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REVIEW ON DC-DC POWER CONVERTER TOPOLOGIES AND CONTROL TECHNICS FOR HYBRID STORAGE SYSTEMS

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ABSTRACT

Hybrid storage systems combine advantages of the different energy storage technologies, such as lithium-ion batteries and supercapacitors. Bidirectional power converters are dedicated to interface storage units to the grid and ensure bidirectional power flow. Proper control and energy management technics have to be applied to ensure efficient and optimal power distribution in the hybrid energy storage. In this paper, a review of bidirectional dc-dc converter topologies relevant to hybrid energy storage, including non-isolated, isolated, and interleaved topologies has been presented. Several control strategies including current-mode control, power control, and sliding mode control have been reviewed.

Keywords: hybrid energy storage system, dc-dc power converter, control of dc-dc power converter, energy management, lithium-ion batteries, supercapacitors

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1. INTRODUCTION

The problem of global warming has made the world society to reduce utilization of fossil fuels and to move ahead renewable energy sources (RES). One of the advantages of the electric energy is that it can be received from clean and efficient renewable sources, such as wind and solar. However, due to the volatile nature of these energy sources, large energy storage systems have to be utilized in the power system in order to maintain the instant balance of power generation and consumption.

Nowadays, a few technologies have been developed allowing to store energy in large scales such as pumped hydroelectric storage (PHES), compressed air energy storage (CAES), flywheel, thermal energy storage (TES) and a number of electrochemical storage systems. PHES and CAES are associated with large capital cost and tied to a specific location of installation. Flywheel energy storage and TES have low power and energy density comparing to electrochemical energy storage systems. The most mature electrochemical storage technologies available on the market are Li-ion, Ni-Cd, NaS and lead-acid batteries. Flow batteries and fuel cells are promising technologies but they are in the developing state yet.

A good option is the combination of different storage technologies in one hybrid energy storage system (HESS) [1]. For example, lithium-ion batteries have relatively high energy density. On the contrary, supercapacitors (SC) have relatively high power density, but a low energy density. Furthermore, Li-ion batteries have limited cycle lifetime, whereas supercapacitors' cycle lifetime is much bigger. Combination of these two technologies using solid-state power electronics devices allows prolonging battery lifetime and decreasing operating costs of an energy storage system.

For efficient HESS utilization, it is important to apply proper control and energy management algorithm. In this paper, a review of dc-dc converter topologies for HESS application and control technics is represented.

2. BIDIRECTIONAL DC-DC CONVERTER TOPOLOGIES

Bidirectional power converters play a key role in power transfer from/to HESS. During the charging mode, the energy comes from the grid or RES and stored in the storage devices. When the grid is not available or additional power is required for the load, that is during the discharging mode, the power flows from the storage devices to the dc bus. To ensure bidirectional power flow capability, the converter utilizes bidirectional power devices as switches. Normally, they are semiconductor devices with antiparallel diodes allowing positive and negative current flow as well as positive and negative voltage blocking capabilities. In this Section, selected non-isolated, isolated and interleaved bidirectional dc-dc converter topologies relevant to the energy storage application are reviewed.

2.1. Bidirectional Buck-Boost DC-DC Converter

Fig. 1 shows a bidirectional buck-boost dc-dc converter [2]. This topology is able to step up or step down the voltage with power flow in both directions. During the charging mode, the converter operates as a buck converter and charges the battery from the dc bus at a voltage V_{DC}. During the discharging mode, the converter operates as a boost converter to transfer power from the battery to the dc bus. Appropriate control algorithms determine the operation mode of the converter.

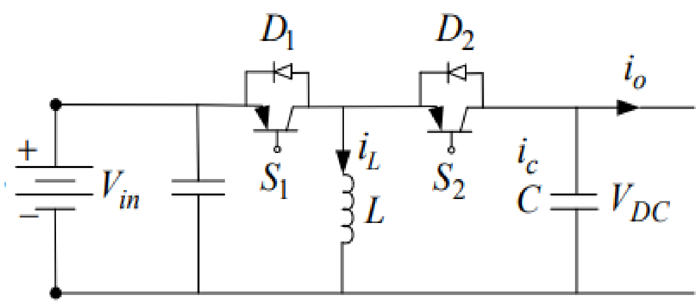

Figure 1 Circuit diagram of the bidirectional dc-dc buck-boost converter [2]

2.2. Bidirectional Buck/Boost DC-DC Converter for Hybrid Storage Systems

A typical topology, including a battery and a supercapacitor, is depicted in Fig. 2. It is suitable for low-cost, power balance control. A supercapacitor is a typical high-power device with long cycle lifetime and fast response, whereas battery is a typical high-energy device with high energy capability, and high energy density but limited cycle lifetime. Battery and supercapacitor can have any voltage level, thus their energy is fully utilized. The control algorithm needs to be employed to choose the appropriate storage unit depending on the type of disturbance or unbalance that needs to be mitigated.

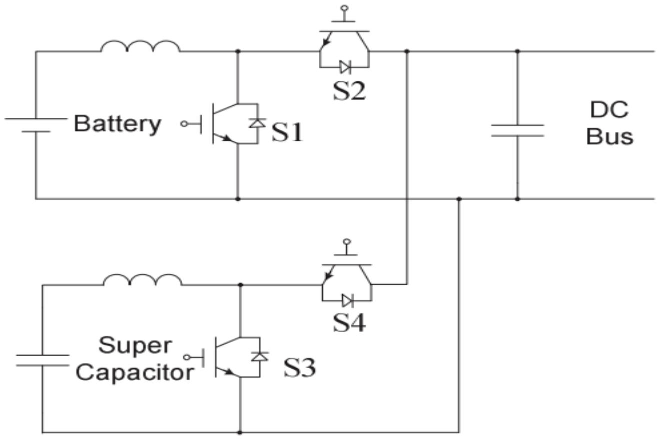

Figure 2 Bidirectional buck/boost converter with common dc bus [3]

2.3. Bidirectional Full-Bridge DC-DC Converter

Topology in Fig. 3 provides galvanic isolation necessary for sensitive and critical loads. A bidirectional full- bridge dc-dc converter utilizes four switches of the low-voltage side bridge and four switches of the high-voltage side bridge. A transformer provides isolation between low-voltage and high-voltage sides and extra conversion ratio. The battery is usually connected to the low-voltage side. During the charging mode, power flows from high-voltage side to low-voltage side and the converter operates as a buck converter. The high-voltage-side bridge acts as an inverter and low-voltage-side bridge acts as a rectifier. During the discharging mode, their operation is reversed. In this case, the power flows from the battery to the dc bus and the converter operates as a boost converter.

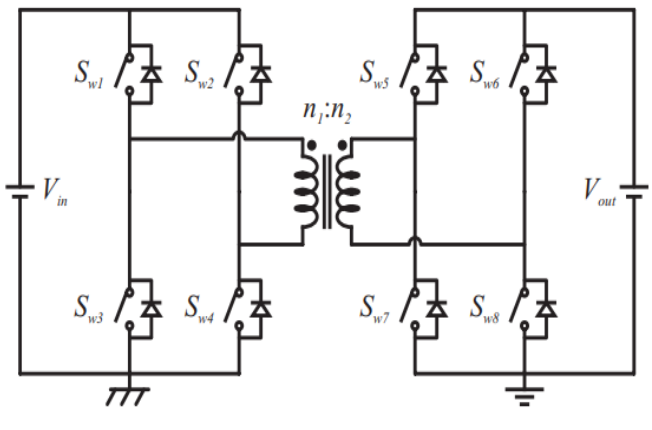

Figure 3 Bidirectional full-bridge dc-dc converter [4]

2.4. Multi-Phase Interleaved Bidirectional DC-DC Converter

In order to obtain high power density, the converters are often operated in discontinuous current mode. This may result in high current ripples, which may decrease the battery health. To solve this issue, multi-phase interleaved dc-dc converters are applied. A three-phase interleaved bidirectional dc-dc converter is shown in Fig. 4. The current is divided between the three phases, allowing to reduce current stresses and inductor and capacitor sizes. A very high power density can be achieved. There is an appropriate phase differences between the three phases, allowing to minimize the total inductor current. The switching losses are reduced and the converter efficiency is increased due to the soft-switching techniques.

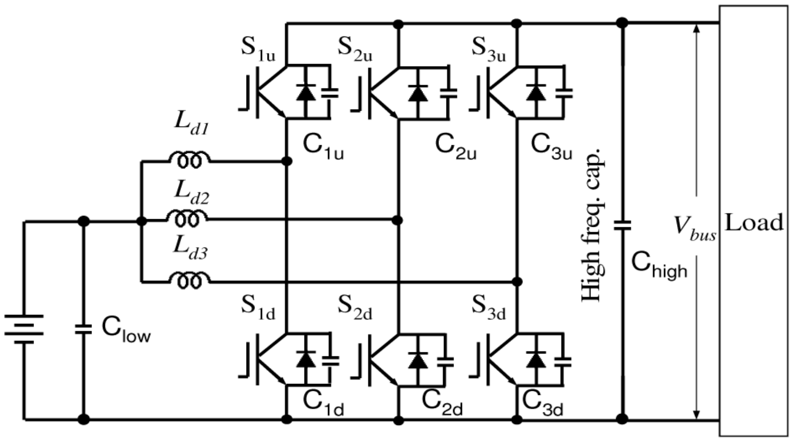

Figure 4 Bidirectional three-phase interleaved dc-dc converter [5]

2.5. Multi-Port DC-DC converters

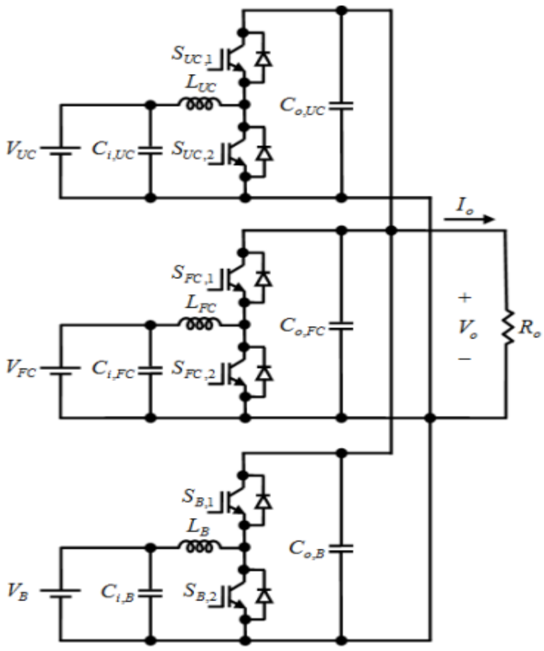

Figure 5 Bidirectional multi-port dc-dc converter [6]

The multi-port dc/dc converters help to utilize the different types of dc voltage sources. The multi-port dc/dc converters are divided into single-input multi-output, multi-input single-output, and multi-input multi-output converters. The multi-input multi-output dc/dc converters can combine the different types of dc voltage sources with different volt-ampere characteristics in input side and generate different levels of dc voltages at the output side. The main aim of using these converters is to reduce the cost and number of power electronic components and to increase the reliability and efficiency of the overall system. Generally, these converters have simple topology, central control, high reliability and low construction cost. Fig. 5 shows an example of the multi-port dc-dc converter including fuel cell, ultra-capacitor and battery [6].

3. CONTROL TECHNICS

The appropriate control strategy of HESS is necessary for detection of the mode of operation, controlling the direction and amount of power transfer to and from the storage unit, and seamless transition between modes, ensuring stability and power quality. This Section represents the most frequently applied control technics.

3.1. Current-Mode Control

The aim of the bidirectional converter control is to maintain the dc bus voltage constant and to regulate charging/discharging current. These targets can be achieved with a current-mode control containing two feedback loops. The inner loop controls current and the outer loop controls voltage. Fig. 6 shows a synchronous buck converter with current-mode control [7]. The inductor current is the battery charging/discharging current. The current controller controls the inductor current. The dc link voltage is the input voltage during the charging mode and the output voltage during the discharging mode. Current-mode control has such advantages as fast response time and short-circuit protection comparing to traditional voltage-mode control. However, it is vulnerable to instability and sub-harmonic oscillations.

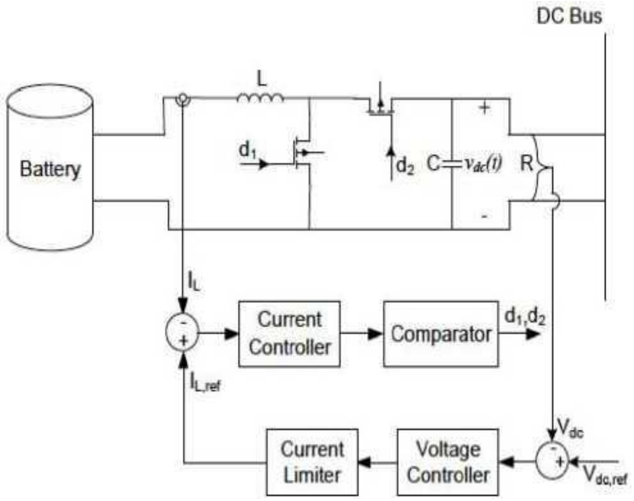

Figure 6 Synchronous buck converter with current-mode control [7]

3.2. Power Control

In the grid-connected mode, the controller task is to track battery state-of-charge (SOC). During the islanded mode, the microgrid stability and power quality should be the highest priority for the controller. In [2], during the grid-connected mode, battery control is based on SOC control. During the islanded mode, fuzzy control [8] or advanced droop control [9] is applied based on the amount of voltage disturbance (Fig. 7).

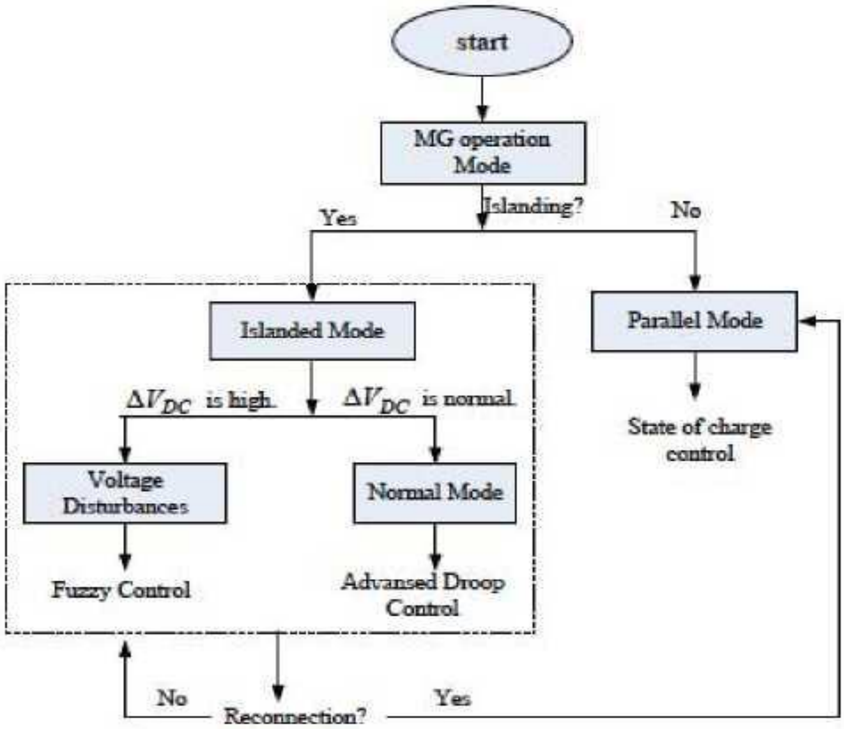

Figure 7 Power control algorithm [2]

3.3. Energy Management

In passive HESS topologies, the power flow will be divided according to the internal impedance of the sources. Thus, supercapacitors in parallel to the battery will carry fast power deviations and prevent the battery from frequent partial discharges. In the active scheme, the power distribution can be achieved with the help of the linear filtering technics. The power reference can be calculated according to the response time of the sources. The low-frequency power is assigned to the long-term storage device, i.e. the battery, and the rest of the load power can be stored or produced by the short-term storage, such as supercapacitors.

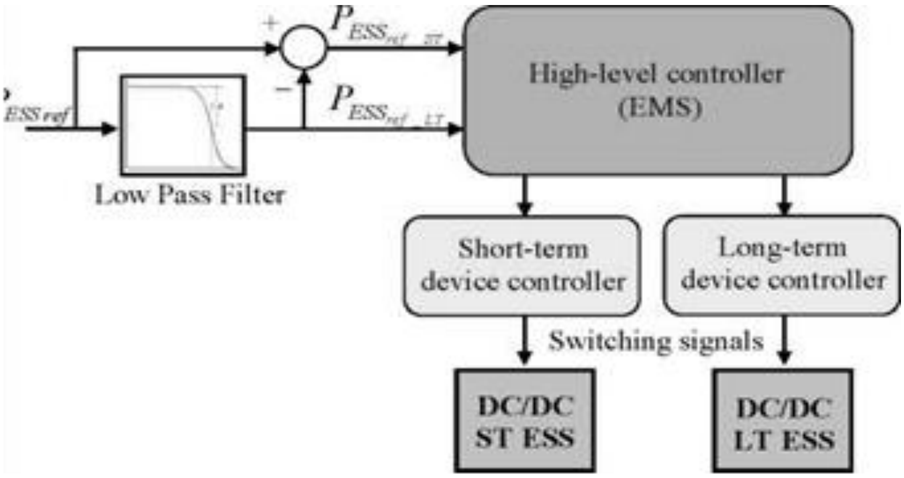

Figure 8 Example of energy management using linear filtering [10]

The linear filtering method is not enough to coordinate HESS in all modes of operation, but it can be used as the base part of the control algorithm. The following parts of the energy management scheme should take into account the power losses of the storage devices, their response times and state of charges, the power-energy limitations and in some cases predictions of the power generated by the RES. The following steps can use more complex algorithms depending on multiple variables and factors, such as the rule-based, fuzzy and neural network-based algorithms. An example of the linear filtering application for energy management in HESS is shown in Fig. 8.

4. CONCLUSIONS

Due to volatile nature of the renewable energy sources, the energy storage systems are the key technology for improving security, stability, and power quality of the power system with high penetration of distributed energy resources. The best characteristics are obtained when different energy storage devices are combined in hybrid energy storage system. Power electronic converters are applied as the interface between the energy storage units and the power system or load. Proper control and energy management technics have to be applied to ensure efficient and optimal power distribution in the hybrid energy storage.

In this paper, a review of bidirectional dc-dc converter topologies relevant to hybrid energy storage, including non-isolated, isolated, and interleaved topologies has been presented. The choice of the appropriate bidirectional converter topology and the control algorithm is crucial for the reliable and stable operation of the system. Several control strategies including current-mode control, power control, and sliding mode control have been reviewed in this paper.

The future research can be dedicated to design and modelling of the control systems of the bidirectional converters, especially for advanced topologies with different modes of operations.

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