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Bidirectional DC-DC Converters for Energy Storage Systems

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1. Introduction

Bidirectional dc-dc converters (BDC) have recently received a lot of attention due to the increasing need to systems with the capability of bidirectional energy transfer between two dc buses. Apart from traditional application in dc motor drives, new applications of BDC include energy storage in renewable energy systems, fuel cell energy systems, hybrid electric vehicles (HEV) and uninterruptible power supplies (UPS).

The fluctuation nature of most renewable energy resources, like wind and solar, makes them unsuitable for standalone operation as the sole source of power. A common solution to overcome this problem is to use an energy storage device besides the renewable energy resource to compensate for these fluctuations and maintain a smooth and continuous power flow to the load. As the most common and economical energy storage devices in medium-power range are batteries and super-capacitors, a dc-dc converter is always required to allow energy exchange between storage device and the rest of system. Such a converter must have bidirectional power flow capability with flexible control in all operating modes.

In HEV applications, BDCs are required to link different dc voltage buses and transfer energy between them. For example, a BDC is used to exchange energy between main batteries (200-300V) and the drive motor with 500V dc link. High efficiency, lightweight, compact size and high reliability are some important requirements for the BDC used in such an application.

BDCs also have applications in line-interactive UPS which do not use double conversion technology and thus can achieve higher efficiency. In a line-interactive UPS, the UPS output terminals are connected to the grid and therefore energy can be fed back to the inverter dc bus and charge the batteries via a BDC during normal mode. In backup mode, the battery feeds the inverter dc bus again via BDC but in reverse power flow direction.

BDCs can be classified into non-isolated and isolated types. Non-isolated BDCs (NBDC) are simpler than isolated BDCs (IBDC) and can achieve better efficiency. However, galvanic isolation is required in many applications and mandated by different standards. The complexity of IBDCs stems from the fact that an ac link must be present in their structure in order to enable power transfer via a magnetically isolating media, i.e. a transformer.

In this chapter, first some NBDC structures are briefly discussed. As isolation and/or voltage matching is required in many applications, more attention in this chapter is paid on the description of different IBDC configurations. It should be stated that in order to improve the efficiency, almost all recently proposed medium-power IBDC configurations have exploited the benefits of soft-switching or resonant techniques to increase the switching frequency and achieve lower size and weight. In this regard, although a variety of configurations employing soft-switching techniques has been proposed by researchers, they can be divided into a few basic families. In this chapter, IBDCs employing soft-switching techniques are divided into three basic families and investigated in more details. Resonant IBDCs which can be considered as a separate family are not covered in this chapter (Krismer et al., 2005; Li, & Bhat, 2010).

2. Non-isolated BDC

Basic dc-dc converters such as buck and boost converters (and their derivatives) do not have bidirectional power flow capability. This limitation is due to the presence of diodes in their structure which prevents reverse current flow. In general, a unidirectional dc-dc converter can be turned into a bidirectional converter by replacing the diodes with a controllable switch in its structure. As an example, Fig. 1 shows the structure of elementary buck and boost converters and how they can be transformed into bidirectional converters by replacing the diodes in their structure. It is noteworthy that the resulted converter has the same structure in both cases.

Fig. 2 shows the basic waveforms associated with Fig. 1.c. In the buck mode of operation, i.e. when the power is transferred from the high voltage (HV) to the low voltage (LV) side, Q_1 is the active switch while Q_2 is kept off. In the boost mode, i.e. when the power is transferred from LV to HV side, Q_2 acts as a controlled switch and Q_1 is kept off. The switching pattern during power (current) reversal is also shown in Fig. 2. The presence of inductor in the LV side results in lower ripple current which is advantageous in some applications. For example, it is usually preferred to charge/discharge batteries with low ripple current in order to achieve higher efficiency and longer life time.

Some of the major limitations associated with the NBDC shown in Fig. 1.c are:

- It can only operate in buck mode in one direction and boost in the other. In technical terms, this means that the voltage ratio d, which is defined as $d= V_B/V_A$, is either smaller or greater than unity in one direction.
- When the voltage ratio becomes large, this structure becomes impractical.
- The lack of galvanic isolation between two sides.

Many improved structures have been proposed to overcome the first two limitations. When the magnitude of two dc bus voltages is close to each other and the voltage ratio of smaller or greater than unity is required, the buck-boost or Cuk converters are the appropriate choice. Fig. 3.a shows the basic configurations of a NBDC based on buck-boost converter. Note that the polarity of dc buses is reverse with respect to a common ground which is a burden in many applications. This problem can be resolved by adding more switches to this configuration as shown in Fig. 3.b. This new configuration can be envisaged as two back-to-back connected converter of Fig. 1.c.

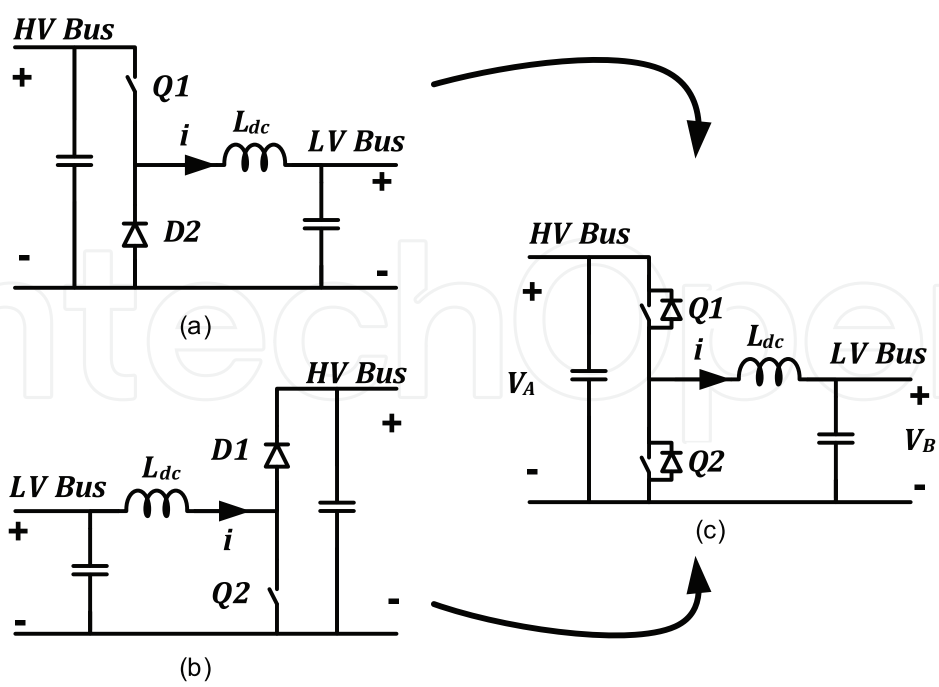


Fig. 1. (a) Elementary unidirectional buck converter, (b) elementary unidirectional boost converter and (c) transformation to bidirectional converter by substituting diodes with a controllable switch.

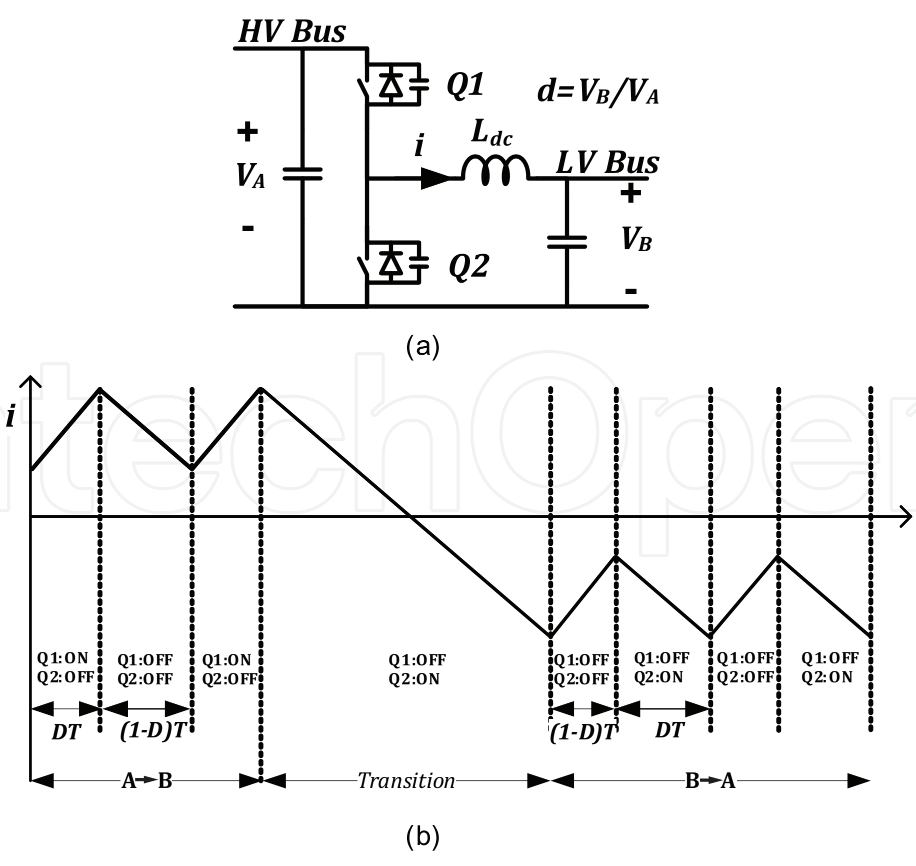
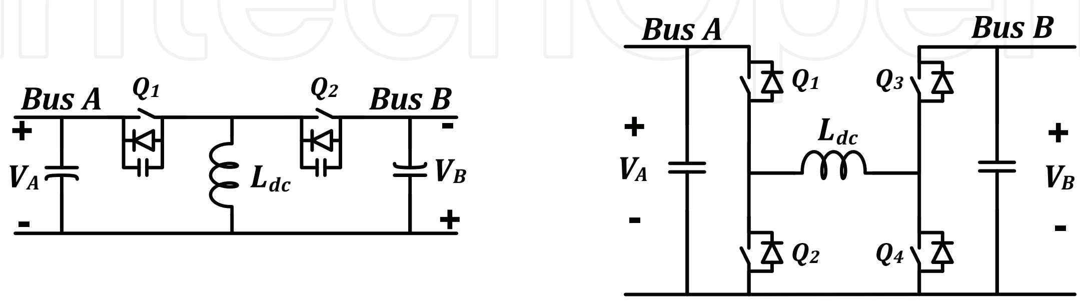


Fig. 2. (a) Basic NBDC and (b) operating waveforms.

The operation of the NBDC of Fig. 3.a is as follows. The inductor is the main energy transfer element in this converter. In each switching cycle it is charged through source side active switch for the duration of $T_{on}=DT$, where $T=1/f_{sw}$ is the switching period and D is the duty-cycle. This energy is then discharged to load during $T_{off}=(1-D)T$. In the four-switch buck-boost converter (Fig. 3.b) the principle of operation is the same. In the left to right power transfer mode, Q_1 and Q_4 act as active switches, while in the right to left power transfer the opposite switches (Q_2 and Q_3) are controlled. Synchronous rectification technique can be employed in this configuration in order to add more features and improve efficiency.



(a) (b)

Fig. 3. (a) Bidirectional buck-boost and (b) two back-to-back connected NBDC of Fig. 1.c.

There are other variants of NBDC proposed by researchers. An example is shown in Fig. 4 with the following advantages:

- The structure is symmetrical.
- It inherently has low ripple current on both sides.
- It employs only two switches which simplifies the driver circuitry and decreases the driving power.
- It can work with wide voltage range and different voltage ratios.
- It has intrinsic protection against short circuit.

3. Isolated BDC (IBDC)

Galvanic isolation between multi-source systems is a requirement mandated by many standards. Personnel safety, noise reduction and correct operation of protection systems are the main reasons behind galvanic isolation.

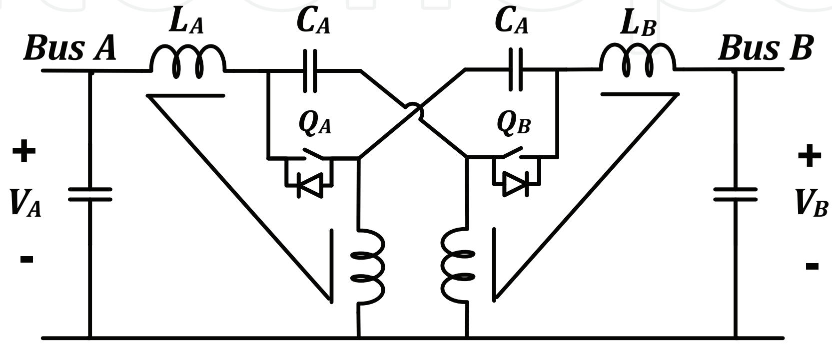


Fig. 4. A different structure for NBDC

Voltage matching is also needed in many applications as it helps in designing and optimizing the voltage rating of different stages in the system. Both galvanic isolation and voltage matching are usually performed by a magnetic transformer in power electronic systems, which calls for an ac link for proper energy transfer. Although this approach is similar to unidirectional dc-dc converters, the need to bidirectional power flow significantly adds to the system complexity. Furthermore, when high efficiency soft-switching techniques are to be applied, this complexity tends to be more.

In this section, the basic structure of common IBDCs is explained. While different terminologies have been proposed and used in the literature, a unified terminology is introduced and used throughout the paper to simplify the comparison between different structures. A classification is provided which helps in understanding the conceptual similarities and differences between different structures.

3.1 IBDC structure

Most, if not all, of medium-power IBDCs have a structure similar to Fig. 5. This structure consists of two high-frequency switching dc-ac converters and a high-frequency transformer which is primarily used to maintain galvanic isolation between two sources. This transformer is also essential for voltage matching in case of large voltage ratio between two sources. The transformer calls for ac quantities at its terminals and thus a dc-ac converter is employed on each side. As energy transfer in either direction is required for the system, each dc-ac converter must also have bidirectional energy transfer capability. With the same token, the dc buses in this structure must also be able to either generate or absorb energy. The dc buses shown in this structure are assumed to have stiff-voltage characteristics, i.e. their Thevenin impedance is negligible. In practice, these buses are connected to a dc source or an active load like battery, ultra-capacitor or dc-link capacitor which resemble an ideal voltage source with stiff voltage characteristics. If the converter is of current-fed type, it is assumed that the required elements to realize stiff current are incorporated inside the converters shown in Fig 5.

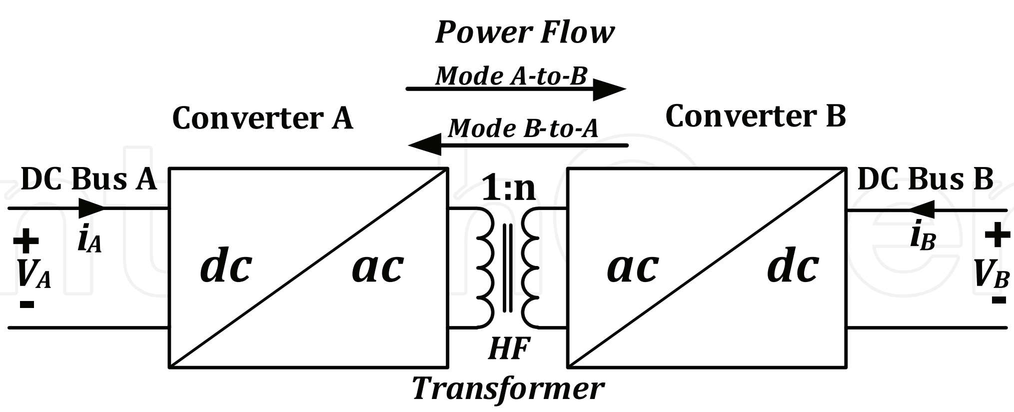


Fig. 5. Basic structure of an IBDC

3.2 Terminology

As the name “bidirectional” implies, there are basically two modes of operation in an IBDC in terms of power transfer. Based on Fig. 5, these modes are denoted by Mode A-to-B and Mode B-to-A in this chapter. It should be noted that other publications in this field may have used different notations. For example, some publications have used the terms “boost” or “step-up” and “buck” or “step-down” modes to describe the two above mentioned modes. This notation usually originates from the fact that the dc voltages at each side have usually different voltage amplitude and thus voltage boosting/bucking takes place along with energy transfer. Other reason behind this notation can be the topology and operation of converters during each mode which resemble conventional buck or boost converters. Some other literature have used “charging” and “discharging” modes, which comes from the fact that at least one of the dc sources in many IBDC applications is a battery, and thus charging and discharging terms become meaningful.

3.3 Classification

Classification of systems with similar functionality but different configurations allows for better comparison among them and helps in understanding the merits and demerits of each of them. The IBDC shown in Fig. 5 can be classified from different viewpoints. The objective of this chapter is not to provide a thorough classification of IBDCs; instead, some basic criteria are presented for better understanding the concepts behind the operation of converters discussed in Sec. 4.

3.3.1 Type of converter

Considering Fig. 5, an important characteristic of an IBDC is the type of converter at each side. Basically, two types of switching converters can be identified. A current-type (or current-fed) structure has an inductor with stiff current characteristic at its terminals which acts like a current source, like conventional boost converter at its input terminals. A voltage-type (or voltage-fed) structure has a capacitor with stiff voltage characteristic at its terminals which acts like a voltage source, like conventional buck converter at its input terminals. The operation, switching strategy and other operational aspects of these converters are different.

3.3.2 Active control in different modes

Bidirectional operation requires both converters in an IBDC to be equipped with controllable switches. Therefore, both converters can be actively controlled in both modes of operation. This capability, however, may or may not be exploited in all proposed IBDCs. In other words, some IBDCs work on the basis of controlling only the source-side converter during each mode, while using the uncontrolled components (i.e. diodes) of the other side for rectification. This, on one hand, reduces the complexity of control, but on the other hand does not allow using the full capabilities and features of the structure. Most recent approaches rely on the active control of both converters irrespective of the direction of power transfer.

4. Common IBDCs

Different configurations have been proposed for IBDC in the literature. Investigation of all these configurations is beyond the scope of this chapter. However, a careful review of various proposed IBDCs shows that they can be categorized into a few basic families into which the majority of configurations fall. Each family can be studied by investigating one of its members that represents the basic operational aspects of that family. To select the representative member of each family, the following criteria have been taken into consideration in this chapter:

- It should be the main member of the family and other schemes have been more or less derived from this configuration.
- It should have been addressed and investigated in more details in the literature.
- Description of its operation should cover the fundamental operational aspects of other members of that family.

Based on the above objectives, the operation of three major IBDC configurations is described in this section by the help of basic illustrative waveforms. Following this description, important characteristics of each configuration are addressed and briefly discussed.

4.1 Configuration 1: (Dual Active Bridge, DAB)

Fig. 6 shows a common IBDC topology which is sometimes called dual active (full) bridge (DAB). The converter is introduced in (De Doncker et al., 1991) and (Kheraluwala et al., 1992). In this configuration, full-bridge voltage-fed converters are used at both sides of the isolation transformer and the control is performed based on soft-switched phase-shift strategy. In its basic form, the diagonal switching pairs in each converter are turned on simultaneously with 50% duty cycle (ignoring the small dead time) and with 180 degrees phase shift between two legs to provide a nearly square wave ac voltage across transformer terminals. The phase shift between two ac voltages, denoted by ϕ, is an important parameter which determines the direction and amount of power transfer between dc buses. By adjusting this phase shift, a fixed frequency operation with full control over the power transfer is possible.

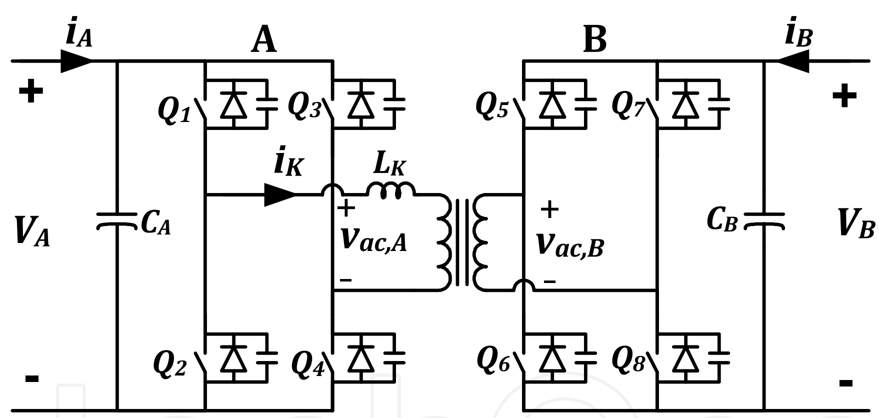


Fig. 6. Circuit diagram of Configuration 1.

Fig. 7 shows the ideal waveforms of A-to-B and B-to-A power transfer modes. The average transferred power can be obtained by calculating the average ac power at the transformer terminals, i.e.

$$P = \frac{1}{2\pi} \int_{0}^{2\pi} (v_{ac,A} \cdot i_K) d(\omega t) \tag{1}$$

which after some mathematical manipulations yields

$$P = \frac{V_A V_B \phi (1 - |\phi|)}{n\pi L_k \omega} \tag{2}$$

where L_K is the transformer leakage inductance (plus any series inductance), n is the transformer turns ratio (Side B to Side A) and ω is the angular frequency. To transfer power from Side A to Side B (A-to-B mode), $v_{ac,A}$ should lead $v_{ac,B}$ and ϕ is considered as positive. In B-to-A mode, $v_{ac,A}$ should lag $v_{ac,B}$ and ϕ is negative. This leading or lagging phase shift is simply implemented by proper timing control of converter switches. L_K is an important element which determines the maximum amount of transferable power with given switching frequency. Therefore, apart from other practical limitations, it is possible to reach a high power density converter with a low leakage transformer.

In most unidirectional dc-dc converters only the input bus has voltage variations and the output voltage is usually regulated. However, in many IBDC applications both dc buses have voltage variations imposed by other sections of the systems. In this regard, an important design parameter in an IBDC which affects soft switching range and other performance characteristics is the voltage ratio defined as

$$d = \frac{V_B}{nV_A} \tag{3}$$

Achieving soft switching over the entire operating range of a converter is always challenging. To have ZVS for the switches in a bridge leg, the current leaving the leg pole (the center of the leg) should lag the pole voltage. In other words, the zero crossing of the leg output current should occur after its voltage zero crossing. It is shown that for the DAB (Fig. 6), soft switching can be achieved in all switches for d = 1 and over the entire control range (De Doncker et al., 1991; Kheraluwala et al., 1992).

Compared to the traditional hard-switched PWM converters, the phase shift converter usually has higher circulating current and thus more conduction losses. However, as the switching frequency increases, the loss reduction caused by soft-switching overweighs the conduction losses and thus the overall efficiency improves.

Some of the advantages of this converter can be listed as below.

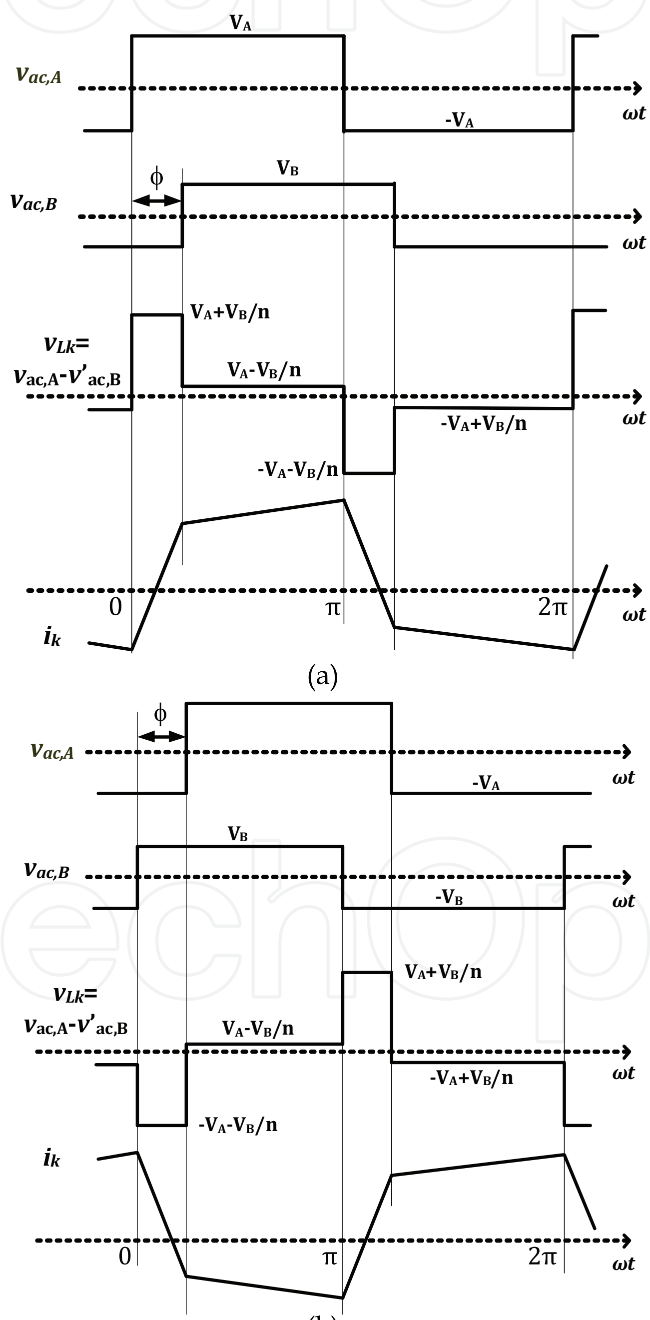
i. In this topology, each converter provides an ac waveform with a peak value close to the dc voltage at its terminal, therefore the voltage stress across each switch is limited to the bus voltage level.
ii. The current stresses of all switches on each side are almost equal.
iii. There is no need for additional active or passive elements for having soft switching.
iv. Transformer has a simple structure that simplifies the designing and manufacturing tasks.
v. Another important feature is the fast dynamic behavior due to lack of additional passive components. Note that in practice the soft switching conditions limit the rate of phase shift variation.
vi. Well-known control methods such as average current mode control or peak current mode control are applicable.
vii. Other control techniques that include duty cycle as a second control variable are also possible. This gives another degree of freedom to improve the converter performance (Zhou & Khambadkone, 2009).

Some of the disadvantages are as follows.

i. The currents flowing in dc buses contain high ripple content; therefore appropriate filtering circuits are necessary.
ii. Proper control is required to prevent dc saturation on both sides as there is no inherent dc current blocking capability for transformer windings.

iii. Similar to many other topologies, the converter may lose soft switching in light load conditions.
iv. The control is highly sensitive to slight variations of ϕ, especially when bus voltages are high. Thus if a digital controller is considered, very high resolution phase shift timers are required.
v. Another disadvantage is relatively high component count that leads to larger driver size, higher gate losses and increased cost compared to low switch count topologies.

Recent publications have presented some improvements in the area of duty cycle control, loss reduction and more advanced soft-switching techniques [Zhou & Khambadkone, 2009; Bai & Mi, 2008; Jain & Ayyanar, 2010; Oggier et al., 2009; Krismer et al., 2006).



(b)

Fig. 7. Operating waveforms of Configuration 1. (a) A-to-B mode and (b) B-to-A mode

4.2 Configuration 2

Fig. 8 shows another configuration proposed in (Wang et al., 1998). This structure consists of a current-fed bridge at Side A and a voltage-fed converter at Side B. The extra transistor Q_C and capacitor C_C at Side A act as an active clamp to limit the overshoots caused by transformer leakage inductance during current commutation (Watson & Lee, 1996; Wang et al., 1998). The operation of this converter is explained as follows.

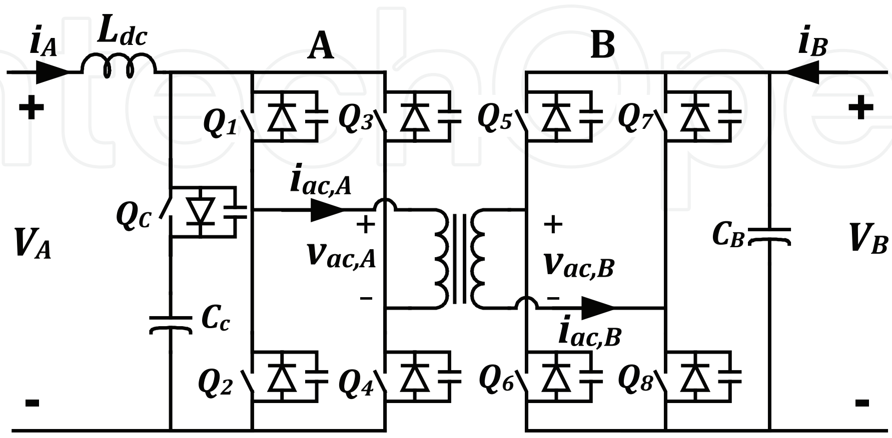


Fig. 8. Circuit diagram of Configuration 2.

4.2.1 Mode A-to-B

Fig. 9.a illustrates the basic idealized waveforms associated with this mode. The circuit operates as an isolated boost full-bridge converter (Wang et al., 1998). Therefore, the reflected output voltage needs to be higher than the input voltage for proper operation. The diagonal switching pairs in the bridge are turned on simultaneously with duty cycle larger than 50% which results in overlapping intervals, as shown in Fig. 5.a. The input inductor is charged during this overlapping interval, and discharged when only one diagonal pair is on. No control has been suggested by (Wang et al., 1998) for the switches on the other side in this mode.

4.2.2 Mode B-to-A

In this mode, the voltage-fed converter (Side B) is the active converter. The control of this converter is performed using conventional phase-shift strategy which enables ZVS operation for Q_5 to Q_8. Furthermore, the active clamp switch Q_C helps in achieving ZCS for one pair of the switches in Converter B. The idealized waveforms are shown in Fig. 5.b. If the switches of Converter A are implemented using MOSFET, they can be controlled to realize synchronous rectification resulting in reduced conduction losses, as shown in Fig. 9.b. More details on soft-switching operation in this configuration along with timing and operation of active clamp circuit can be found in (Wang et al., 1998).

Using current-fed topology in a dc-dc converter constitutes several advantages and disadvantages. Some of the advantages that are beneficial for an IBDC are:

i. Inherent protection against over-current and short-circuit.
ii. Insensitive to transformer saturation in the case of any switching mismatch and even small dc current as the transformer is current driven.
iii. Relatively low-ripple input current which makes it suitable for PFC or battery operated applications.

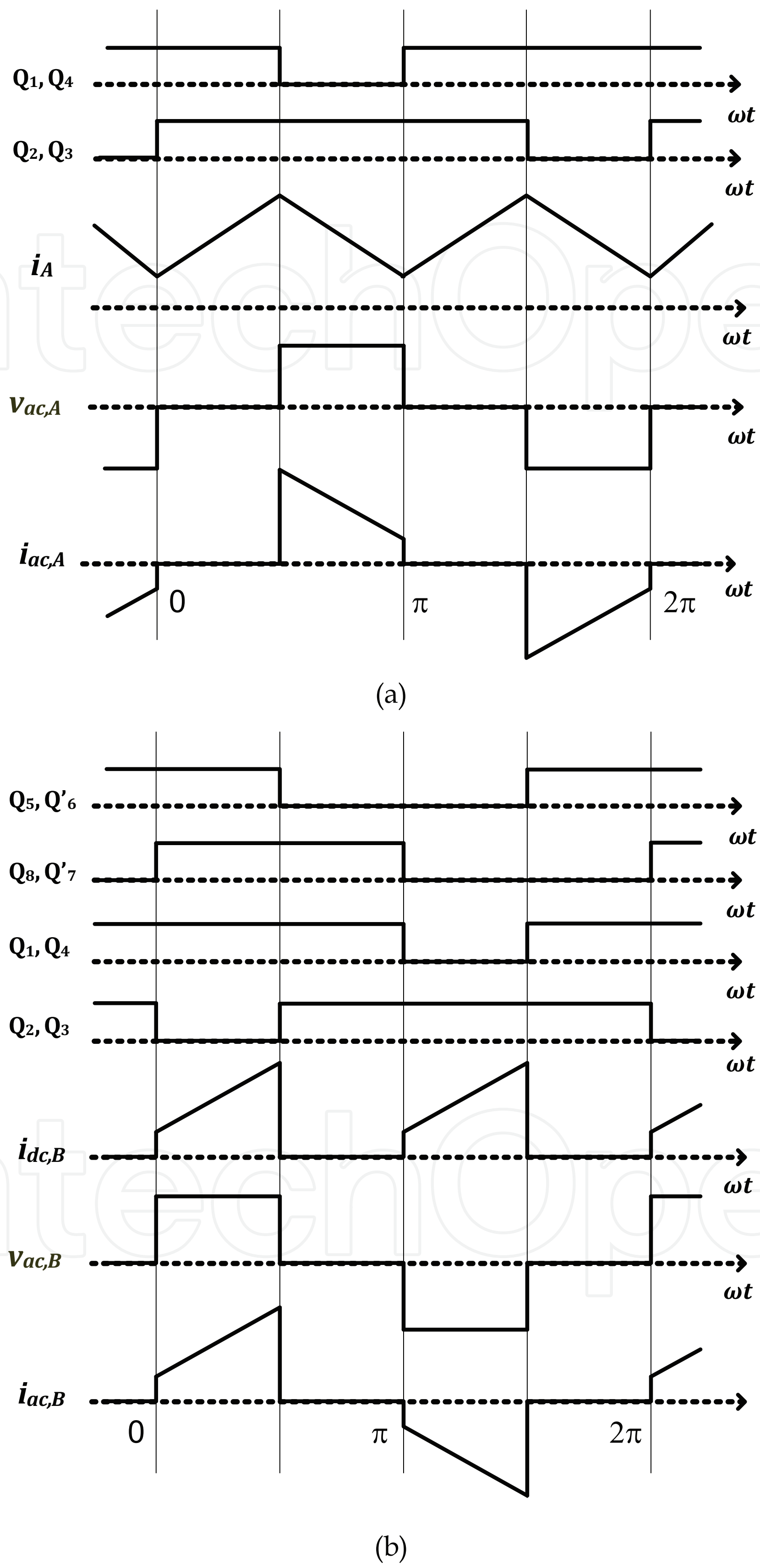


Fig. 9. Operating waveforms of Configuration 2. (a) A-to-B mode and (b) B-to-A mode

Other advantages of current-fed topologies such as good cross-regulation in multi-output dc-dc converters are not applicable in IBDC.

On the other hand, some of the disadvantages of current-fed topologies are:

i. Difficult start-up procedure which normally calls for extra circuitry.
ii. Voltage spikes due to transformer leakage inductance which could cause high losses in high frequency applications.
iii. Relatively bulky input side inductor.
iv. High ripple output current which calls for high quality capacitors.
v. Need to use semiconductor switches with voltage rating significantly higher than the dc bus voltage (due to both boost operation and voltage spikes).
vi. Susceptibility to loss of gate drive which could lead to current interruption and large voltage spikes.

The characteristics associated with this configuration makes it more suitable where Side B converter is implemented using IGBTs. In such a case, some characteristics like ZCS operation of Side B switches become advantageous. It is worth mentioning that the full benefits of active switches are not exploited in this configuration as Converter B is not actively controlled during A-to-B mode.

Some improvements have been made on this configuration by other researchers. Specifically, more advanced soft-switching techniques have been proposed in (Zhu, 2006; Wu et al., 2010) to reduce the losses associated with active clamp circuit.

4.3 Configuration 3: (Dual Half Bridge, DHB)

Fig. 10 illustrates another IBDC converter introduced in (Peng et al., 2004) for hybrid vehicle applications that is called dual half bridge (DHB). This topology consists of one voltage-fed half bridge converter in Side B (usually higher voltage side) and a modified current-fed half bridge converter (also called boost-half bridge) in Side A. The current-fed side is the lower voltage side because it usually consists of battery or ultra capacitor dc energy sources in which low ripple current is desirable. In practice the voltage amplitude is a few tens of volts for the low voltage side (battery or ultra capacitor) and a few hundreds of volts for the high voltage side. Similar to DAB (Configuration 1) discussed in Sec. III.A, the power regulation is achieved by controlling the phase shift between the voltages applied to two sides of transformer, or equivalently to the leakage inductance of the transformer. The leakage inductance (plus any series inductance) is the energy transfer element like in DAB.

To understand the operation of the converter first note that Q_1 and Q_2 has dual roles in both modes of operations. In the A-to-B mode their first role is acting as a traditional boost converter to produce dc voltage V_M on the auxiliary dc bus from the side A source. At the same time they invert voltage V_M from auxiliary dc bus onto the transformer primary to produce square wave voltage $v_{ac,A}$ as their second role. Q_3 and Q_4 on the other side of transformer rectify the ac current from transformer to transfer power to the side B dc bus. Note that Q_3 and Q_4 rectification is not realized only by acting as diodes or synchronous rectifiers. They have to turn on and off in such a way that the square wave appeared on the transformer secondary, $v_{ac,B}$, has the required phase shift with respect to transformer primary voltage, $v_{ac,A}$. This is also the key to keep the soft switching on Q_3 and Q_4.

In the B-to-A power flow mode Q_3 and Q_4 act as an inverter to produce an ac voltage $v_{ac,B}$ on the transformer secondary . Q_1 and Q_2's first role in this mode is rectifying this ac voltage to produce dc voltage V_M on the auxiliary dc bus. Their second role is acting as a traditional buck converter to send power from auxiliary bus (voltage V_M) to Side A dc bus (voltage V_A).

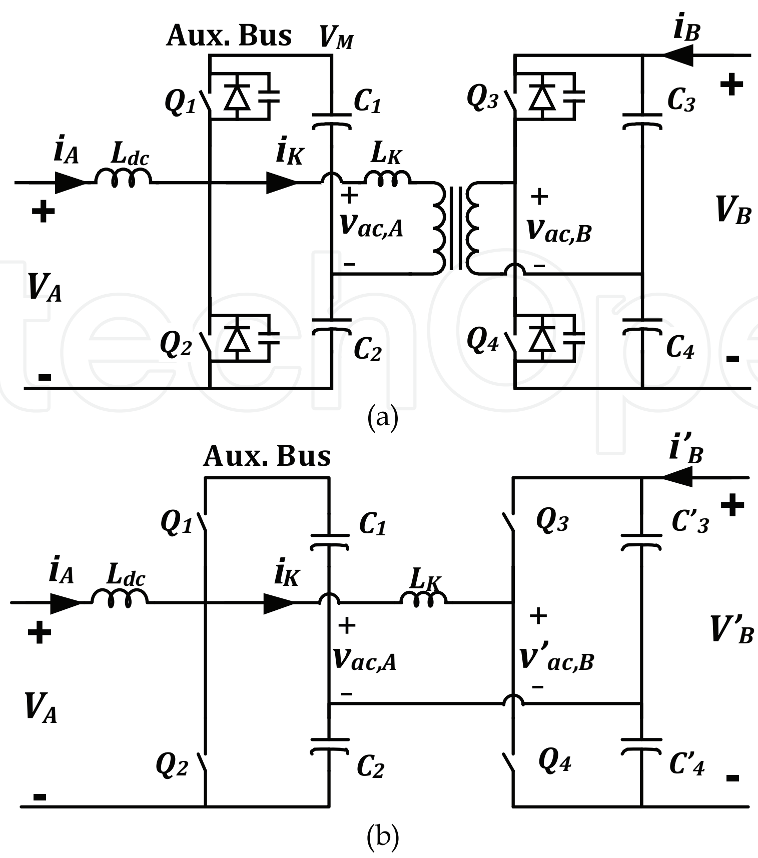


Fig. 10. (a) Circuit diagram of Configuration 3 and (b) idealized model.

Basic waveforms of the converter with 50% duty cycle in both power flow modes are shown in Fig 11 with the help of an idealized model shown in Fig. 10.b. The waveforms of both modes are basically the same, the main difference is negative phase shift and negative dc current in dc input inductor for B-to-A mode. The converter has a unified operation principle and direction of power flow can be changed seamlessly.

The average power transfer can be calculated similar to DAB configuration and based on (1). For DHB configuration it will lead to

$$P = \frac{V_A V_B \phi (1 - |\phi|)}{2 n \pi L_k \omega} \tag{4}$$

Similar to DAB configuration, the maximum power transfer is at $|\phi|$=90 degrees. So the converter full range of bidirectional power transfer can be gained by controlling phase shift in -90 to +90 range. To decrease the current stress and increase the efficiency of converter the amount of reactive power transfer through the transformer should be limited. Higher reactive power results in more circulating current and higher conduction losses. Normally higher phase shift angle results in more reactive power similar to sine wave utility systems. From this point of view, it is preferred to design the converter with a lower series inductance (L_K) so that desired power rating of the converter can be reached in lower phase shift values. Control aspects of this configuration can be found in (Li & Peng, 2004; Hui et al. 2005; Ma et al. 2009). Some other IBDCs that are based on this configuration can be found in (Tao et al., 2008; Yu at al., 2010).

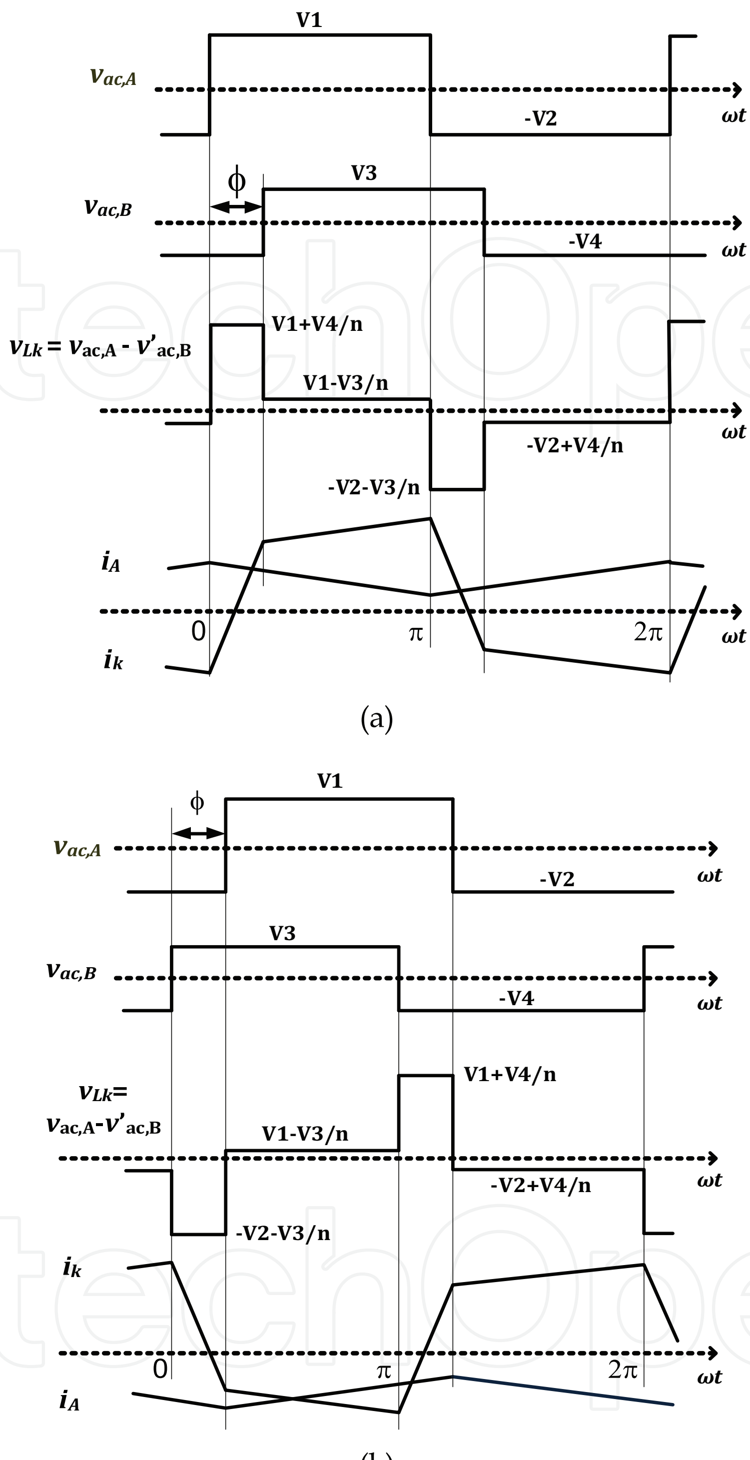


Fig. 11. Operating waveforms of Configuration 3. (a) A-to-B mode and (b) B-to-A mod

With proper design, all converter switches operate in zero voltage switching (ZVS) in a wide range of dc bus voltages or load variations. ZVS for the switches in each leg is achieved when the total current leaving the leg pole is lagging the same point voltage. So in this case, (i_K-i_A) should lag V_{Q2} and (-i_K) should lag V_{Q4}. This way each switch will turn on while its body diode is already conducting (turn on ZVS). Turn off ZVS is also achieved as the device voltage is kept close to zero by snubber capacitor during turn off and the device current is also transferred to snubber capacitors. Snubber capacitors include the device parasitic output capacitors. For more details of ZVS conditions and detailed transition resonance see (Peng et al., 2004).

The main advantages of this configuration can be listed as follows.

i. Low switch count compared to other topologies that normally use full bridge converters.
ii. According to [14] the total device rating of active elements is same as a DAB with the same power.
iii. Relatively wide soft switching (ZVS) range against bus voltages and load variations.
iv. Relatively simple control of the converter based on well known phase shift modulation.
v. Low ripple current at the current fed side that is desirable for batteries and ultra capacitors.

The main drawbacks of the converter are

i. Large ripple current in the splitting capacitors especially in LV side.
ii. Unbalanced current stress between two switches in the LV side.

5. Applications

Minimizing greenhouse gas effects by reducing CO_2 and other emissions is one of the most challenging issues that human is presently facing. As electricity generation is one of the major causes of the pollution, finding alternative clean electricity generation methods is thus becoming attractive. In this regard, renewable energy resources such as wind and solar energy are among the most important substitutes for traditional fuel-based energy production. However, the intermittent nature of most renewable sources does not allow having a reliable and continuous source of energy when these resources are used alone. The fluctuating energy produced by these sources may also cause adverse effects on the power quality of the grid that these resources are connected to. By using energy storage devices, these fluctuations can be absorbed to deliver smooth power to consumers and at the same time maximize the energy output of renewable resources. This reduces the output required from conventional power stations which directly reduces CO_2 emissions.

Besides smoothing the energy output of renewable resources, energy storage systems have other technical applications in the utility grid including grid stabilization, frequency and voltage support, power quality and reliability enhancement and load shifting. Furthermore, restructured electricity markets provide opportunities for exploiting energy arbitrage markets and making revenue by purchaseing the low-cost off-peak electricity and selling the high-cost peak electricity.

In the above mentioned applications and when the storage media is an electrochemical battery, a set of power conversion stages is required to connect the battery to the grid. Fig. 12 shows the structure of a typical energy storage system connected to an ac grid (Inoue & Akagi, 2007). As explained in Sec. 3, isolation and/or voltage matching are usually required in these applications. In the system of Fig. 12, the isolation/voltage matching is done through a line frequency (50 or 60-Hz) transformer. The dc-dc converter shown in this system is usually of non-isolated type, e.g. the converter shown in Fig. 2.

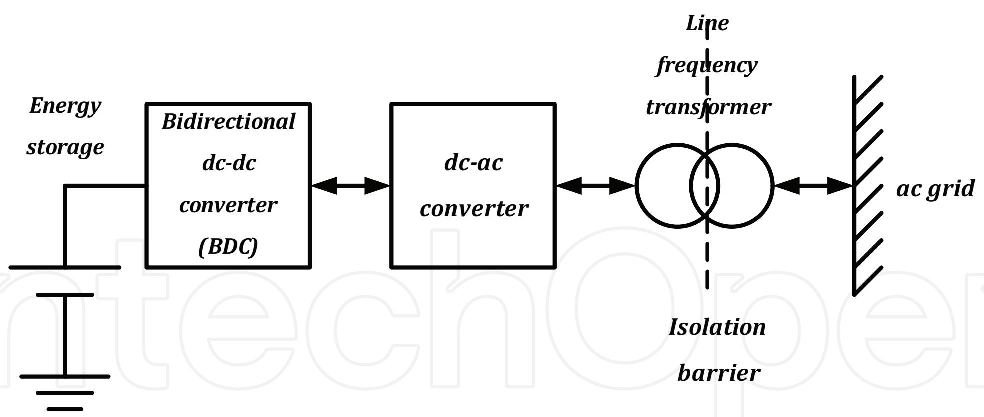


Fig. 12. Basic structure of an energy storage device connected to an ac grid through a line-frequency transformer.

The line frequency transformer in the system of Fig. 12 makes it heavy and bulky. This problem can be largely alleviated by using a high frequency transformer as the isolation stage. Using the existing technologies, the best location to implement such a high frequency transformer is in the dc-dc conversion stage, which results in an IBDC as shown in Fig. 13. In this way, the isolation barrier moves from the low frequency bulky transformer to the high frequency transformer incorporated in the IBDC. Using high frequency transformers lead to more compact and flexible systems. Furthermore, this configuration provides more flexibility in terms of selection of dc voltage amplitude in different stages for optimized operation.

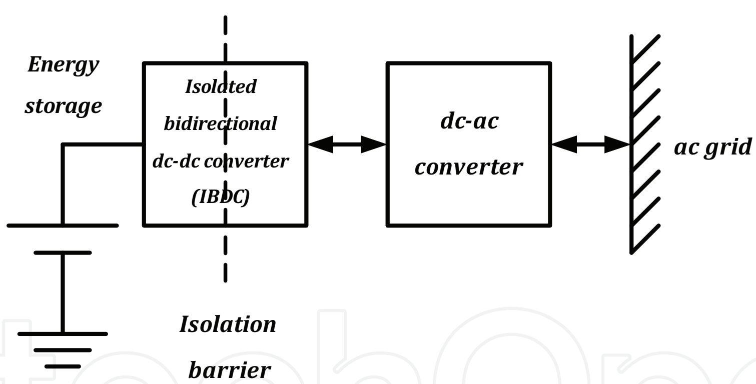


Fig. 13. Basic structure of an energy storage device connected to an ac grid with high frequency isolation barrier inside IBDC.

In (Inoue & Akagi, 2007) an energy storage system based on the structure of Fig. 13 has been discussed. The IBDC structure used in this work is similar to Configuration 1 described in this chapter and rated at 10 kW and 20 kHz with rated dc voltage of 320 V at each side.

6. Conclusion

Bidirectional dc-dc Converters (BDC) are one of the key elements in electrical energy storage systems. They provide a flexible power processing interface between a energy storage device (e.g. battery) and the rest of system. Two main families of BDCs are non-isolated and isolated structures. A review of isolated bidirectional dc-dc converters (IBDC) was presented. The basic structure of these converters along with the terminology used in the literature was described. Despite various configurations proposed for IBDCs in the literature, they can be categorized into a few basic families. A classification was presented to help understand the similarities and differences among the families. The key operational aspects of each family were described by the help of basic waveforms corresponding to a basic member of that family. The advantages and disadvantages of each configuration were briefly stated.

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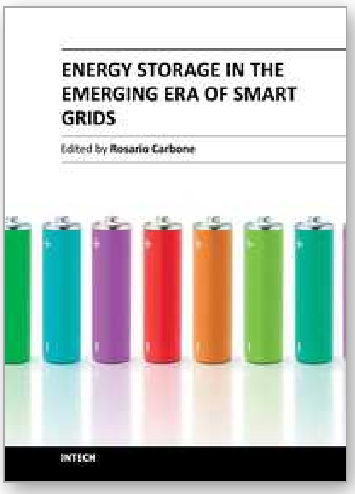

Energy Storage in the Emerging Era of Smart Grids

Edited by Prof. Rosario Carbone

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Reliable, high-efficient and cost-effective energy storage systems can undoubtedly play a crucial role for a large-scale integration on power systems of the emerging â€œdistributed generationâ€ (DG) and for enabling the starting and the consolidation of the new era of so called smart-grids. A non exhaustive list of benefits of the energy storage properly located on modern power systems with DG could be as follows: it can increase voltage control, frequency control and stability of power systems, it can reduce outages, it can allow the reduction of spinning reserves to meet peak power demands, it can reduce congestion on the transmission and distributions grids, it can release the stored energy when energy is most needed and expensive, it can improve power quality or service reliability for customers with high value processes or critical operations and so on. The main goal of the book is to give a date overview on: (I) basic and well proven energy storage systems, (II) recent advances on technologies for improving the effectiveness of energy storage devices, (III) practical applications of energy storage, in the emerging era of smart grids.

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