Fusion of Multidisciplinary Research, An International Journal (FMR) , Vol. **3**, Iss. **1**, 2022
https://doi.org/10.63995/YPYR7862

ARTICLE

Acknowledging the Role of Buck Converter in DC-DC Conversion

Sarah Afiq, Maryam Fikri, Rahman Ethan, and Amsyar Isfahann*

Department of Electrical, Electronic and System, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia
*Corresponding author: amsyar.isfa@eng.ukm.my

(Received: 19 October 2021; Revised: 02 January 2022; Accepted: 10 February 2022; Published: 21 February 2022)

Abstract
The buck converter, a type of DC-DC converter, plays a crucial role in modern electronic systems by efficiently stepping down voltage levels. This process is essential for devices that require stable and lower voltage inputs from a higher voltage source, such as batteries or power supplies. The buck converter operates through a combination of switching elements, typically a transistor and a diode, and energy storage components like inductors and capacitors. By rapidly switching the transistor on and off, the converter regulates the voltage output, minimizing energy loss and enhancing efficiency. This capability is pivotal in various applications, including portable electronics, electric vehicles, and renewable energy systems, where efficient power management is critical. The buck converter's ability to maintain high efficiency, compact size, and reliable performance makes it a fundamental component in the design of power supplies for a wide range of electronic devices, contributing to energy conservation and system optimization.

Keywords: DC-DC Conversion; Efficiency; Inductor; Portable Electronics; Power Management; Switching Regulator; Voltage Regulation

Abbreviations: CCM: Continuous Conduction Mode, DCM: Discontinuous Conduction Mode, DCR: DC resistance, SiC: Silicon Carbide

1. Introduction

In modern electronics, the ability to efficiently regulate and convert DC voltages is crucial for powering a wide range of devices. Among the various DC-DC converters, the buck converter stands out as a fundamental component for stepping down input voltages to lower output levels. These efficient power electronics devices utilize a switching topology and energy storage elements to achieve precise voltage regulation, making them invaluable in applications ranging from portable electronics to industrial systems (Fig. 1) [1, 2, 3, 4, 5, 6, 7, 8].

The buck converter operates by controlling the duty cycle of a switching transistor, typically a MOSFET, in conjunction with an inductor and capacitor. During the on-state, the inductor stores energy, while in the off-state, the stored energy is released to maintain the desired output voltage as explained with (Fig. 2). This cyclic operation, combined with feedback control, allows the buck converter to dynamically adjust the output voltage based on load requirements, minimizing current ripple and ensuring high efficiency, often exceeding 90% [9, 10, 11, 12, 13].

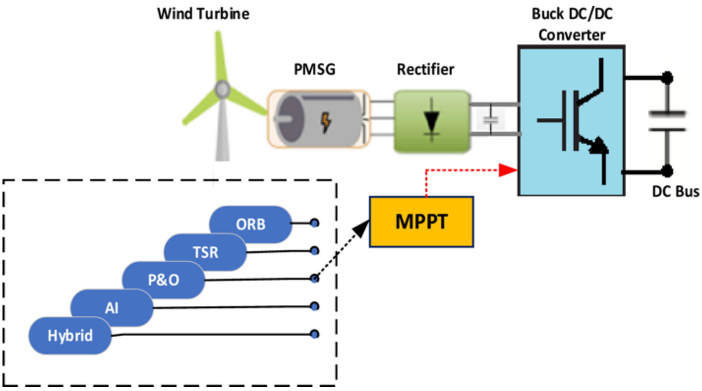


Figure 1. System under consideration.

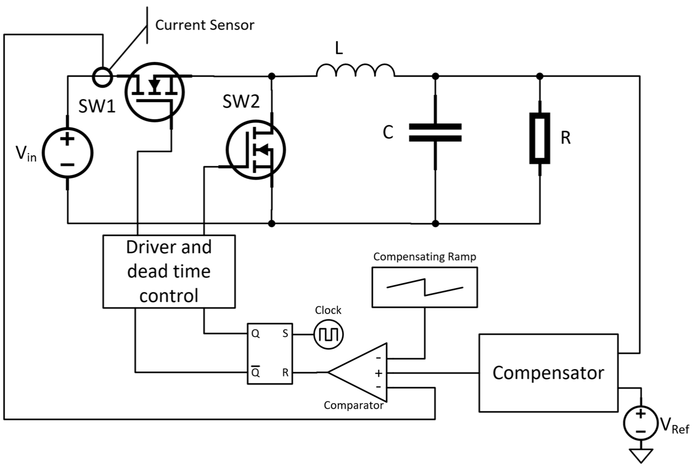


Figure 2. Block diagram of the buck converter under peak-current-mode control.

1.1 Principles of Operation

The buck converter operates by rapidly switching the input voltage on and off to an inductor and capacitor. This switching action is controlled by a transistor or MOSFET, which acts as the switching element. The key principles governing the operation of a buck converter are as follows:

1. **Switching Operation**
   - When the switch is closed (on-state), the input voltage is applied across the inductor, causing the inductor current to ramp up and store energy in its magnetic field.
   - When the switch is open (off-state), the inductor current flows through a freewheeling diode, transferring the stored energy to the output capacitor and load.
2. **Duty Cycle Control**
   - The ratio of the on-time to the total switching period is known as the duty cycle.
   - By adjusting the duty cycle through pulse-width modulation (PWM), the average output voltage can be regulated to a desired level lower than the input voltage.
   - The output voltage is directly proportional to the duty cycle, following the relationship: Vout = D × Vin, where D is the duty cycle.

3. **Continuous and Discontinuous Conduction Modes**
   - In continuous conduction mode (CCM), the inductor current never drops to zero, resulting in a smoother output with lower ripple.
   - In discontinuous conduction mode (DCM), the inductor current drops to zero during each switching cycle, leading to higher ripple but potentially higher efficiency at light loads.
4. **Inductor and Capacitor Filtering**
   - The inductor acts as an energy storage element, smoothing out the pulsating input voltage.
   - The output capacitor filters the inductor's ripple current, providing a relatively constant output voltage to the load.
5. **Feedback Control**
   - A feedback control loop compares the output voltage to a reference and adjusts the duty cycle accordingly to maintain the desired output voltage level.
   - This closed-loop control ensures accurate regulation and compensation for load variations and component tolerances.

The buck converter's ability to efficiently step down voltages while maintaining tight regulation makes it a crucial component in various electronic systems, from portable devices to industrial applications, where precise power management is essential [14, 15, 16, 17].

1.2 Types of DC-DC Converters

The main types of DC-DC converters can be categorized as follows:

1. **Buck (Step-Down) Converters**: These converters efficiently reduce a higher input DC voltage to a lower output voltage. They are widely used in applications where a regulated lower voltage is required from a higher input source.
2. **Boost (Step-Up) Converters**: Conversely, boost converters increase the input voltage to a higher output voltage. They are particularly useful in battery-powered systems where a higher voltage is needed than what the battery can provide.
3. **Buck-Boost Converters**: These versatile converters can either increase or decrease the input voltage as needed, maintaining a stable output voltage. They are suitable for applications where the input voltage can vary above or below the desired output voltage.

Additionally, DC-DC converters can be classified based on their isolation characteristics:

- **Non-isolated DC-DC Converters**: These converters have a direct connection between the input and output circuits, with no electrical isolation between them.
- **Isolated DC-DC Converters**: In these converters, the input and output circuits are electrically isolated, providing enhanced safety and protection against voltage spikes or ground loops as explained in Table 1. Common isolated topologies include:
  - Flyback Converters
  - Forward Converters

Table 1. DC-DC converters are typically categorized as

Input Voltage Range	Converter Type
<40V	Low Voltage
40-70V	Mid Voltage
>70V	High Voltage

Furthermore, there are specialized variations of buck converters, such as:

- **Synchronous Buck Converters**: These replace the freewheeling diode with a second switch, improving efficiency by reducing conduction losses.
- **Multiphase Buck Converters**: These utilize multiple parallel buck converter circuits to improve transient response, reduce output ripple, and increase overall current handling capability.

The choice of converter topology depends on factors such as input voltage range, output voltage requirements, efficiency, isolation needs, and power levels, among others[18, 19, 20].

1.3 Key Parameters and Specifications

When selecting a buck converter for a specific application, several key parameters and specifications must be considered to ensure optimal performance and reliability. These include:

1. **Input/Output Voltage and Current Requirements**:
   - The input voltage range and the desired regulated output voltage are crucial specifications.
   - For low-voltage (LV) buck converters, the typical input range is 2.5V to 5.5V.
   - For high-voltage (HV) buck converters, the input range can be from 4.5V to 18V or even up to 36V.
   - The application's average and peak current requirements should not exceed the converter's rated current, considering power dissipation and thermal conditions.
2. **Switching Frequency**:
   - Switching frequencies in the range of 500kHz to 800kHz are common for 12V applications, balancing size and efficiency.
   - Lower frequencies (< 500kHz) are better suited for high input voltage (> 18V) and high current applications to reduce switching losses.
3. **Control Topology**:
   - Control topologies like Current Mode (CM), Current Mode Constant On-Time (CMCOT), and Advanced Constant On-Time (ACOT®) offer trade-offs in transient response and compensation requirements.
   - The choice depends on the application's specific needs and design constraints.
4. **Operating Modes**:
   - Force-PWM mode maintains a fixed switching frequency across the load range.
   - Pulse Skip Mode (PSM) reduces switching frequency at light loads to improve efficiency but can introduce higher output voltage ripple and larger voltage undershoot during load transients.
5. **Additional Features**:
   - Buck converters may offer additional features like external soft-start, external compensation, programmable frequency, external sync input, low-dropout mode, power good function, and different over-current protection modes.
6. **Package Options**:
   - Package options include CSP, TSOT, DFN, TSSOP with varying pin counts, thermal performance, and cost.
   - Flip-chip packages offer better electrical and thermal performance compared to wire-bonded packages.
7. **Design Parameters**:
   - key design parameters include input/output specifications, duty cycle, switching frequency, inductor selection, and capacitor selection.

- Inductor selection involves calculating the required inductance and selecting a component with the appropriate saturation current rating and DC resistance.
- Output capacitor selection is based on limiting output voltage overshoot and ripple, while input capacitor selection is based on the calculated input ripple current.
- Diode and MOSFET selection must consider power dissipation, voltage drop, and current ratings to ensure reliable operation.

Careful consideration of these key parameters and specifications is essential for selecting the appropriate buck converter and designing an efficient and reliable power conversion system tailored to the specific application requirements [21].

2. Design Considerations

When designing a buck converter, several critical factors must be considered to ensure optimal performance, efficiency, and reliability. These include:

2.1 Inductor Selection

The inductor is a crucial component in a buck converter, and its selection plays a significant role in the overall performance. New developments in winding and core technologies allow specifying inductors at higher power levels, higher frequencies, and higher ripple currents [19]. Factors such as inductance value, saturation current rating, and DC resistance (DCR) must be carefully evaluated to meet the application's requirements.

2.2 Capacitor Selection

The output capacitor plays a vital role in filtering the inductor's ripple current and maintaining a relatively constant output voltage. Larger capacitor values, such as 500 μF, provide better disturbance rejection compared to smaller capacitor values like 150 μF . However, the capacitor's equivalent series resistance (ESR) and voltage rating must also be considered to ensure stable operation.

2.3 Controller Design

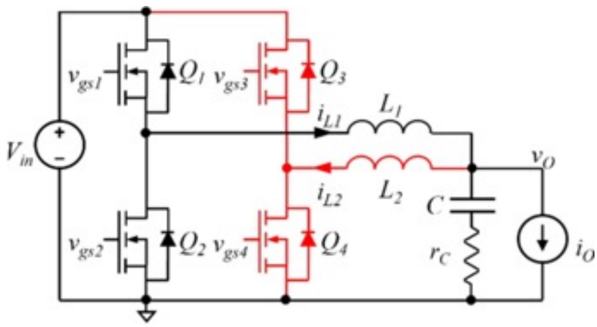
The controller design is critical for maintaining stable performance and accurate voltage regulation. When system parameters like inductor (L) and capacitor (C) values change significantly (e.g., ±10%), the controller design may need to be adjusted to compensate for these variations . Different control topologies, such as current mode, constant on-time, and advanced control modes, offer trade-offs in transient response, compensation requirements, and external component needs as explained in (Fig. 3).

2.4 Power Loss Minimization

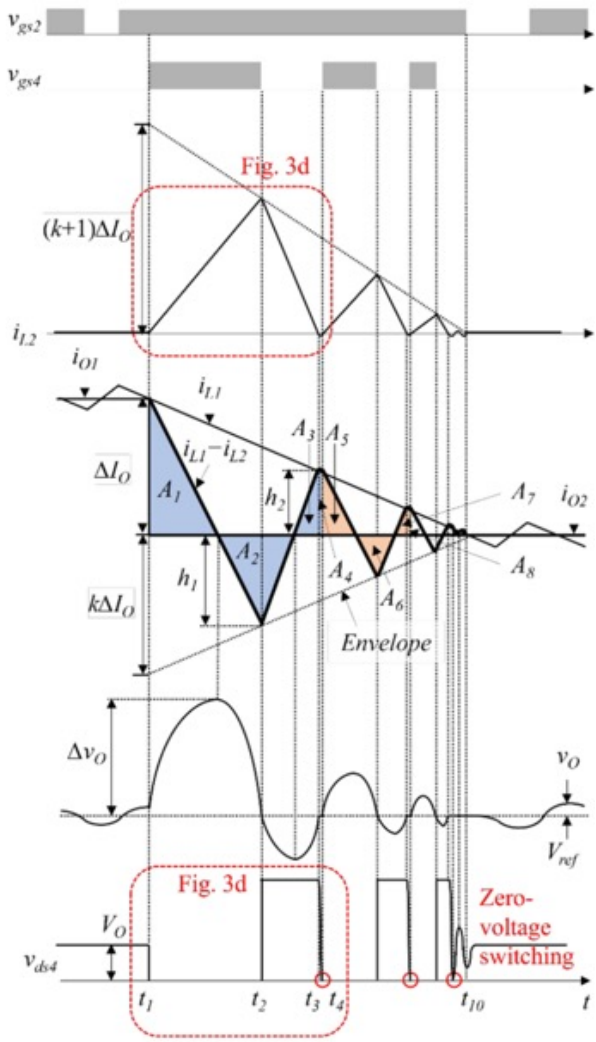
Minimizing power losses is crucial for achieving high efficiency in buck converters. Sources of power losses include:

- Conduction losses in switches, inductor, and diode
- Switching losses in the switches
- Magnetic losses in the inductor
- Capacitive losses

Careful component selection and design techniques, such as synchronous rectification and optimized gate driving, can help maximize efficiency [21, 22, 23].



(a)



(b)

Figure 3. Auxiliary current control

2.5 PCB Layout Considerations

Proper placement and routing of the buck converter components on the printed circuit board (PCB) are essential to avoid performance issues like excessive noise, poor voltage regulation, and instability [24]. Key layout considerations include:

- Placing the input capacitor, inductor, and output capacitor as close as possible to the converter IC to minimize trace lengths and inductance
- Keeping the routing of critical power paths short and using 45-degree or rounded corners on traces to avoid impedance changes
- Ensuring a low-impedance ground routing with the thermal pad of the converter IC connected to the nearest reference plane
- Using PCB design tools with design rule capabilities to set up routing parameters and spacing rules for different power and ground circuits

By carefully considering these design factors, engineers can develop efficient, reliable, and high-performance buck converter solutions tailored to specific application requirements.

3. Applications

Buck converters find widespread applications across various industries and electronic systems due to their ability to efficiently step down voltages while providing precise regulation. Some notable applications include:

1. **Portable Electronics**
   - Used in USB On-The-Go applications, allowing smartphones to power peripheral devices through a bidirectional synchronous buck converter .
   - Employed in battery chargers for smartphones, tablets, and portable power banks to quickly charge batteries without excessive heating .
   - Utilized in battery-powered devices like mobile phones, laptops, and power banks to efficiently step down the battery voltage to the required level for the electronics .
2. **Computing Systems**
   - Serve as Point-Of-Load (POL) converters in PCs and laptops, providing efficient power to low-voltage microprocessors on motherboards .
   - Used as point of load converters to efficiently drive high current loads, often in PCs and motherboards .
3. **Renewable Energy Systems**
   - Incorporated in solar chargers with maximum power point tracking to efficiently charge batteries from solar panels .
   - Utilized in renewable energy systems, such as solar power, to efficiently regulate and manage power from the energy sources .
4. **Automotive Electronics**
   - Employed in automotive electronics for voltage regulation and power management in various systems within the vehicle .
5. **Industrial and Consumer Electronics**
   - Used in industrial automation systems for voltage regulation and power management in various control and monitoring devices .
   - Found in a wide range of consumer electronics, such as TVs, audio equipment, and gaming consoles, to regulate voltage and improve power efficiency .

- Utilized in LED lighting systems to provide the necessary voltage and current regulation for efficient operation .

6. **Motor Control**
   - Synchronous buck converter topology is used in brushless motor controllers to drive the coils of brushless motors .
   - Synchronous buck converter topology is used in brushed motor controllers for high-side motor control .
7. **Power Conversion and Distribution**
   - Used in power factor correction circuits .
   - Employed in distributed power architecture systems .
   - The inversion power stage in pure sinewave power inverters uses a half-bridge topology similar to a synchronous buck converter .
8. **Audio Applications**
   - Class D audio amplifiers use a synchronous buck converter as the power stage .

This wide range of applications highlights the versatility and importance of buck converters in modern electronics, enabling efficient power conversion and management across various industries and devices [24].

4. Efficiency and Power Losses

Achieving high efficiency is a critical design consideration for buck converters, as it directly impacts power losses and thermal management as given in (Fig. 4). Several factors contribute to power losses in these converters:

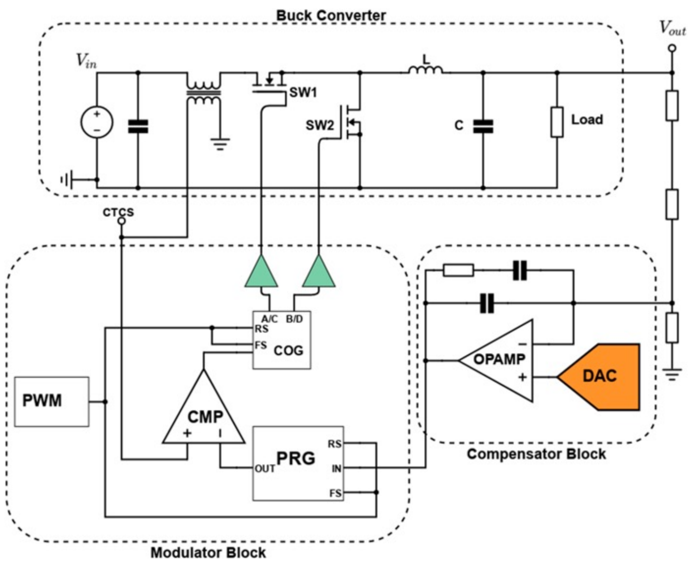


Figure 4. CIP Hybrid Power Starter kit in peak-current-mode control configuration.

1. **Switching Losses**:
   - Switching losses occur during the transition of the power switches (typically MOSFETs) between on and off states.

- These losses are proportional to the switching frequency and can be minimized by selecting MOSFETs with low gate charge and optimizing the gate drive circuitry.
- Buck converters typically operate with a switching frequency range from 100 kHz to a few MHz. Higher switching frequencies allow for smaller inductors and capacitors but also increase switching losses [25].

2. **Conduction Losses**:
   - Conduction losses are caused by the resistance of the power switches, inductor, and other components in the current path.
   - These losses are proportional to the square of the current flowing through the components and their respective resistances.
   - Synchronous rectification, where a low-resistance MOSFET replaces the freewheeling diode, can significantly reduce conduction losses.
3. **Magnetic Losses**:
   - Magnetic losses occur in the inductor due to core losses and winding losses.
   - Core losses are caused by the hysteresis and eddy currents in the magnetic core material.
   - Winding losses are due to the resistance of the inductor windings and the skin effect at high frequencies.
4. **Capacitive Losses**:
   - Capacitive losses are associated with the equivalent series resistance (ESR) of the input and output capacitors.
   - These losses are proportional to the ripple current flowing through the capacitors and their respective ESRs.

To mitigate efficiency losses and improve overall performance, several design techniques and material advancements have been employed:

- **Silicon Carbide (SiC) Power Electronics**: Companies like Alencon have mitigated efficiency losses in isolated DC-DC converters using silicon carbide (SiC) power electronics and value engineered their products to be price-competitive with non-isolated devices [26].
- **Synchronous Rectification**: By replacing the freewheeling diode with a low-resistance MOSFET, synchronous rectification can significantly reduce conduction losses, improving efficiency.
- **Advanced Control Techniques**: Techniques like constant on-time control and advanced current mode control can improve transient response and efficiency across varying load conditions.
- **Optimized Gate Driving**: Proper gate drive circuitry and optimization of gate resistance can minimize switching losses and improve efficiency.
- **Careful Component Selection**: Selecting low-resistance inductors, low-ESR capacitors, and low-resistance power switches can minimize conduction and capacitive losses.

By addressing these sources of power losses through innovative design techniques and material advancements, buck converter manufacturers can achieve high efficiency levels, often exceeding 90% in practical applications [27].

5. Control and Regulation

The thesis focuses on modeling and control of a buck converter, which is a type of DC-DC converter that converts a higher DC voltage to a lower DC voltage . The main objectives are to design a buck converter controller based on discrete polynomial controller theory, implement the controller as a Pulse Width Modulated (PWM) signal, and evaluate the system's performance under various disturbances .

The paper covers the following aspects:

1. **Modeling the Buck Converter System**: Developing a mathematical model to represent the behavior of the buck converter, including its electrical and dynamic characteristics.
2. **Designing a Polynomial Controller**: Using pole placement method, a polynomial controller is designed with the poles placed at z = 0.5 . This controller aims to regulate the output voltage of the buck converter effectively.
3. **Implementation in Simulink/MATLAB**: The buck converter and the designed polynomial controller are implemented in a simulation environment (Simulink/MATLAB) for evaluation and analysis.
4. **Simulation Results and Analysis**: The simulation results demonstrate the ability of the polynomial controller to regulate the buck converter's output voltage to the desired reference voltage, even in the presence of disturbances and noise [28, 29].

Buck converters typically employ two regulating loops for precise control:

- **Voltage Regulation Loop**: This outer loop compares the output voltage to a reference voltage and adjusts the duty cycle accordingly to maintain the desired output voltage . This feedback loop ensures accurate voltage regulation.
- **Current Regulation Loop**: An inner loop measures the output current using a current sensor and provides a feedback signal to the control circuit. This allows the controller to limit the maximum output current , protecting the system from overcurrent conditions.

By incorporating both voltage and current regulation loops, buck converters can independently control the output voltage and current as in Table 2. This dual-loop control architecture offers the following advantages:

Table 2. Current and voltage Regulation Loop

Regulation Loop	Benefit
Voltage Loop	Maintains precise output voltage regulation, compensating for load variations and disturbances.
Current Loop	Limits the maximum output current, preventing overcurrent situations and protecting the load.

The combination of these two control loops enables buck converters to provide stable and reliable power delivery while ensuring protection against overcurrent conditions, making them suitable for a wide range of applications [27, 29].

6. Isolation and Safety

Isolation in DC-DC converters plays a crucial role in ensuring safety and preventing potential hazards. It is a fundamental requirement for power supply equipment placed in the European Union market, as mandated by the EMC Directive and Low Voltage Directive as shown in (Fig. 5) .

These directives reference various harmonized standards, including:

- **IEC/EN 61131-2**: Specific requirements for Programmable Logic Controllers (PLCs).

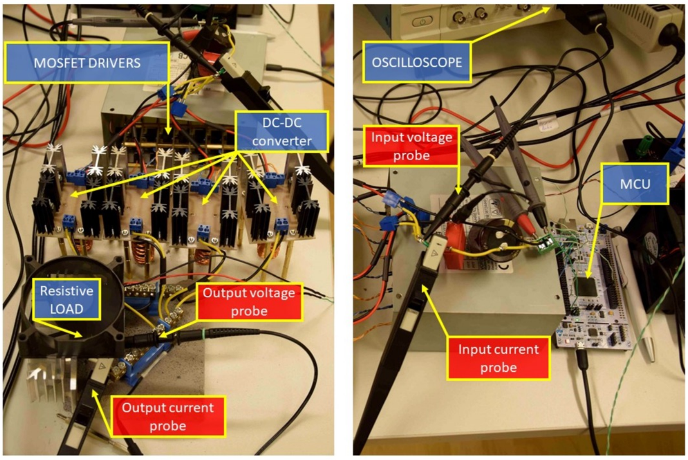


Figure 5. Experimental setup illustration.

- **IEC/EN 61000-6-2/-4**: Generic immunity and emission standards for industrial environments.
- **IEC/EN 60664-1**: Insulation coordination for low-voltage systems.

To comply with these standards, power solutions must meet stringent transient immunity tests specified in the IEC/EN 61000-4 series, which cover electrostatic discharge (ESD), electrical fast transients, lightning surges, and conducted/radiated RF immunity [30].

One solution that addresses these EMC compliance requirements is the Fly-Buck topology, based on the LM5160 synchronous regulator. This topology provides isolated ±12V outputs and a 12V primary-side output, featuring:

- Wide input voltage range
- Isolated outputs via a center-tapped transformer secondary
- EMC filtering
- Tolerance to transformer leakage inductance

Isolation in DC-DC converters serves purposes beyond just protection against electric shock. It helps prevent ground loops, reduces noise, and allows flexibility in output polarity as given in Table 3. The isolation grade depends on the robustness of the isolation barrier, with common classes including:

Table 3. EMC compliance requirements

Isolation Grade	Description
Functional	Transformer windings wound directly over one another, relying on wire lacquer for insulation. Can withstand up to 4 kVdc isolation testing.
Basic	Secure insulation between windings, such as a physical barrier or potted-core construction.
Supplementary	Provides basic insulation in addition to another layer of insulation.
Reinforced	Multiple layers of insulation, making the transformer bulkier but providing higher safety.

Manufacturers like Alencon offer a range of isolated DC-DC converter products, including the SPOT, BOSS, CUBE, GARD, and ACE series. Key benefits of isolated converters include:

- Isolating the grounding between input and output
- Mapping significantly different levels of DC voltage
- Very low capacitance on their output

In multi-converter systems, a non-isolated "intermediate bus converter" (IBC) can be used to step down the input voltage before further conversion by non-isolated "point-of-load" converters. Companies like Flex Power Modules offer several non-isolated IBC products, such as the BMR490, BMR350, BMR351, and BMR310 series, providing high power density, efficiency, and cost-effectiveness compared to isolated solutions [31].

7. Emerging Trends and Future Developments

The DC-DC converter market is experiencing significant growth, driven by increasing demand from various sectors such as industrial and automation, consumer electronics, and medical devices as depicted in (Fig. 6). According to market research reports, the global DC-DC converter market is expected to grow from an estimated $11,348.54 million in 2022 to $20,401.62 million by 2028, at a CAGR of 10.27% during the forecast period [32]. Another report projects the market to reach a value of$7.87 million by 2032, with a CAGR of 6.1% from 2024 to 2032.

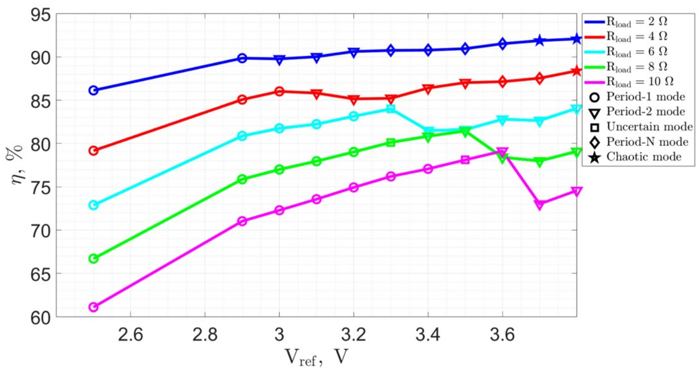


Figure 6. Efficiency dependence.

Several key trends are shaping the future of the DC-DC converter market:

1. **Miniaturization and Integration**: The demand for compact and integrated solutions is driving the development of smaller and more efficient DC-DC converters. This trend is particularly evident in portable and wearable electronics, where space and power constraints are critical.
2. **High-Efficiency Converters**: As energy efficiency becomes increasingly important, there is a growing focus on developing DC-DC converters with higher efficiency levels. This includes the adoption of advanced topologies, wide-bandgap semiconductor technologies, and innovative control algorithms.
3. **Adoption in Electric Vehicles and Renewable Energy**: The rising popularity of electric vehicles and the growing emphasis on renewable energy sources are creating new opportunities for DC-DC converters. These applications require efficient and reliable power conversion solutions to manage and distribute energy effectively.
4. **Digital Control and Advanced Power Management**: The integration of digital control and advanced power management algorithms is enabling more intelligent and adaptive DC-DC con-

verters. These converters can dynamically adjust their operation based on load conditions, optimizing efficiency and performance.

5. **Hybrid and Multi-Stage Converters**: To address diverse power requirements and improve overall system efficiency, researchers and manufacturers are exploring hybrid and multi-stage converter topologies. These converters combine multiple conversion stages, each optimized for specific voltage or current levels as explained in Table 4.

Table 4. Hybrid and Multi-Stage Converters

Key Trend	Description
Miniaturization and Integration	Compact and integrated solutions for space-constrained applications
High-Efficiency Converters	Adoption of advanced topologies and technologies for improved efficiency
Electric Vehicles and Renewable Energy	Growing demand from emerging sectors like EVs and renewable energy
Digital Control and Power Management	Integration of intelligent control and adaptive power management
Hybrid and Multi-Stage Converters	Combining multiple conversion stages for diverse power requirements

The Asia-Pacific region is currently the dominant market for DC-DC converters, driven by the presence of major electronics manufacturing hubs. However, other regions, such as North America and Europe, are also expected to experience significant growth due to the increasing adoption of DC-DC converters in various applications.

8. Conclusion

In conclusion, the buck converter is an indispensable component in the realm of DC-DC conversion, providing efficient voltage regulation essential for numerous electronic applications. Its ability to step down voltage levels with minimal energy loss is crucial for the operation of portable electronics, electric vehicles, and renewable energy systems, where precise and efficient power management is paramount. The integration of switching elements and energy storage components enables the buck converter to achieve high efficiency and reliability, ensuring optimal performance of electronic devices. As technology continues to advance, the role of buck converters will become even more significant, driving innovations in power supply design and contributing to energy conservation efforts. Acknowledging the importance of buck converters underscores the need for ongoing research and development to enhance their capabilities, paving the way

References

[1] Naeim Safari. *Design of a DC/DC buck converter for ultra-low power applications in 65nm CMOS Process.* 2012.

[2] Arjyadhara Pradhan and Bhagbat Panda. "Design of DC-DC converter for load matching in case of PV system". In: *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS).* IEEE. 2017, pp. 1002–1007.

[3] Sadman Sakib, Md Fahim Hasan Khan, Md Ashiqur Rahman, and Md Zamilur Reza. "DC-DC and AC-DC Zeta and buck converter design and analysis for high efficiency application". PhD thesis. Department of Electrical and Electronic Engineering, Islamic University of …, 2017.

[4] Sudip K Mazumder, Muhammad Tahir, and Srividya Lavanya Kamisetty. "Wireless PWM control of a parallel DC-DC buck converter". In: *IEEE transactions on power electronics* 20.6 (2005), pp. 1280–1286.

[5] Dhananjay Choudhary and Anmol Ratna Saxena. "DC-DC buck-converter for MPPT of PV system". In: *International Journal of Emerging Technology and Advanced Engineering* 4.7 (2014), pp. 813–821.

[6] Haoyu Yuze and He Bo. "Microbiome Engineering: Role in Treating Human Diseases". In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 1.1 (2020), pp. 14–24.

[7] Jia-Ming Liu, Pai-Yi Wang, and Tai-Haur Kuo. "A current-mode DC–DC buck converter with efficiency-optimized frequency control and reconfigurable compensation". In: *IEEE transactions on power electronics* 27.2 (2011), pp. 869–880.

[8] Abdullah Altamimi and Zafar A Khan. "A DC-DC buck converter with maximum power point tracking implementation for photovoltaic module application". In: *2017 IEEE Conference on Energy Conversion (CENCON)*. Ieee. 2017, pp. 305–310.

[9] Suresh Singh and Deepak Fulwani. "Voltage regulation and stabilization of dc/dc buck converter under constant power loading". In: *2014 IEEE international conference on power electronics, drives and energy systems (PEDES)*. IEEE. 2014, pp. 1–6.

[10] Shafinaz A Lopa, Shahzad Hossain, MK Hasan, and TK Chakraborty. "Design and simulation of DC-DC converters". In: *International Research Journal of Engineering and Technology (IRJET)* 3.01 (2016), pp. 63–70.

[11] Irfan Jamil, Zhao Jinquan, and Rehan Jamil. "Analysis, Design and Implementation of Zero-Current-Switching Resonant Converter DC-DC Buck Converter". In: *International Journal of Electrical and Electronics Engineering (IJEEE) Vol* 2 (2014), pp. 1–12.

[12] Nakamura Shuto, Akari Chiyo, Himari Ken, and Sato Tanaka. "Quantum Materials to the Pioneering Future of Computing and Communication". In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 1.1 (2020), pp. 50–62.

[13] DW Spier, German Gustavo Oggier, and SAO Da Silva. "Dynamic modeling and analysis of the bidirectional DC-DC boost-buck converter for renewable energy applications". In: *Sustainable Energy Technologies and Assessments* 34 (2019), pp. 133–145.

[14] Vincent Wai-Shan Ng. *Switched capacitor DC-DC converter: Superior where the buck converter has dominated*. University of California, Berkeley, 2011.

[15] Zaohong Yang and PC Sen. "DC-to-DC buck converters with novel current mode control". In: *30th Annual IEEE Power Electronics Specialists Conference. Record.(Cat. No. 99CH36321)*. Vol. 2. IEEE. 1999, pp. 1158–1164.

[16] Carlos Restrepo, Javier Calvente, Angel Cid-Pastor, Abdelali El Aroudi, and Roberto Giral. "A noninverting buck–boost DC–DC switching converter with high efficiency and wide bandwidth". In: *IEEE transactions on Power Electronics* 26.9 (2011), pp. 2490–2503.

[17] Jimeno Estanislau, Federico Hermogenes, and Bernardo Clemente. "Battery Energy Transformation and Unravelling the Thermodynamics of Energy Storage and Conversion". In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 2.1 (2021), pp. 122–135.

[18] Claudio H Rivetta, Ali Emadi, Geoffrey A Williamson, Ranjit Jayabalan, and Babak Fahimi. "Analysis and control of a buck DC-DC converter operating with constant power load in sea and undersea vehicles". In: *IEEE Transactions on Industry Applications* 42.2 (2006), pp. 559–572.

[19] Jeffrey Hwang, Alland Chee, and Wing-Hung Ki. "New universal control methods for power factor correction and DC to DC converter applications". In: *Proceedings of APEC 97-Applied Power Electronics Conference*. Vol. 1. IEEE. 1997, pp. 59–65.

[20] Fang Lin Luo and Hong Ye. *Advanced dc/dc converters*. crc Press, 2016.

[21] NH Baharudin, TMNT Mansur, FA Hamid, R Ali, and MI Misrun. "Performance analysis of DC-DC buck converter for renewable energy application". In: *Journal of Physics: Conference Series*. Vol. 1019. IOP Publishing. 2018, p. 012020.

[22] Humam Al-Baidhani, Thomas Salvatierra, Raúl Ordóñez, and Marian K Kazimierczuk. "Simplified nonlinear voltage-mode control of PWM DC-DC buck converter". In: *IEEE Transactions on Energy Conversion* 36.1 (2020), pp. 431–440.

[23] Bauyrzhan Satipaldy, Taigan Marzhan, Ulugbek Zhenis, and Gulbadam Damira. "Geotechnology in the Age of AI: The Convergence of Geotechnical Data Analytics and Machine Learning". In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 2.1 (2021), pp. 136–151.

[24] Fang Lin Luo and Hong Ye. *Essential Dc/Dc Converters*. CRC Press, 2018.

[25] K Bendaoud, S Krit, M Kabrane, H Ouadani, M Elaskri, K Karimi, H Elbousty, and L Elmaimouni. "Fuzzy logic controller (FLC): Application to control DC-DC buck converter". In: *2017 International Conference on Engineering & MIS (ICEMIS)*. IEEE. 2017, pp. 1–5.

[26] Sharmila Sumsurooah, Milijana Odavic, Serhiy Bozhko, and Dushan Boroyevich. "Robust stability analysis of a DC/DC buck converter under multiple parametric uncertainties". In: *IEEE Transactions on Power Electronics* 33.6 (2017), pp. 5426–5441.

[27] Paulo Henrique Feretti and Fernando Lessa Tofoli. "A DC-DC buck-boost converter based on the three-state switching cell". In: *2017 Brazilian Power Electronics Conference (COBEP)*. IEEE. 2017, pp. 1–6.

[28] Adrichem De Jong, Mark Jansen, Jeffrey Van Dijk, and Johannes Meyer. "Analysis of Innovative Practices in Advanced Materials and Structural Engineering". In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 2.1 (2021), pp. 178–188.

[29] Sudip K Mazumder, Ali H Nayfeh, and Dushan Boroyevich. "Theoretical and experimental investigation of the fast-and slow-scale instabilities of a DC-DC converter". In: *IEEE Transactions on Power Electronics* 16.2 (2001), pp. 201–216.

[30] Mustafa Abbas Fadel Al-Qaisi, Mohanad A Shehab, Ammar Al-Gizi, and Mohammed Al-Saadi. "High performance DC/DC buck converter using sliding mode controller". In: *International Journal of Power Electronics and Drive Systems* 10.4 (2019), p. 1806.

[31] Seong Joong Kim, Qadeer Khan, Mrunmay Talegaonkar, Amr Elshazly, Arun Rao, Nathanael Griesert, Greg Winter, William McIntyre, and Pavan Kumar Hanumolu. "High frequency buck converter design using time-based control techniques". In: *IEEE Journal of Solid-State Circuits* 50.4 (2014), pp. 990–1001.

[32] Yan Zhang, Jinjun Liu, Xiaolong Ma, and Junjie Feng. "Comparison of conventional DC-DC converter and a family of diode-assisted DC-DC converter in renewable energy applications". In: *Journal of Power Electronics* 14.2 (2014), pp. 203–216.