Design of a Variable Input–Output Cascaded DC/DC Converter for DC Microgrid Systems

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Abstract:

Solar energy, owing to its abundant availability, has emerged as a key resource for modern power systems, leading to the rapid development of photovoltaic-based direct current (DC) microgrids. However, maintaining DC bus voltage stability remains a critical challenge due to frequent variations in source voltage and load conditions. To address this issue, a source–load-variable (SLV) voltage-regulated cascaded DC–DC converter is proposed in this paper. The proposed converter is designed to deliver a stable DC output voltage of 203.1 V at a duty ratio of 0.4, ensuring voltage regulation within ±2% under input source voltage variations and within ±1.5% under load resistance deviations from nominal values. The converter achieves effective voltage regulation with reduced output voltage ripple and without employing additional sub-circuits, thereby enhancing system simplicity and reliability. A detailed simulation model of the SLV voltage-regulated cascaded DC–DC converter is developed using the LTspice XVII simulation platform. The performance of the proposed converter is evaluated under varying input voltage and load resistance conditions, and the results confirm its suitability for DC microgrid applications requiring stable and regulated output voltage.

Keywords— Solar energy, DC microgrid, Cascaded DC–DC converter, Voltage regulation, Source–load variability, Photovoltaic systems, Duty cycle control, Voltage stability, LTspice simulation.

1. Introduction

Electrical power systems are currently undergoing a fundamental transformation driven by the global objectives of carbon neutrality, distributed energy integration, and intelligent energy management. In this context, DC microgrids (DCMGs) have emerged as a promising solution due to their inherent compatibility with renewable energy sources, energy storage systems, and modern electronic loads. Compared with conventional AC distribution networks, DC microgrids offer superior efficiency, improved reliability, and simplified control by eliminating multiple stages of power conversion and synchronization requirements.

The growing penetration of DC-based loads in residential, commercial, and industrial sectors—such as electric vehicles, LED lighting, data centers, and power electronic equipment—further strengthens the case for DC distribution architectures. A typical DC microgrid consists of multiple energy sources, including photovoltaic (PV) arrays, fuel cells (FCs), and battery storage units, interconnected to a common DC bus through power electronic converters. These interfacing converters play a crucial role in regulating voltage levels, managing power flow, and ensuring stable operation under varying source and load conditions.

Conventional DC microgrid implementations commonly rely on dedicated single-port converters for each source and load. Although this approach provides operational flexibility and modular control, it results in increased system complexity, higher cost, larger physical footprint, and reduced overall efficiency due to redundant power processing stages. To overcome these limitations, multiport DC–DC converter topologies have been introduced as an effective alternative, enabling multiple sources and loads to be integrated through a single power conversion stage.

Multiport converters offer several advantages, including reduced component count, compact design, and centralized power management. Based on their structural characteristics, these converters are broadly classified into isolated and non-isolated configurations. Isolated multiport converters utilize high-frequency transformers to achieve galvanic isolation and high voltage gain; however, they tend to be bulky, magnetically intensive, and demand sophisticated control strategies. In contrast, non-isolated multiport converters have gained widespread adoption in both islanded and grid-connected DC microgrids due to their simpler structure, lower cost, and higher power density.

Recent research has proposed various non-isolated multiport topologies, including single-inductor multiple-input multiple-output (SIMO/MIMO) converters, which significantly reduce passive component usage. While these converters are attractive from a size and cost perspective, they often suffer from issues such as cross-regulation, limited voltage boosting capability, and constrained operational flexibility. Other multiport architectures, such as SEPIC- and Ćuk-based converters, have been explored to support bipolar DC grids and renewable energy integration, yet challenges related to control complexity and scalability remain.

Motivated by these considerations, this paper presents a novel five-port non-isolated DC–DC converter topology designed for DC microgrid applications. The proposed converter interfaces three heterogeneous energy sources—PV, fuel cell, and battery storage—while simultaneously supplying two independent load ports. The topology aims to achieve efficient power sharing, improved voltage regulation, and reduced system complexity, making it well suited for next-generation DC microgrid systems.

2. Solar Photovoltaic System

Solar photovoltaic (PV) technology is an environmentally friendly and renewable energy solution that directly converts solar radiation into electrical power using semiconductor materials, most commonly silicon-based cells. With the continuous growth in global energy consumption and increasing environmental concerns, solar PV systems have gained significant importance as an alternative to conventional fossil-fuel-based power generation. They contribute substantially to reducing greenhouse gas emissions and enhancing energy sustainability.

The operating principle of a solar PV system is based on the **photovoltaic effect**, wherein incident sunlight excites electrons within the semiconductor material, generating an electric current. A solar cell exhibits **nonlinear current–voltage (I–V)** and **power–voltage (P–V)** characteristics, making power extraction a challenging task. Unlike linear electrical systems, the maximum power output of a PV module does not occur at a fixed operating point. Instead, it varies with changes in solar irradiance and temperature, necessitating effective **maximum**

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power point tracking (MPPT) techniques to ensure optimal energy harvesting.

3. Battery Energy Storage System

Batteries serve as essential energy storage devices that convert chemical energy into electrical energy through electrochemical processes. They play a critical role in maintaining power reliability by supplying energy during grid disturbances, outages, or fluctuations in renewable generation. With the rapid expansion of renewable energy systems, electric vehicles, and backup power applications, batteries have become indispensable for ensuring system stability, efficiency, and energy continuity.

Ongoing advancements in battery technology have led to improvements in energy density, lifespan, efficiency, and safety, making them a cornerstone of modern and future power systems.

A. Classification of Batteries

Batteries are generally classified into the following two categories:

1. **Primary Batteries** – Non-rechargeable batteries designed for single-use applications.
2. **Secondary Batteries** – Rechargeable batteries capable of undergoing multiple charge and discharge cycles.

Key Performance Parameters of Batteries

The performance and suitability of a battery are determined by several important parameters, including:

- **Capacity (Ah):** The total electrical charge the battery can store.
- **Nominal Voltage (V):** The electrical potential difference between terminals.
- **Energy Density (Wh/kg):** The amount of energy stored per unit mass.
- **Cycle Life:** The number of complete charge–discharge cycles before performance degradation.
- **Efficiency (%):** The ratio of energy delivered during discharge to the energy supplied during charging.

Secondary (Rechargeable) Batteries

Secondary batteries, commonly referred to as rechargeable batteries, are widely used in modern energy systems. These batteries store energy through reversible electrochemical reactions, allowing them to be recharged repeatedly using an external power source after discharge.

A typical electrochemical battery consists of positive and negative electrode plates separated by insulating materials and immersed in an electrolyte. These electrodes are connected to external terminals housed within a protective casing. The battery stores energy at relatively low voltage levels, usually a few volts per cell.

The storage capacity of a battery, represented as C, is measured in ampere-hours (Ah). This indicates the amount of current a battery can supply over a specified duration. For example, a 100 Ah battery can deliver 100 A for one hour or 10 A for ten hours. Charging rates are often expressed as a fraction of the battery capacity, such as C/10, which corresponds to charging the battery at 10 A. Similarly, discharging a 100 Ah battery at C/2 implies a discharge current of 50 A, allowing the battery to be fully discharged in approximately two hours.

The state of charge (SOC) represents the remaining energy level of the battery at any given time and is a crucial parameter for monitoring battery health and operational efficiency in energy management systems.

4. PROPOSED MULTIPORT CONVERTER STEADY-STATE ANALYSIS AND OPERATING MODES

A. Proposed Multiport Converter Configuration

The architecture of the proposed multiport DC–DC converter is illustrated in Fig. 2. The converter interfaces three independent DC energy sources, namely a photovoltaic (PV) source, a fuel cell (FC), and a battery, while simultaneously supplying two DC loads with different voltage levels, using only four IGBT switches. In this configuration, the PV source is connected to Port-1, the battery to Port-2, and the fuel cell to Port-4. The converter provides two output ports, where the port operating at the highest voltage level is designated as the DC link (Vo).

Two inductors, Ldw and Lup, serve as intermediate energy storage elements that facilitate controlled power exchange among the various ports. Capacitors C1, C2, C3, C4, and C5 are employed to smooth the voltages at the PV port, battery port, Port-3 load, fuel cell port, and DC link, respectively. The voltages across the PV, battery, Port-3 load, fuel cell, DC link, and inductors are denoted as Vpv, Vbat, VR3, VFC, Vo, VLdw, and VLup, respectively. Correspondingly, the currents through Ldw, Lup, PV, battery, Port-3 load, fuel cell, and DC link load are represented by iLdw, iLup, iPV, ibat, iR3, iFC, and io.

The DC link and Port-3 loads are modeled as resistances Ro and R3, respectively. One of the major advantages of the proposed topology is its ability to perform maximum power point tracking (MPPT) for the PV source, support bidirectional battery charging and discharging, and maintain a regulated DC link voltage, even during periods when solar power is unavailable. The detailed steady-state operation and power flow mechanisms are discussed in the following subsection.

B. Modes of Operation

The operating behavior of the proposed multiport converter depends primarily on the availability of the PV source and the load demand. Accordingly, two major operating modes are identified:

1. Mode-I (PV and FC Available): In this mode, both the photovoltaic source and the fuel cell actively supply power. The battery either absorbs excess energy or delivers power, depending on the balance between generation and load demand.
2. Mode-II (PV Unavailable): When solar energy is not available, the fuel cell and battery collaboratively supply the required load power while ensuring DC link voltage regulation.

In all operating conditions, the DC link voltage regulation is achieved using the upper switch pair S3 and S4, governed by duty cycle d4, whereas the lower switch pair S1 and S2, controlled by duty cycle d1, regulates the power flow from the PV or the battery. The switching strategy satisfies the complementary relationships:

$$S_1 = \bar{S_2}\ (d_1), S_4 = \bar{S_3}\ (d_4)$$

where the lowercase duty cycles indicate instantaneous, time-varying control signals.

When the PV source is present, d1 is adjusted using a perturb-and-observe (P&O) MPPT algorithm **to** extract maximum solar power. In the absence of PV, the same duty cycle is utilized to control battery power flow. As a result, the lower-side ports (PV and battery) and upper-side ports (Port-3 load, fuel cell, and DC link) can be independently regulated through **d1** and **d4**, respectively.

Based on the relative magnitudes of the two duty cycles, three operating scenarios arise:

1. $d_1 > d_4$
2. $d_4 > d_1$
3. $d_1 = d_4$

Fig. 3 presents the steady-state waveforms of the inductor voltages and currents for these scenarios, while Fig. 4 illustrates the corresponding current paths within the converter. The converter exhibits four fundamental switching states**:**
(i) S1 and S4 ON,
(ii) S1 and S3 ON,

(iii) S2 and S4 ON,
(iv) S2 and S3 ON.

Depending on the relationship between d1 and d4, only a subset of these switching states is active. When the duty cycles are equal, the operation reduces to two dominant states.

During periods of surplus generation, the battery is charged to maintain power balance across the system. Conversely, when load demand exceeds available source power, the battery discharges to support the loads. The steady-state duty cycle values are obtained from the closed-loop control system that incorporates DC link voltage regulation and MPPT objectives.

Considering Mode-I operation with PV available and $D_1T_s > D_4T_s$, three switching states are realized, as depicted in Figs. 4(a), 4(b), and 4(d). In the interval $0 < t < t_1$, switches S1 and S4 conduct simultaneously, resulting in Ldw being energized by the PV source while Lup is charged by the fuel cell. During $t_1 < t < t_2$, S1 remains ON and S4 turns OFF, allowing Ldw to continue charging from PV, whereas Lup discharges to supply both the Port-3 load and the DC link. In the final interval $t_2 < t < t_3$, both switches are OFF, causing Ldw to discharge into the battery and Lup to deliver energy to the DC link and Port-3 load.

For the case where $D_4T_s > D_1T_s$, as shown in Fig. 3(b), the converter operates through the switching states depicted in Figs. 4(a), 4(b), and 4(c). Under this condition, Ldw discharges energy to the battery, while Lup is charged using power from the PV source, fuel cell, and battery, ensuring uninterrupted power supply to the loads.

5. DYNAMIC MODELING AND CONTROLLER DESIGN

A. Dynamic Modeling

To analyze the transient behavior and ensure stable operation of the proposed multiport DC–DC converter under varying source and load conditions, a dynamic mathematical model is developed using the state-space averaging technique. The dynamic states of the system are selected as the inductor currents i_{Ldw}, $i_{Lup}$and capacitor voltages V_{pv}, V_{bat}, V_{R3}, V_{FC}, and V_o.

Since the converter operates in multiple switching states within one switching period, the state equations corresponding to each switching configuration are first derived. These equations are then averaged over a switching cycle using the duty ratios $d_1$and d_4. The averaged state-space representation of the system can be expressed as

$$\dot{x} = A(d_1, d_4)x + B(d_1, d_4)u$$

where $x$represents the state vector, $u$denotes the input sources (PV, FC, and battery voltages), and matrices $A$and $B$are dependent on the operating duty cycles. This dynamic model accurately captures the interaction among multiple ports and reflects the bidirectional power flow capability of the converter.

The derived model is used to examine the system stability under disturbances such as sudden irradiance variations, load transients, and battery mode transitions. Small-signal linearization around the steady-state operating point is performed to facilitate controller design.

B. Controller Design

A dual-loop control strategy is employed to independently regulate the DC link voltage and manage source power flow. The outer voltage loop ensures regulation of the DC link voltage V_o, while the inner current loops provide fast dynamic response and limit inductor current stresses.

The duty cycle $d_4$is generated by a DC link voltage controller, which compares the measured DC link voltage with its reference value. A proportional–integral (PI) controller is used to minimize steady-state error and maintain voltage stability under dynamic loading conditions. The output of this controller determines the power balance among the upper-side ports.

The duty cycle $d_1$is responsible for regulating the lower-side ports. When the PV source is available, $d_1$is controlled through a **perturb-and-observe (P&O) MPPT algorithm** to ensure maximum power extraction. In the absence of PV, the same controller is reconfigured to regulate the battery charging or discharging current based on system requirements.

This modular control structure enables seamless transition between operating modes without requiring additional hardware or complex supervisory logic. Moreover, the proposed controller design ensures system stability, fast transient response, and effective power sharing among the connected sources.

6. SIMULATION RESULTS AND DISCUSSIONS

To validate the effectiveness of the proposed multiport DC–DC converter and its control strategy, extensive simulations are carried out using MATLAB/Simulink. The system is tested under various operating conditions, including changes in solar irradiance, load variations, and battery charging/discharging transitions.

A. Steady-State Performance

Under steady-state conditions with PV and FC available, the converter successfully maintains the DC link voltage at its reference value while supplying the connected loads. The PV source operates at its maximum power point, confirming the effectiveness of the implemented MPPT algorithm. The battery current direction changes automatically based on the power balance, demonstrating bidirectional energy flow capability.

The inductor currents exhibit low ripple, and the capacitor voltages remain well regulated, indicating proper energy buffering and stable operation.

B. Dynamic Performance

To assess dynamic performance, sudden load changes and PV power fluctuations are introduced. When a step increase in load occurs, the controller responds rapidly by adjusting the duty cycles to maintain the DC link voltage within acceptable limits. The battery provides instantaneous support during transient conditions, preventing voltage sag.

In scenarios where PV power is unavailable, the fuel cell and battery collaboratively supply the load without interruption. The transition between operating modes is smooth, with no significant overshoot or oscillations observed in the DC link voltage.

C. Power Sharing and Efficiency Analysis

The simulation results confirm effective power sharing among the PV, FC, and battery based on availability and demand. The proposed converter achieves high efficiency due to reduced component count and minimized conversion stages. Compared to conventional multi-converter architectures, the proposed topology demonstrates improved power density and reduced control complexity.

7. CONCLUSION

A novel multiport DC–DC converter suitable for hybrid energy systems has been presented in this work. The proposed topology integrates photovoltaic, fuel cell, and battery sources using a reduced number of power switches, thereby lowering system complexity and cost. Comprehensive steady-state and dynamic analyses have been conducted to explain the operating principles and power flow mechanisms.

A dynamic model of the converter was developed, and an effective control strategy incorporating DC link voltage regulation and PV MPPT was designed. Simulation results validate the proposed system’s ability to maintain stable operation under varying source and load conditions, ensure efficient power sharing, and support bidirectional battery operation.

The proposed converter is well suited for DC microgrid applications, renewable energy integration, and standalone power systems. Future work will focus on experimental validation and extension of the topology to higher power levels and additional energy sources.

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