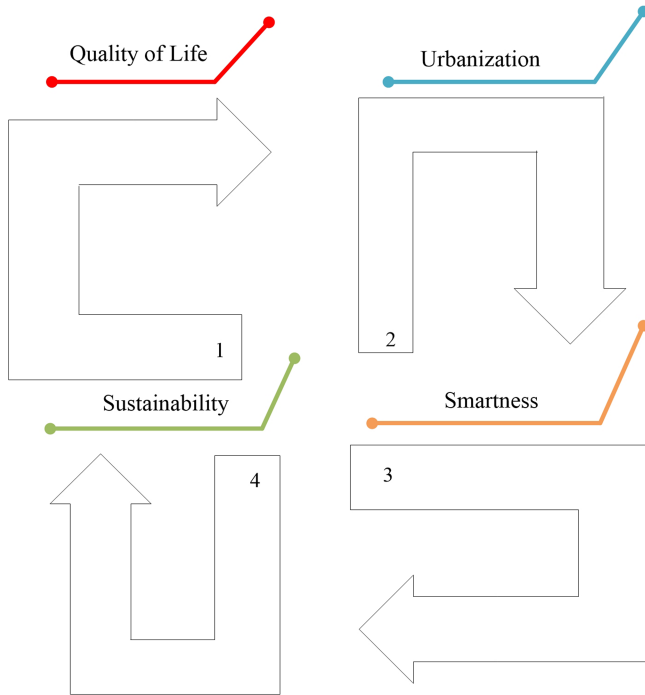


Figure 1.1 Characteristics of smart cities.

enhance the quality of life by providing comfort, convenience, security, and energy management for citizens. Remote healthcare monitoring systems help patients receive individual care, decreasing hospital visits. Smart cities deploy intelligent techniques and advanced technologies like surveillance systems, predictive analysis, and sensors to improve the safety and security of residents. Smart cities emphasize citizens participation in decision-making processes and involves in urban planning and policy making. Smart cities encourage innovation and attract investment [7]. They promote economic growth and job creation by fostering a climate that encourages technical development and entrepreneurship. By embracing technology and innovation, smart cities have the ability to overcome the urban issues and build healthier, more flexible, and successful communities.

Power electronics technology plays a vital role in the development and functioning of smart cities, revolutionizing the way we generate, distribute, and consume electrical energy [8]. As urban areas become increasingly complex and energy-intensive, power electronics offer a range of solutions that are essential for creating sustainable, efficient, and intelligent urban environments. Figure 1.2 shows the schematics of advanced power electronics technology in a smart city. Power electronics is essential for the operation and control of smart grids, which form the back bone of smart cities. The two

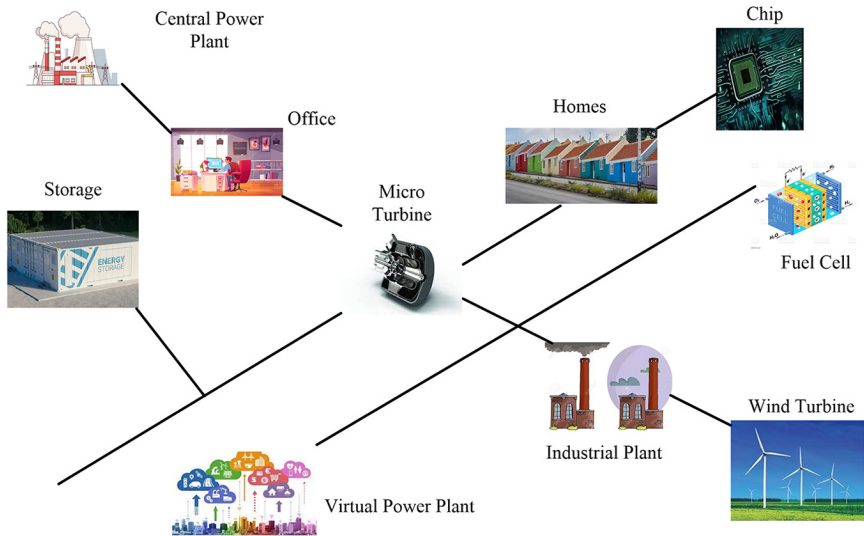


Figure 1.2 Block diagram of power electronics in smart city.

major functions of power electronics in a smart grid are (a) electrical power transmission and (b) electrical power distribution. Power can be transmitted through two ways: (a) HVDC transmission and (b) power transmission through FACTS devices [9]. Both techniques use power electronic devices like IGBT, GTO, and SCR. FACTS improve the reliability and stability of transmission systems by combining existing power electronic devices with modern ones. The quick control of FACTS technology may help China's energy supply and demand reach a more favorable equilibrium, boost electrical power transmission and distribution, and resolve the issue of voltage fluctuation [10]. The application of power electronic technology helps to maintain power quality and reliability in smart cities by setting up technical evaluation, economy assessment systems, rules, and regulations [11]. Solutions based on power electronics increase power grid stability, and dependability, and resilience also helps to reduce problems like power factor distortion, voltage fluctuations, and harmonics. Power electronics enable the seamless integration of renewable energy generation systems, such as solar photovoltaic panels and wind turbines, into the power grid. In a solar photovoltaic system, a DC/DC converter is used to link separate solar panels in series or parallel. Power electronics converters are used to interface two solar panels since they are not identical and direct interfacing is ineffective. Additionally, this increases the array's general effectiveness, since solar PV supplies DC and for grid integration this is converted into AC via a power electronic converter, that is, DC/AC. In the case of wind power plants, these power electronic converters perform the function of integrating wind power plants (WPP) to the grid as well as active and reactive power control.

With the help of power electronics, electricity can be converted, controlled, and managed properly, ensuring that there should be optimal energy usage and minimal waste in various sectors and industries. For sustainable usage of energy, integration of demand response systems, renewable energy sources, and energy storage systems are utilized to achieve this. In metropolitan regions, buildings are substantial energy users. LED lighting, for example, which greatly lowers electricity use, is made possible by power electronics. Additionally, it offers the effective regulation of heating, ventilation, and air conditioning (HVAC) systems, optimizing energy consumption depending on utilization, temperature, and environmental factors. In the event of power outage, energy storage systems are used to supply backup power to generators. Due to these energy storage technologies, the grid reliability is increased. Flywheel is the most significant device for energy storage as it can store the maximum amount of kinetic energy possible. Electric vehicle (EV) adoption and infrastructure development are supported by smart cities. In EV charging stations, power electronics is essential for effective power transfer, charging control, and grid integration. Fast-charging, two-way power flow and intelligent charging techniques that balance energy consumption and grid stability are made possible by power electronic converters. Additionally, power electronics aids in the effective management of vehicle performance, optimal energy usage, and electric drive trains in EVs.

In this chapter a comprehensive understanding and overview of the fundamental concepts, applications, and importance of power electronics in the context of smart cities is provided. This chapter also investigates the function of power electronics in the development and operation of various aspects of smart cities such as smart grids, smart buildings, and electric mobility.

1.2 BASICS OF POWER ELECTRONICS

Power electronics refers to the technology that deals with power electronics devices like diodes, transistors, switches, converters, inverters, and rectifiers used for control and conversion of electrical power in order to meet a desired requirement. It can also be defined as the branch of electrical engineering that utilizes solid-state semiconductor apparatus to efficiently control and convert power from one form to another. The first power electronic apparatus that came into existence was a mercury arc rectifier in 1900 [12]. The first real power electronics revolution was started by Brattain, Bardeen, and Shockley in 1956 at the Bell Laboratory with the invention of the Silicon Controlled Rectifier (SCR) or PNP transistor [13]. The second revolution was started by the General Electric Company (GEC) in 1958 with the introduction of power devices or commercial thyristors like MOSFET, GTO, TRIAC, BJT, IGBTs, MCTs, and ICTs [14]. Due to this,

the modern age of power electronics started and different power electronic devices with their control techniques are presented in Table 1.1. Power electronics plays a vital role in revolutionizing the power sector by controlling the generation, transmission, and distribution sectors. Examples include energy storage systems including supercapacitors and batteries, FACTS used to control power grids, inverters and converters used for integration of renewable energy resources with the grid, current limiting devices, transfer switches, and solid-state semiconductor devices [15].

1.2.1 Characteristics of power semiconductor devices

The characteristics of power semiconductor devices are: (i) fast switching speed, (ii) high-power handling capacity, (iii) low-power losses, (iv) gate drive requirements, (v) voltage blocking capability, and (vi) temperature stability. The three main classifications of power semiconductor devices are: (a) Diode, (b) SCR, and (c) Transistors.

Depending on the number of terminals in the device, power semiconductor devices are separated into two groups: (i) two-terminal device (Schottky diodes, Fast recovery diodes) and (ii) three-terminal device (SITs, MCT, MOSFET, IGBT, BJT, SCR) [6]. Based on the carrier used for conduction in semiconductor devices, these devices are classified as: (i) majority carrier semiconductor devices (MOSFET, SIT) and (ii) minority carrier semiconductor devices (MCT, GTO, IGBT, Thyristor, Power Diode). On the basis of the number of layers in semiconductor devices, semiconductor devices are grouped into categories: (i) two-layered device (Power Diodes), (ii) three-layered device (BJTs, MOSFETs), and (iii) four-layered device (SCR).

Table 1.1 Characteristics of power semiconductor devices

| Semiconductor device | Maximum frequency (KHz) | Voltage/ Current rating | Turn-on time | Turn-off time |
|----------------------|-------------------------|-------------------------|----------------|-----------------|
| DIODE | 1 | 5 KV/5 KA | 50–100 μ s | 50–100 μ s |
| SCR | 1 | 10 KV/5 KA | 2–5 μ s | 2–100 μ s |
| MOSFET | 100 | 1 KV/50 A | 0.1 μ s | 1–2 μ s |
| BJT | 10 | 1400 V/400 A | 2 μ s | 9–30 μ s |
| IGBT | 50 | 3.3 KV/2.500 A | 0.2 μ s | 2–5 μ s |
| GTO | 2 | 5 KV/3 KA | 3–5 μ s | 10–25 μ s |
| TRIAC | 0.5 | 1200 V/300 A | 2–5 μ s | 200–400 μ s |
| MCT | 20 | 1200 V/100 A | 0.2 μ s | 50–110 μ s |
| SIT | 100 | 1200 V/500 A | – | – |

1.2.2 Power conversion techniques

A power electronic converter is used for the control or conversion of input power from one form to output power of another form by utilizing the switching characteristics of power devices. These power conversion tasks are effectively and efficiently executed by static converters. Solid-state devices with inductors and capacitors are used in power electronic switches. Comparing inductors and capacitors to resistors, they often show small power loss characteristics. The various power electronic converters are categorized as:

- *AC/DC Rectifiers (Diode Rectifier and Phase Controlled Rectifier)*
The term AC to DC converter refers to a converter that converts an AC input signal into a DC signal. Such a device that performs this conversion is known as a rectifier. These rectifiers are further grouped into two categories as:
 - *Diode Rectifier:* These device circuits convert input AC voltage into fixed DC voltage. The input voltage applied could be either 1 \emptyset or 3 \emptyset . These rectifiers are widely used in uninterruptible power supplies, welding, etc. They are employed in electromechanical processing like electroplating, electric transaction, battery charging, and many more.
 - *Phase Controlled Rectifier:* Phase Controlled Rectifiers transform a constant AC input voltage into a variable amount of DC output voltage in contrast to diode rectifiers. These converters are also known as naturally commutated converters or line commutated AC/DC converters because they operate on line voltages for the commutation process or turn-off process. In these rectifiers, the applied AC input voltage may be 1 \emptyset or 3 \emptyset AC source. These rectifiers are widely used in synchronous machines for excitation purposes, chemical, and metallurgical industries.
- *DC/DC Converters (Choppers)*
These converters convert a fixed frequency DC input signal into a variable DC output signal. These converters have the ability to produce DC output voltage that may differ in amplitude from the source voltage. MOSFETs, power transistors, and thyristors are commonly employed semiconductor devices used for their construction. The output of DC choppers is controlled by utilizing low-power control signals and in this scenario, power transistors are used in place of thyristors. The choppers are categorized according to the nature of commutation and the direction in which power is delivered. Some significant applications for choppers include electric traction, battery-powered vehicles, SMPS, subway cars, and so on.
- *DC/AC Converters (Inverters)*
An inverter transforms the input that is fixed DC voltage commonly sourced from batteries into an variable AC output voltage with adjustable voltage and frequency. Here, line commutation or

forced commutation is used to turn off the thyristor devices. Multiple semiconductor components including power transistors, MOSFETs, GTOs, IGBTs, and thyristors are used in the fabrication of inverters. These devices are designed to handle various power levels, with traditional thyristors utilized in high-power applications, whereas power transistors are utilized in low-power applications. Inverters are widely employed in synchronous motor drives, HVDC transmission, UPS, and flash photography cameras. Due to their versatile nature, they are adopted for effective power conversion over a wide range of power requirements.

- *AC/AC Converters*

This converter transforms the fixed frequency AC input voltage into a variable AC output voltage. This converter is further divided into:

- *Cycloconverters*: A cycloconverter converts fixed AC voltage at single frequency into a variable AC output voltage at another frequency employing a single-stage conversion process. The resulting output voltage signal has a lower frequency than the input voltage signal. These converters primarily utilize the line commutation technique. They are predominantly adopted for applications requiring low-speed speed, high-transaction AC drives such as multi-megawatt AC motor drives.
- *AC voltage Controllers*: They are also known as AC voltage regulators as they convert a fixed voltage AC signal into a variable AC voltage signal with the same frequency as the input. These AC voltage controllers operate by using a pair of thyristors placed in an antiparallel arrangement and natural commutation is used to turn both devices off. The output voltage is effectively regulated by changing the delay angle. These controllers find wide application in tap changers, speed regulation of fans, lighting control, and so on.
- *Static Switch*

The power devices can function as contractors or static switches and the source of power to these switches might be DC or AC, so these switches are referred to be DC switches or AC static switches respectively. Compared to mechanical and electromechanical circuit breakers, static switches have various benefits. The various advantages are:

- i. The switching speed of a static switch is about 3 μ s.
- ii. The static switches don't bounce when turned on.
- iii. There are reduced changes of wear and tear due to the absence of any moving part.
- iv. Static switches possess longer operational life.

1.3 POWER ELECTRONICS IN SMART GRIDS

The smart grid is known as the modernization of the electrical grid through the use of advanced metering infrastructure (AMI), digital transmission

substation, and current sensing technology by incorporating modern technology in relay protection devices. It is a new kind of power grid that integrates components of control technology, communication technology, information technology, and power electronics technology. The distinguishing features of smart grid are flexibility, efficiency, environmental safety, and reduced maintenance costs. In contrast to conventional grid, the smart grid offers continuous safety evaluation, fault detection, early warning system, reduced maintenance cost, and self-healing capabilities. Power electronic devices are essential for the development of the intelligent power grid and power systems in many ways, including energy storage systems (flywheel, batteries, super capacitors, water containers etc.), harmonics mitigation, integration of renewable energy resources, power quality improvement, bidirectional flow of power, load management, and so on. The importance of power electronic devices in power systems has substantially increased due to developments in modular converter units, intelligent control techniques, and high-voltage and high-power electronic devices. The growing significance of the power electronics technology in the field of smart grid development is highlighted by the rising global demand for power electronic devices in applications, including distributed independent power systems, power quality improvement, wind and solar power generation, large-scale industrial processes, and high-voltage inverters.

1.3.1 Role of power electronics in integration of renewable energy sources to grid

The main impediments to global sustainability are due to a shortage of raw materials and environmental contamination brought on by traditional energy sources such as coal and oil. The Paris Agreement (2015) stressed the need to achieve an energy transition through the development and use of renewable energy sources (RESs). As a result, several nations have taken significant steps to integrate RES, including wind, solar PV, ocean wave energy, and bioenergy into their energy systems in an effort to shift their energy paradigms. For example, Denmark intends to be 100% fossil fuel independent and 100% carbon neutral through the use of RESs in 2050 [16–18]. The increased penetration of RES is accompanied by two challenges: one is integrating RES into the electrical grid to guarantee stability during system outage and the other is how to utilize power electronics for energy conversion, transmission, distribution, and utilization efficiently. Therefore power electronic technologies have evolved quickly and grid integration standards are constantly being revised for RESs particularly in wind and PV systems [19, 20]. Recent years have seen fast advancements in power electronics, driven by two important aspects. The first is the development of very efficient high-power semiconductor switches and the second is the incorporation of real-time computer controllers with improved control algorithms. These two aspects made it possible to develop inexpensive and grid-friendly

converters. Power converter topologies for low-power RESs focused on high-power density and high efficiency, with transformer-less topologies evolving as more efficient and less costly. In order to improve the grid integration of RESs, multi-port converters are being incorporated into energy storage systems [21]. Control algorithms for RES have first shifted from grid following to grid supportive and then to grid-forming capabilities in order to improve grid resiliency [22]. The consolidation of grid integration requires reliability-oriented control and power converters cooped with RES must be able to respond to individual end-user requests for uninterrupted power supply and system operators' global management directives.

1.3.2 Power quality and stability considerations in smart grids

The implementation of power quality technology in smart grids should strongly focus on development and enhancement of the power quality evaluation technique and hierarchical systems. It is also required to develop internal technical grade evaluation systems, user economic assessment systems and policies, and rules and regulations in order to accomplish “economically-efficient and high-quality operation” of smart grids. Table 1.2 shows the main technical parameter of power quality technology.

The use of power quality technology in the smart grid includes a number of related technologies such as unified power quality controller (UPQC), adaptive static reactive power compensation, high-quality power parks, and so on. UPQC plays a significant role in ensuring effective power quality for its users.

1.3.3 Demand-side technology in smart grids

Demand-side technology is largely concerned with satisfying the unique power quality and reliability demands of consumers or fulfilling the needs of customers with specialized power supply requirements. It involves the integration of power electronic technology and distribution automation technology to produce power supply solutions that closely match customer expectations. Power companies are faced with the dual challenge of balancing the need to satisfy rising power demand with the requirement of energy conservation due to the increasingly challenging landscape of power

Table 1.2 Main technical parameter of power quality technology

| | <i>Frequency test error</i> | <i>Voltage deviation</i> | <i>Phase angle error</i> | <i>Power deviation</i> | <i>Power consumption</i> |
|-----------|-----------------------------|--------------------------|--------------------------|------------------------|--------------------------|
| Parameter | ≤ 0.01 Hz | $\leq 0.2\%$ | $\leq 0.2\%$ | $\leq 0.5\%$ | < 4 VA |

load and power quality. Power companies must improve their technological capabilities in order to meet these problems. Demand-side technology is essential for ensuring a new energy grid and clean energy and offers creative solutions for problems like fault current limit prevention.

1.4 POWER ELECTRONICS IN SMART BUILDINGS

Power electronics is a rapidly advancing field that plays a crucial role in the development and implementation of smart buildings. With the rise of smart technologies and the increasing demand for energy-efficient solutions, power electronics has emerged as a key enabler in transforming traditional buildings into intelligent and sustainable infrastructures [1]. By effectively managing and controlling the flow of electrical power, power electronics systems in smart buildings optimize energy consumption, enhance power quality, and enable the integration of renewable energy sources, ultimately leading to improved comfort, cost savings, and environmental sustainability.

In smart buildings, power electronics technology is utilized across various applications, such as lighting, HVAC, energy storage systems, electric vehicle charging, and more. It facilitates efficient power conversion, voltage regulation, and power factor correction, enabling the seamless integration of diverse energy sources, energy storage systems, and energy management systems [2]. Moreover, power electronics devices, including inverters, converters, and controllers, enable bidirectional power flow, allowing for grid-to-building and building-to-grid energy exchange, promoting grid stability and resilience. The integration of power electronics into smart buildings not only enables advanced control and automation but also paves the way for intelligent energy management systems that adapt to the occupants' needs and preferences, optimizing energy consumption and reducing environmental impact.

1.4.1 Role of power electronics in energy-efficient systems

Power electronics plays a crucial role in enabling energy-efficient systems by effectively managing and controlling the flow of electrical power. It involves the conversion, conditioning, and control of electrical power to ensure optimal performance and reduced energy losses. Power electronic devices, such as converters, inverters, and controllers, provide the necessary tools to efficiently transform, regulate, and distribute electrical energy. One key aspect of power electronics is its ability to facilitate energy conversion between different sources and loads [3]. For example, in renewable energy systems, power electronics are used to convert the variable and often unpredictable output from sources like solar panels or wind turbines into a usable form of electricity. This conversion process ensures that the power generated

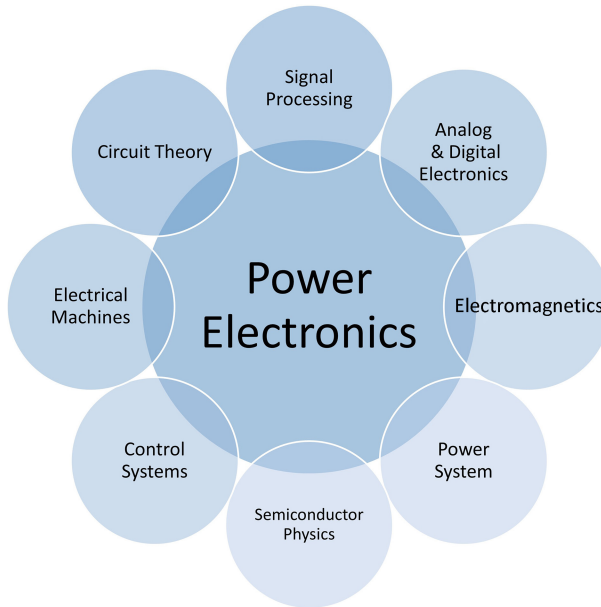


Figure 1.3 Power electronics role.

matches the requirements of the connected loads, enhancing overall system efficiency. Power electronics also enable bidirectional power flow, allowing energy to be efficiently stored in batteries and other energy storage systems, and then discharged when needed. As illustrated in Figure 1.3.

Moreover, power electronics devices contribute to energy efficiency by minimizing power losses during energy conversion. They employ advanced switching techniques, such as pulse-width modulation (PWM), to control the output voltage and current waveforms with high precision. This precise control helps in reducing energy losses through improved voltage regulation, reduced harmonic distortion, and efficient power factor correction. Additionally, power electronics systems incorporate features like soft switching and active clamping to further enhance energy efficiency by minimizing switching losses.

1.4.2 Power electronics applications in HVAC

Power electronics has significant applications in HVAC systems, contributing to their improved efficiency, control, and performance. One of the key areas where power electronics is employed in HVAC is in motor drives. Power electronic motor drives, such as variable frequency drives (VFDs), are utilized to regulate the speed of motors used in HVAC equipment like fans and pumps presented in Figure 1.4. By adjusting the motor speed based on the actual cooling or heating demands, VFDs enable the precise control of

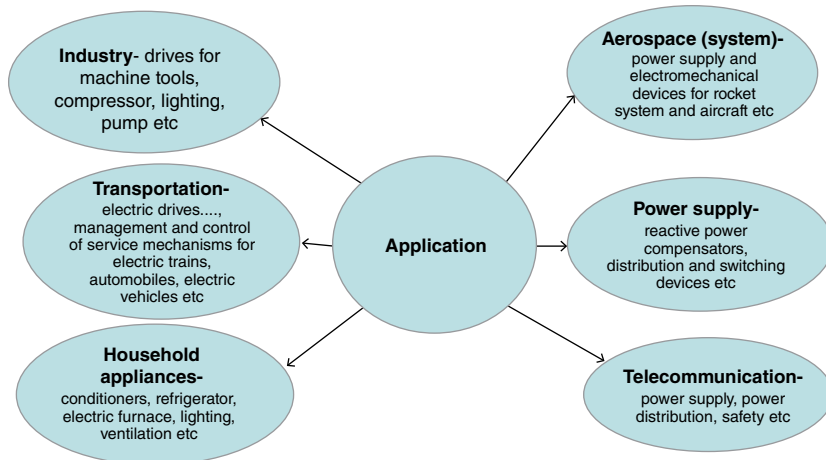


Figure 1.4 Applications of power electronics in HVAC.

airflow and water flow rates, resulting in reduced energy consumption and enhanced system efficiency [4]. Furthermore, VFDs offer soft-start capabilities, which minimize the inrush current during motor startup, extending the lifespan of the motor and reducing equipment wear and tear.

Another application of power electronics in HVAC is in the implementation of energy-efficient cooling systems. Air conditioning systems often employ compressors to provide cooling, and power electronics is employed to regulate and optimize their operation. Variable speed compressors, controlled by power electronic devices, allow for modulation of the cooling capacity based on the actual cooling load. This enables the system to operate at varying capacities, matching the cooling requirements precisely. As a result, energy wastage due to constant on/off cycling of the compressor is minimized, leading to significant energy savings and improved overall HVAC system performance.

1.4.3 Building automation and control systems enabled by power electronics

Power electronics plays a vital role in enabling building automation and control systems, enhancing energy efficiency, comfort, and overall operational performance. Building automation systems utilize power electronic devices to control and manage various building functions, including lighting, HVAC, security, and power distribution. By integrating power electronics, these systems can optimize energy usage, improve occupant comfort, and provide intelligent control and monitoring capabilities. Power electronic devices such as solid-state relays, electronic switches, and motor drives are employed in building automation systems to regulate and control electrical loads. These devices enable precise and efficient switching of electrical circuits, allowing

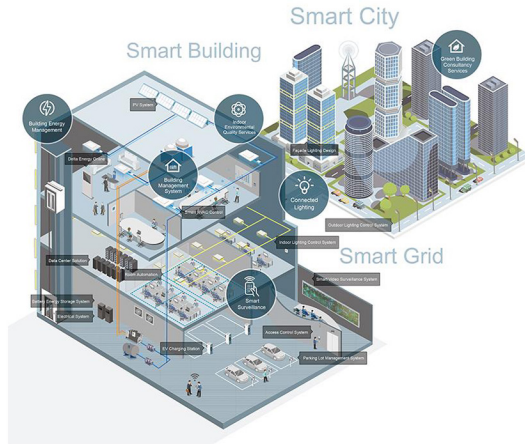


Figure 1.5 Building automation.

for intelligent control of lighting systems, motorized shades, and other electrical equipment. Additionally, power electronics facilitates power factor correction and voltage regulation, ensuring a stable and reliable power supply within the building, while reducing energy losses. Furthermore, power electronics enable advanced energy management strategies in building automation systems. Energy storage systems, such as batteries or supercapacitors, integrated with power electronics, can store excess energy during low-demand periods and release it during peak demand periods, optimizing energy usage and reducing utility costs [23] as represented in Figure 1.5. Power electronics also enable demand response capabilities, where the building's energy consumption can be dynamically adjusted based on real-time pricing or grid signals, contributing to load balancing and grid stability.

1.4.4 Power factor correction and load management in smart building

Power factor correction and load management are essential aspects of smart building systems, and power electronics plays a crucial role in implementing these functionalities. Power factor correction is the process of improving the power factor of a building's electrical system by reducing reactive power and bringing it closer to unity. Power electronics devices, such as capacitors and power factor correction controllers, are used to compensate for reactive power and adjust the power factor. By improving the power factor, smart buildings can minimize energy losses, optimize the use of electrical infrastructure, and reduce electricity costs. Power factor correction also enhances the overall efficiency of the electrical system and reduces stress on electrical equipment, leading to increased equipment lifespan and improved reliability. Load management in smart buildings involves the intelligent control and optimization of energy consumption based on demand, availability, and cost

factors. Power electronics devices, such as programmable logic controllers (PLCs), sensors, [24] and actuators, enable real-time monitoring and control of loads in the building. These devices collect data on energy usage, occupancy patterns, and external factors to dynamically adjust the operation of electrical equipment and optimize energy consumption. Load management strategies can include load shedding during peak demand periods, load shifting to take advantage of off-peak electricity rates, and load balancing to ensure efficient distribution of energy within the building. By effectively managing loads, smart buildings can reduce peak demand, minimize energy waste, and enhance overall energy efficiency.

1.5 POWER ELECTRONICS IN ELECTRIC TRANSPORTATION

At the heart of electric transportation, power electronics devices such as inverters, converters, and motor controllers are utilized to convert DC power from the battery into AC power for the electric motor, providing smooth and precise control over the vehicle's propulsion. Power electronics also enable regenerative braking, where the kinetic energy during deceleration is converted back into electrical energy and stored in the battery for reuse [25]. Additionally, power electronics systems are integrated into EV charging infrastructure to regulate the charging process, providing safe and efficient charging for EV owners. This includes power conversion from AC to DC to charge the vehicle's battery, as well as communication and control functionalities to monitor charging status, manage power levels, and integrate with smart grid systems illustrated in Figure 1.6.

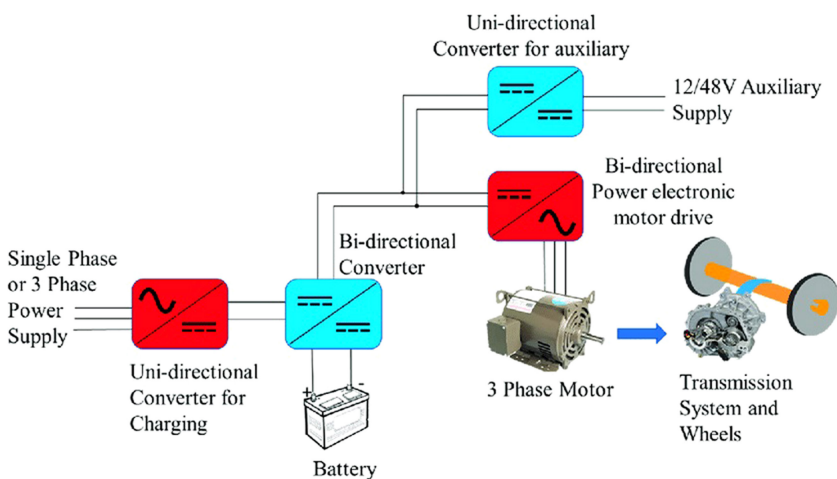


Figure 1.6 Electronics in transportation.

1.5.1 Overview of electric transportation in smart cities

Electric transportation plays a pivotal role in the development of electric cities, where sustainable and environmentally friendly modes of transportation are prioritized. Electric transportation encompasses various forms of EVs, including electric cars, electric buses, electric bikes, and electric scooters. These vehicles are powered by electricity instead of fossil fuels, resulting in reduced emissions and a cleaner urban environment. Electric transportation offers numerous benefits for electric cities. One of the primary advantages is the significant reduction in air pollution and greenhouse gas emissions. Electric vehicles produce zero tailpipe emissions, resulting in improved air quality and reduced carbon footprint. This contributes to creating healthier and more sustainable living environments for residents. Moreover, electric transportation contributes to noise reduction in cities [26]. Electric vehicles operate more quietly compared to conventional combustion engine vehicles, resulting in reduced noise pollution, especially in densely populated urban areas. This can lead to improved quality of life for residents, as well as quieter and more peaceful neighborhoods.

1.5.2 Overview of power electronics technology for electric transportation in smart cities

Power electronics plays a crucial role in the charging infrastructure of EVs, enabling efficient and reliable charging processes. Power electronic devices and systems are employed at various stages of the charging infrastructure to facilitate the conversion, control, and distribution of electrical power. At the charging station level, power electronics are used in AC/DC converters. These converters are responsible for converting the alternating current (AC) power from the grid to the direct current (DC) power required for charging the EV's battery. Power electronic converters ensure efficient power conversion, high-power quality, and compatibility with different charging standards [27]. Within the EV itself, power electronics are integral to the on-board charger. The on-board charger converts the AC power received from the charging station into the appropriate DC voltage and current levels for charging the EV's battery pack. Power electronic converters within the on-board charger ensure efficient power conversion, power factor correction, and control of charging parameters.

1.5.3 Overview of grid integration for electric transportation in electric cities

Integration of EV charging infrastructure with the power grid is a crucial aspect of the ongoing transition toward sustainable transportation. As the adoption of electric vehicles continues to grow, it becomes imperative to

establish a seamless connection between the grid and EV charging systems to ensure efficient and reliable charging services. This integration allows for optimized charging strategies, grid management, and the utilization of renewable energy sources, facilitating the widespread adoption of electric mobility while minimizing the strain on the power grid. By integrating EV charging infrastructure with the power grid, several benefits can be realized. First, it enables the implementation of smart charging solutions that take advantage of off-peak hours and grid conditions, ensuring cost-effective charging for EV owners. Through communication protocols and advanced metering systems, charging stations can receive real-time data on electricity prices and grid demand, enabling them to adjust charging rates accordingly. This not only helps to balance the load on the grid but also encourages EV owners to charge their vehicles during periods of lower demand, reducing strain on the grid during peak hours. Additionally, this integration paves the way for Vehicle-to-Grid (V2G) technology, allowing electric vehicles to act as mobile energy storage units. During periods of high demand or grid instability [28], EV batteries can feed electricity back into the grid, providing support and flexibility to the overall power system. This bidirectional power flow not only enhances grid reliability but also enables the integration of renewable energy sources by absorbing excess generation and mitigating fluctuations in supply and demand. Overall, the integration of EV charging infrastructure with the power grid establishes a symbiotic relationship between electric vehicles and the energy system, contributing to a more sustainable and efficient transportation ecosystem.

1.6 POWER QUALITY AND RELIABILITY IN SMART CITIES

Power quality and reliability are critical factors in the development and operation of smart cities. As cities become increasingly connected and reliant on digital technologies, ensuring a consistent and high-quality power supply becomes paramount. Power quality refers to the characteristics of electrical power, including voltage stability, harmonic distortion, and frequency fluctuations, that can affect the performance of electronic devices and systems. In the context of smart cities, maintaining optimal power quality is essential for the smooth operation of various interconnected systems, such as smart grids, intelligent transportation systems, and smart buildings [29].

In smart cities, power quality issues can have far-reaching implications. For instance, voltage sags or fluctuations can disrupt the operation of sensitive equipment, leading to system failures and downtime. Harmonic distortions can cause interference and malfunctions in communication systems and electronic devices, affecting the overall efficiency and reliability of the city's infrastructure. Therefore, smart cities need advanced power quality monitoring and control systems that can detect and mitigate power quality

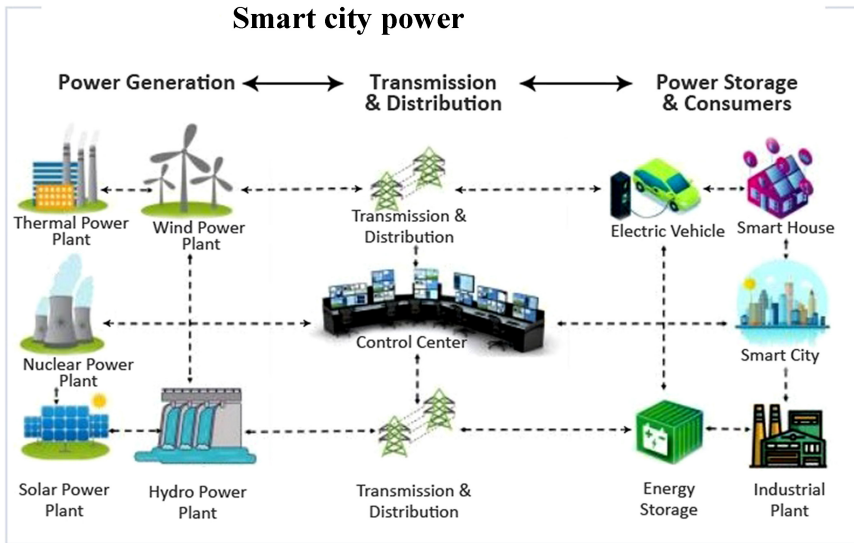


Figure 1.7 Smart grid power.

disturbances in real-time. Such systems employ smart sensors, data analytics, and automated control mechanisms to identify and address power quality issues promptly, minimizing their impact on critical systems and ensuring reliable operation as shown in Figure 1.7. Moreover, incorporating energy storage systems and microgrids into smart city infrastructure can provide backup power during outages, enhance grid stability, and improve power quality and reliability by regulating voltage fluctuations and minimizing disruptions. By prioritizing power quality and reliability in smart city planning and implementation, cities can ensure the uninterrupted and efficient operation of their interconnected systems, promoting sustainable growth and enhancing the overall quality of life for their residents.

1.6.1 Importance of power quality in smart cities

Power quality holds immense importance in the context of smart cities as it directly affects the performance, efficiency, and reliability of various interconnected systems and devices. In a smart city, where a multitude of critical infrastructure relies on digital technologies, maintaining optimal power quality is vital for uninterrupted operations and seamless connectivity. A high-quality power supply ensures that electronic devices, sensors, communication networks, and intelligent systems can function efficiently, accurately, and securely, leading to enhanced service delivery, improved safety, and overall productivity. One of the key reasons power quality is crucial in smart cities is its impact on the performance of sensitive electronic equipment and

systems. Voltage sags, surges, and interruptions can cause disruptions, data loss, and system failures, leading to financial losses and service disruptions. In smart grids, for example, power quality issues can hamper the accurate monitoring and control of energy distribution, affecting the reliability and efficiency of the entire grid. Similarly, in smart buildings, poor power quality can result in malfunctions of automation systems, HVAC systems, and other critical infrastructure [30], impacting occupants' comfort and increasing energy consumption. By ensuring high-power quality, smart cities can mitigate these risks and optimize the performance of their interconnected systems, enabling seamless data exchange, efficient energy management, and effective decision-making.

Furthermore, power quality is essential for the successful integration of renewable energy sources and energy storage systems in smart cities. As cities strive to reduce carbon emissions and enhance sustainability, they increasingly rely on renewable energy generation. However, the intermittent nature of renewable sources like solar and wind can introduce power quality challenges, such as voltage fluctuations and harmonics. By addressing power quality concerns, smart cities can effectively integrate renewable energy into their grids, ensuring stability, grid resilience, and optimal utilization of clean energy. Additionally, power quality management facilitates the integration of energy storage systems, enabling cities to store excess energy and release it during peak demand periods, contributing to load balancing and grid stability.

1.6.2 Challenges and solutions for maintaining power quality in power electronic systems

Maintaining power quality in power electronic systems presents several challenges due to the complex nature of these systems and the impact of power disturbances on their performance. However, there are various solutions available to address these challenges and ensure optimal power quality. One major challenge in power electronic systems is the generation of harmonics and distortions that can result from the switching operations of power electronic devices. These harmonics can cause voltage and current distortions, leading to power quality issues. To mitigate this challenge, active power filters and passive filters can be employed to reduce harmonic distortions and maintain a clean power supply. Active power filters use advanced control algorithms to inject compensating currents that cancel out the harmonic components, while passive filters use inductors, capacitors, and resistors to filter out the harmonics. Implementing proper filtering techniques helps to minimize harmonic distortions and maintain power quality within acceptable limits [31].

Another challenge is the voltage fluctuations caused by varying load conditions and grid disturbances. Power electronic systems are susceptible to

voltage sags, swells, and interruptions, which can disrupt their operation. Voltage regulators, such as voltage sag compensators and uninterruptible power supplies (UPS), can be utilized to address this challenge. Voltage sag compensators are devices that inject compensating voltages to mitigate the effects of voltage sags, ensuring a stable voltage supply to the power electronic systems. UPS systems, on the other hand, provide backup power during voltage interruptions, preventing disruptions and maintaining continuous operation [32]. By implementing voltage regulation solutions, power electronic systems can operate reliably and maintain power quality even in the presence of voltage disturbances [33].

1.6.3 Reliability considerations and fault-tolerant strategies

Reliability considerations and fault-tolerant strategies are of utmost importance in various systems and industries, particularly in critical applications where system failures can have severe consequences [34]. In the context of power electronics, ensuring reliability is crucial to maintain uninterrupted operation, mitigate downtime, and prevent potential hazards. Fault-tolerant strategies are implemented to detect, isolate, and accommodate faults or failures within power electronic systems, enabling continued operation or a graceful degradation to ensure system reliability. One key aspect of reliability considerations in power electronics is the design of robust and fault-tolerant systems. Redundancy is often employed to enhance reliability by duplicating critical components or subsystems. For example, redundant power modules or converters can be utilized in parallel to provide backup or alternate paths in the event of a failure. Fault detection and diagnostic techniques, such as current and voltage sensing, can be integrated into the system to monitor the health of components and detect abnormalities or faults [35]. Fault isolation techniques, such as circuit breakers or fault detection algorithms, are employed to isolate faulty components or subsystems, preventing the spread of faults and minimizing their impact on the overall system [36]. Additionally, fault-tolerant control strategies such as reconfigurable control algorithms or fault-tolerant control hardware [37] can be implemented to ensure system stability and functionality in the presence of faults.

Furthermore, fault-tolerant strategies are designed to provide system resilience and recovery. This involves the implementation of backup power sources, such as UPS or energy storage systems, to ensure a continuous power supply during fault conditions or power outages. These backup systems are equipped with seamless switchover mechanisms that activate in the event of a fault, ensuring uninterrupted power to critical loads. Additionally, fault-tolerant strategies incorporate fault management protocols and automated diagnostic systems that can identify the root cause of faults, expedite troubleshooting, and facilitate timely repairs or replacements. By promptly

addressing faults and failures, these strategies reduce downtime, increase system availability, and enhance overall reliability. In summary, reliability considerations and fault-tolerant strategies are essential in power electronics to ensure continuous operation, mitigate the impact of failures, and enhance system resilience. By employing redundancy, fault detection and isolation techniques, and fault-tolerant control strategies, power electronic systems can withstand faults, maintain functionality, and minimize disruptions. Incorporating backup power sources and fault management protocols further enhances system reliability and recovery. These reliability considerations and fault-tolerant strategies play a crucial role in critical applications, where system failures can have significant financial, operational, or safety consequences, promoting the overall dependability and performance of power electronic systems.

1.6.4 Mitigation of harmonics in voltage fluctuations and grid interactions

Mitigating harmonics in voltage fluctuations and grid interactions is essential to maintain power quality and ensure the reliable operation of power electronic systems. Harmonics, which are multiples of the fundamental frequency, can introduce distortion in voltage and current waveforms, leading to various issues such as equipment malfunctions, increased losses, and interference with communication systems. Several strategies can be employed to effectively mitigate harmonics and minimize their impact. One approach is the use of passive and active harmonic filters. Passive harmonic filters consist of passive components such as inductors, capacitors, and resistors that are designed to attenuate specific harmonic frequencies [38]. These filters are connected in parallel with the load to create a low-impedance path for the harmonics, diverting them away from sensitive equipment and preventing their propagation. Active harmonic filters, on the other hand, employ advanced control algorithms and power electronic devices to actively inject compensating currents that cancel out the harmonic components. These filters dynamically adapt to changes in harmonic content and offer precise control over the compensation process, resulting in effective harmonic mitigation [39].

Another approach to mitigate harmonics is through the implementation of grid-interaction standards and guidelines. Utility companies and regulatory bodies often define limits on harmonic distortion levels to ensure power quality and prevent adverse effects on the grid. Compliance with these standards helps to reduce the injection of harmonics into the grid by power electronic systems. It may involve the use of appropriate filtering techniques, compliance testing, and adherence to grid codes and regulations. By adhering to these standards, power electronic systems can minimize their impact on the grid and ensure compatibility with other connected loads and generation sources.

1.7 SUMMARY

The chapter on the fundamentals of power electronics in smart cities provides an overview of the crucial role that power electronics plays in the development and operation of smart cities. It covers the basic principles and key components of power electronics systems and explores their applications and benefits in the context of smart cities. The chapter emphasizes that power electronics is essential for efficient energy conversion, power management, and control in various smart city infrastructure, including smart grids, smart buildings, and electric transportation [40]. It highlights the significance of power quality and reliability considerations in smart cities, discussing the challenges faced in maintaining optimal power quality and the solutions available to address them. The chapter also delves into fault-tolerant strategies and the importance of resilience in power electronics systems, particularly in critical applications where system failures can have severe consequences. Furthermore, the chapter touches upon the integration of power electronics with renewable energy sources, energy storage systems, and grid management techniques, showcasing their role in enhancing sustainability and promoting clean energy utilization in smart cities. In summary, the chapter on the fundamentals of power electronics in smart cities provides a comprehensive overview of the essential aspects of power electronics in the context of smart city development. It highlights the significance of power quality, reliability, and fault-tolerant strategies, while emphasizing the integration of power electronics with renewable energy and energy storage systems. The chapter underscores the vital role that power electronics plays in the efficient and sustainable operation of smart city infrastructure, contributing to improved energy management, enhanced grid stability, and the promotion of clean and reliable power supply.

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