Key Technologies and Development Trends of DC-DC Converters in Smart Grid Applications

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Abstract. As important parts that can realize efficient energy conversion and control in power electronic system, the DC-DC converters become more and more important with the continuous development of smart grid technology which are widely used in smart grid system. This paper performs a review of the main technologies, development trends in smart grids to comprehensively examine the types of technologies, operational principles, usage conditions, development status of these devices. First of all, an introduction to the basic principle and types of DC-DC converters both non-isolated as well as isolated converters. Also is it about applicable areas for each type. afterward, the paper will show some applications of the DC-DC converters to the smart grid like integration of distributed energy resources, Energy Storage Systems, EV chargers, etc. to prove the converters will help improve flexibility, reliability, and energy efficiency of the grid. The article carries out an analysis of the main technologies of the DC-DC converter and shows the role played by the converter in the system. Finally, after this review, this paper wants to give a certain amount of theoretical basis and technical references to those who are engaged in a similar field of work, and at the same time, this paper also hope that this research can help with the development of Dc—Dc converters used in smart grids.

Keywords: DC-DC converter, smart grid, distributed energy, energy storage system, electric vehicle charging.

1. Introduction

The global energy structure is undergoing continuous improvement, leading to a sustained increase in the intelligence level of power systems. Smart grids, as an essential component of modern power systems, are increasingly becoming the core driving force for promoting efficient energy utilization and sustainable development [1]. By integrating advanced information and communication technologies with automated control methods, smart grids can significantly enhance the operational efficiency and stability of power systems, while also enabling precise regulation of energy consumption [1]. In industrial electrical systems, the implementation of smart grids facilitates energy consumption reduction and improved energy utilization efficiency, thereby making it easier to achieve energy-saving and emission-reduction goals. In recent years, the growing proliferation of distributed energy resources, along with the widespread application of energy storage systems and electric vehicles (EVs), has imposed more stringent requirements on the power system. DC-DC converters are crucial power electronic devices that interface different voltage levels and energy forms, making them essential in smart grids. To accommodate the integration requirements of clean energy sources such as photovoltaics, fuel cells, and wind power generation, there is a need to design DC-DC converters featuring high voltage gain, low power loss, and low switch voltage stress [2]. Such converters not only enhance system compatibility but also improve overall efficiency. With the significant rise in EV ownership, the development of charging infrastructure necessitates higher technical standards for DC-DC converters. Isolated bidirectional multi-port DC-DC converters based on Gallium Nitride (GaN) devices have demonstrated superior efficiency and dynamic response capability in EV charging systems [3]. This progression validates that technological advancements in DC-DC converters are instrumental in making smart grids more efficient, flexible, and reliable. The evolution of smart grids imposes more rigorous demands on DC-DC converters, and the sustained deepening of related research will ensure technical support for the intelligent transformation of power systems.

2. Basic Principles and Classification of DC-DC Converters

2.1. Basic Operating Principle of DC-DC Converters

DC-DC converters are power electronics which converts a DC voltage to some other DC voltage, mainly matching the voltages at the input and output and the transmission and regulation of power. DC-DC converters have a number of different topologies, and so they also have a number of different strategies for controlling the circuit, meaning there are a number of different options for converting different voltage, such as a step up (boost), and a step down (buck). Their working principles are mainly achieved by periodically switching devices such as MOSFETs and IGBTs, using energy storage components like inductors and capacitors for energy storage and release. Take the buck converter as an example: while the switch is in the on position, the input voltage charges through the inductor, and stores energy into this inductor; when the switch from on to off, the inductor will release that energy through a diode to load, meaning that the output will be less than the input voltage. Bidirectional DC-DC converters can realize energy flow in two directions, making them suitable for the charge and discharge control of energy storage systems. Furthermore, their dynamic response capability is crucial. When sudden load changes or input voltage fluctuations occur in a smart grid, the converter must rapidly adjust the output voltage to maintain system stability. For instance, in the research of Current-Fed Dual Active Bridge (CF-DAB) DC-DC converters, optimizing magnetic integration technology not only increased power density and widened the voltage range but also significantly enhanced stability across the load range [4]. Regarding the basic operating principle of DC-DC converters, there are generally three points: switching control, energy storage and dissipation, and voltage modification. It is their performance that directly affects whether all kinds of application system work effectively.

2.2. Common Types of DC-DC Converters

2.2.1. Non-isolated DC-DC converter

Non-isolated DC-DC converter has a simple structure and is often adopted in the places where the electrical isolation isn't strictly required. Common types include the Buck, Boost, and Buck-Boost converters. The Buck Converter controls a switch that is turned on and off, which lowers the input voltage into whatever the desired output voltage is making the Buck converter perfect for LEDs where the input voltage has to be higher than the output voltage, as in an LED driver. on the other end, a boost converter cooperates with both of its energy storage circuit inductor and a capacitor to step up the level from input voltage to a significantly high value, which is used in photovoltaic system. The buck-boost converter can be utilized as either stepping up or down, so it can be used for some complex situations where input voltage can be higher or lower than the voltage output for instance, in an electric vehicle battery management system. There are also some modified non-isolated DC-DC converters like the Cuk and the Sepic converters. Non-isolated DC-DC converters have the highest cost effect and the highest energy efficiency, but they do not have galvanic isolation, which is also a problem in a high voltage or high safety environment.

2.2.2. Isolated DC–DC Converter

Isolated DC-DC converter uses a transformer to isolate the input and output, so it is relatively safe and can work under better anti interference conditions. These converters can prevent the DC parts, while changing the step-up and step-down, and they are commonly used for stuff like when researchers want to include distributed power generation into a smart grid. The most common forms of isolated DC-DC converters are DAB converters, Flyback Converter and Forward Converter. DAB converters are really efficient and have little loss, they also have a good dynamic response so they do well for medium and high-power stuff. The efficiency of the DAB converter using ZVS is greater than 95 percent. And it can also transfer energy in both directions, so it is suitable for energy storage vehicle and electric car's bi-directional charging and discharging. The Flyback converter relies on the energy storage and release process of the transformer, regulating the duty cycle to stabilize the output voltage, and is commonly used in low-power scenarios. But it can only transmit energy in one direction, which is not suitable for high-power transmission. The operating principle of the Forward converter is similar to the Flyback converter, but it achieves continuous energy transfer by adding a freewheeling diode, thereby increasing the output power and efficiency. Isolated DC-DC converters are a critical component within smart grids. With the continuous advancement of power electronic technology, isolated DC-DC converters are constantly improving in terms of efficiency, reliability, and integration, which drives the high-efficiency operation and sustainable development of smart grid systems.

3. Applications of DC-DC Converters in Smart Grids

3.1. Specific Applications of DC-DC Converters in Smart Grids

3.1.1. Applications in Distributed Energy Access

In a smart grid, the output of Distributed Energy Resources (DERs), such as photovoltaic (PV) and fuel cells, is typically low voltage and highly fluctuating. Therefore, DC-DC converters are essential to step up and stabilize the voltage for grid connection. To address this requirement, isolated and non-isolated high-gain converters are the two primary technical solutions. Isolated three-level DC-DC converters are suitable for medium-voltage grid-tie applications. Alkaloid Khaled et al. proposed a converter integrating a three-level neutral-point-clamped (NPC) circuit with a full-bridge structure. This topology significantly reduces switching losses using the zero-current switching (ZCS) technique and limits the voltage stress on the switches to only half the input voltage. This effectively broadens the converter's adaptability range to PV output voltage fluctuations. Coupled with dual-transformer isolation and simple PWM control, this solution achieves an efficiency of 97.9% and a voltage gain of 42 times while ensuring safety. It is capable of meeting the medium-voltage DC grid-connection requirements for large-scale PV power stations [5]. Conversely, non-isolated coupled-inductor DC-DC converters offer the advantages of high-power density and low cost, making them more suitable for DC microgrids. Nader Mohammadi Ali et al. developed an ultra-high step-up converter based on a two-winding coupled inductor (CI). This design achieves ultra-high gain at a low duty cycle through the cooperative control of the coupled inductor turn ratio and the duty cycle, thereby avoiding the conduction loss issue associated with high duty cycles in conventional circuits. Both the power switch and multiple diodes operate under zero-current switching (ZCS), and the voltage stress on the switch is low (e.g., approximately 1/3 of the output voltage when $n=1.5$), allowing the selection of low-voltage-rating devices to further reduce losses. A 150W prototype, utilizing a single-core design, achieved an efficiency of 95.47% and a power density of 3.72 mW/mm^3. Its non-isolated common-ground structure helps suppress electromagnetic interference (EMI), making it highly suitable for short-distance, high-efficiency connection of distributed energy sources [6].

Table 1. Key Performance Comparison of Two Categories of DC-DC Converters for Distributed Energy Resource Integration [5-6]

Characteristics Dimensions	Isolated Three-Level Converter	Non-isolated Coupled- Inductor Converter
Core Topology	Isolated Three-Level NPC + Dual Transformer	Non-isolated Dual-Winding Coupled Inductor
Technical Features	Zero-current Switching (ZCS), Galvanic Isolation, Simple PWM Control	Zero-Current Switching (ZCS), Dual-Parameter Control of Duty Cycle and Turns Ratio, Common Ground (CG)
Power Density	Not Explicitly Emphasized	3.72 mW/mm³
Efficiency	97.9%	95.47% (at 150W)
Switch Voltage Stress	Approximately Half the Input Voltage	Significantly Lower than Output Voltage (e.g., when n=1.5, approximately 1/3 of the output)

Table 1 clearly illustrates the distinct positioning of the two DC-DC converter technology approaches. The solution proposed by Alkhaledi Khaled focuses on safety, reliability, and medium-voltage applications, making it suitable for long-distance grid connection of large-scale distributed energy resources. Unlike, Nader Mohammadi Ali’s scheme is focused on cost-effectiveness, compactness, and flexibility, which makes it the best fit for being the Distributed Energy Interface inside of DC microgrids. The combination of the two solutions gives a spectrum of technological solutions for the integration of Distributed Energy Resource (DER) into the smart grids; solutions are differentiated for different applications.

3.1.2. Applications in Energy Storage Systems

In smart grids, the Energy Storage System (ESS) is a key component for maintaining grid stability, enabling energy time-shifting, and achieving power balance. As the interface between energy storage units and the DC bus, the performance of DC-DC converters directly affects system efficiency, reliability, and response speed. In recent years, multi-port DC-DC converters have been widely adopted in energy storage systems due to their compact structure and flexible control. Currently, technological developments primarily focus on two core objectives: enhanced system stability and high-efficiency power management. DC microgrid is low-inertia power, it's power perturbation on the bus voltage of DC microgrid. Liang Yuxin's team proposed an Improved Virtual Capacitance (IVC) control strategy for isolated multi-port converters (FPICs). This strategy innovatively enables the virtual capacitance value C_vir to be dynamically adjusted based on the rate of change and the deviation of the DC bus voltage. Especially as the severity of the voltage disturbance increases, it can improve inertia and decrease voltage changes during the recovery period, it successfully achieves a balance between inertia and dynamics. Secondly, by adopting power allocation with respect to state of charge (SOC), it can make certain that each parallel ESS unit does an autonomous power sharing and SOC equalizing management, to make the overall system have higher long-term operations' availability [7]. In some cases, like EV fast-charging, Liu Shiqiang et al created a non-isolated MP-BDC. It is mainly because of the interleaving parallel connection and a switched-capacitor network that can obtain a high voltage conversion ratio. Therefore, this kind of high efficiency like EV fast-charging is matched well with the big range of voltage conversion from the low-voltage store to a high-DC-bus voltage. To deal with the problem in the current sharing for multi-port system, the research comes up with the asymmetric duty cycle limit control, A-DLC. This way the average inductors currents across all the ports will be equal in terms of the whole span of duty cycle time. Though there will be some great change to circuit parameters, the system still has very good robust. It is self-balancing nature so it’s quite easy to control. Using SiC mosfet on this, Liu's team got around a 98% of efficiency on a 2.5kw prototype and a compact, highly efficient power storage in the system [8]. And the team headed by Liang and Liu’s relevant research results are listed in Table 2 as follows.

Table 2. Comprehensive Comparison of Two Technical Approaches for DC-DC Converters in Energy Storage Systems [7-8]

Comparison Dimensions	Isolated - Virtual Inertia Control Approach	Non-isolated - Current Self-Balancing Approach
Main Topology Structure	Full-Bridge Interleaved Converter (FPIC)	Full-Bridge Interleaved Converter (FPIC)
Key Technology	Improved Virtual Capacitance (IVC) Control	Asymmetric Duty-cycle Limit Control (A-DLC)
Core Problem Solved	1. Voltage fluctuations caused by low inertia in DC microgrids 2. Power and SOC balancing among multiple energy storage units	1. High conversion ratio requirement between low-voltage energy storage and high-voltage bus 2. Inherent current balancing across multiple ports
Technical Advantages	1. Dynamic Inertia Support: Adjustable inertia, balancing stability and fast recovery 2. Smart Management: SOC-based active power sharing	1. High Efficiency: Peak efficiency >98% 2. High Robustness: Automatic current sharing even with parameter deviation 3. High Power Density: More compact non-isolated structure

4. Key Technologies of DC-DC Converters

4.1. Advanced Control Strategies

It is needed to have control strategies to have a good dynamic performance and robustness from the DC-DC converter. Traditional PID control and PWM do have their own application fields instead state, they are good for maintaining balance, but in cases where there's some kind of uncertainty, if researcher's facing something like a change in the input voltage, if there's a sudden load change, traditional controls just aren't really up to snuff. In recent years or so has been a period of swift emergence for model-based robust control. Ahmad et al proposed a robust switching control method based on a parameter estimation with an equilibrium point of the controller with real time estimates of the input voltage and load current, obtaining a global stable region. and it has a hysteresis and a noise suppression as well, meaning it increases how useful this system is in reality [9].

4.2. Application of Wide-Bandgap Power Devices

The wide band-gap semiconductors such as SiC and GaN replaces most silicon-based gadgets due to their advantage, being able to have a high breakdown field and thermal resistance and have a high switching frequency. Parvez et al. also stated that GaN HEMTS and SiC MOSFETs will reduce switching losses by a large quantity which in turn making converters dense and more efficient at high frequency and temperatures. For example, a GaN - based Boost converter maintains over 92% efficiency at a switching frequency of 200 kHz, which is far from the Si - IGBT solutions that are way below [10]. Furthermore, the trend toward integration of GaN devices provides possibilities for realizing more compact and efficient power modules.

4.3. Modular and integrated design technologies

Modular and integrated design can boost the performance of DC-DC converter in smart grid, the performance and power are achieved by building sub-modules flexibly, and the system level performance will be more effective and reliable as the result of superior topological integration.

An important aspect of modular design has to do with balancing voltages of series connected modules. To address this, an integrated self-voltage balancing scheme has been proposed. In an output-series structure based on dual half-active bridges, Sun Changjiang et al. embedded an LC resonant branch between adjacent modules to form a non-isolated resonant dual-active bridge. This design utilizes the low impedance characteristic of the resonant circuit at the switching frequency to automatically equalize the output voltages of the modules without additional sampling or control circuits. Meanwhile, the soft-switching feature of the original converter is preserved, achieving high efficiency and high reliability [11].

For application scenarios requiring high step-up ratios and high-power levels, such as renewable energy DC collection systems, another dynamically reconfigurable modular topology has demonstrated advantages. A topology developed by Li Binbin's team incorporates half-bridge/full-bridge submodules, thyristors, and diodes. Through time-sequencing control, all submodules are periodically connected in parallel on the low-voltage side to share current and in series on the high-voltage side to withstand voltage. This "parallel charging, series discharging" mechanism optimizes stress distribution from a system architecture perspective, significantly improves device utilization, and achieves both high efficiency and low cost [12].

The modular and integrated designs have evolved from basic combinations to deep integrated involving the integration of the system solution. This is a prerequisite for the DC-DC converter to be able to meet the requirements of the smart grid's high voltage and high power in the future.

5. Conclusion

DC-DC converters are an important part in the effective electrical energy conversion and control, so it is an important role in smart grids such as having distributed sources. In general, the first thing is to talk about the basic working principles and types of DC - DC conversion: and goes on to mention the use of DC-DC converters in smart grids. Then for its key technologies, it introduces the research situation of advanced control strategy, and another related research. This literature goes through the issues and roads map in technologically application scenario in DC-DC which will help electrical engineer to see how these new ways of development on technology compares to side. And also, some latest updates. It lays down a theoretical basis and practical guidance for the development of Smart Grid Systems with good, stable, high-frequency, and compact power conversion systems.

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