International Journal of Engineering & Technology, 7 (4.5) (2018) 360-365

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Bidirectional dc to dc Converters: An Overview of Various Topologies, Switching Schemes and Control Techniques

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Abstract

Bidirectional dc to dc converter is used as a key device for interfacing the storage devices between source and load in renewable energy system for continuous flow of power because the output of the renewable energy system fluctuates due to change in weather conditions. In electric vehicles also, bidirectional converter is used between energy source and motor for power supply from battery to motor. Thus, bidirectional dc to dc converters are getting more and more attention in academic research and in industrial applications. Bidirectional dc to dc converters work in both buck and boost mode and can manage the flow of power in both the direction between two dc sources and load by using specific switching scheme and phase shifted control strategy and hence generated excess energy can be stored in batteries/super capacitors. Therefore, the basic knowledge and classification of bidirectional dc to dc converters on the basis of galvanic isolation, the comparison between their voltage conversion ratio and output current ripple along with various topologies researched in recent years are presented in this paper. Finally, zero current and zero voltage soft switching schemes and phase shifted controlling techniques are also highlighted.

Keywords: *DHB-IBDC (Dual half bridge-isolated Bidirectional dc-dc converter); DAFB-IBDC (Dual Active full bridge-isolated bidirectional dc-dc converter); IBDC (Isolated Bidirectional dc-dc converter); NIBDC (Non-isolated Bidirectional dc-dc converter);*

1. Introduction

Recently the use of renewable energy resources has been increased to save the environment and remaining fossil fuel and the requirement of storing the energy is also increased. In many applications like electric vehicles the need of interfacing of energy storage with load and source is increased for a reliable and efficient system. Bidirectional dc to dc converter is the main device used to interface the Battery and super capacitor as a storage device to increase the system reliability. Moreover, As shown in FIG. 1.(a), in electric vehicle bidirectional dc-dc converters used for capturing the kinetic energy of motor and charging the battery during regenerative breaking by reverse flow of energy [1]–[5][6]. Similarly, the output of the hybrid system in Fig 1(b) the consisting of wind energy, solar energy etc. are environment dependent so fluctuation of output power and sudden change in load demand makes this hybrid system unreliable so, the solution for this issue is use of storage system like battery, super capacitor etc. with the help of bidirectional dc to dc converter for power conditioning and smooth flow of power to the load [7]–[10] . In industrial application also, bidirectional dc-dc converters are used in many applications because devices are switch on and off at high frequency so DAB (Dual active bride)-IBDC (isolated bidirectional dc to dc converter) provide both galvanic isolation, storage of surplus energy and efficient flow of power without wasting the energy [11]. For proper understanding of hybrid energy system and electric vehicle, it is necessary to have knowledge the working principle of dc to dc converter. Therefore, this paper discusses the basic concept of bidirectional dc to dc converter, their classification based on galvanic isolation and various topologies such as interleaved converter and DAB converter. Also, the comparison between soft Switching and hard switching schemes is given. Finally, different control strategies such as SPS (single-phase shift), DPS (double phase shift), EPS (extended phase shift) and TPS (triple phase shift) employed in IBDC for bidirectional power flow are highlighted.

2. Bidirectional dc to dc Converter

A conventional buck-boost converter can management the power flow in one direction only but power can flow in both the direction in bidirectional converter. Bidirectional dc-dc converters are the device for the purpose of step-up or step-down the voltage level with the capability of flow power in either forward directions or in backward direction. Bidirectional dc-dc converters work as regulator of power flow of the DC bus voltage in both the direction. In the power generation by wind mills and solar power systems, output fluctuates because of the changing environment condition. These energy systems are not reliable to feed the power as a standalone system because of the large fluctuations in output and hence these energy system systems are always connected with energy storage devices such as batteries and super capacitors Fig. 1(b). These energy storage devices store the surplus energy during low load demand and provide backup in case of system failure and when the output of energy system changes due to weather conditions. Thus, a bidirectional dc-dc converters are needed to allow power flow in both forward and backward the directions [12]–[18]. A conventional dc-dc converter can be converted into a bidirectional converter using bidirectional switch by using diode in anti-parallel with MOSFET or IGBT allowing current flow in both the direction using controlled switching operation.

3. Types of Bidirectional Converter

There are two types of Bi-directional dc/dc converter on the basis of galvanic isolation provided between input and output [19].

- NIBDC
- IBDC

3.1. Non-Isolated Bidirectional Dc to Dc Converter (NIBDC)

NIBDC is a converter which does not use high frequency transformer to provide any electrical isolation between source and load. Hence these converters are not used in high power applications due to safety reasons but in low power application theses converter are more efficient because these are easy to control and light weight due to absence of transformer [20].

3.1.1. Bidirectional Buck-boost Converter

This topology is basic circuit of bidirectional dc-dc converter Fig.1 (c). It is the anti-parallel combination of buck-boost converters. During the step-up operation Q1 is conduct according to the duty cycle whereas Q2 will not conduct in this mode. In step-down mode Q2 will conduct according to the duty cycle and Q1 will not conduct in this mode. A small dead time provided between both the operation so that cross conduction can be avoided [17][21]. Given topology is a non-isolated half-bridge BDC topology and it is designed by the combination of boost converter connected antiparallel with buck converter [22], [23]. This topology is simple and has greater efficiency [24].

3.1.2. Cascaded Bidirectional Buck-boost Converter

This topology Fig. 1(d) is obtained by cascading buck converter with boost converter [28]–[31]. With this topology all four quadrant is possible hence this topology works as buck mode and boost mode in both the direction. 4-quadant operation of this topology makes this topology most flaxible but it has some limitations also: more number of switches which leads to more switching losses, complex control algorithm and more turn-on losses because of reverse reconevry of diodes

3.1.3. Bidirectional CUK Converter

Bidirectional CUK converter [25] is obtained from unidirectional CUK converter by using MOSFET in place of diode Fig. 1 (e). The output of this converter has low ripple as compared to above described topologies hence this converter can be a better option for interfacing super-capacitor-battery in circuits [26], [27]. The ripple output current can be reduced by coupling of inductor L1and L2. In the forward power flow, Q1 works as controlled switch and Q2 remain off and body diode of switch Q2 works as main diode. Similarly, in backward power flow Q2 works as controlled switch and Q1 remain off and body diode of switch Q1 works as main diode.

3.1.4. Bidirectional SEPIC-ZETA dc to dc Converter

SEPIC-ZETA dc to dc converter is modification of CUK converter so its output is not opposite polarity like CUK converter Fig. 2(a). In forward power flow mode this converter works as SEPIC converter and in negative power flow mode, this converter works as ZETA. SEPIC-ZETA converter works in both buck and boost mode [28], [29]. In forward power flow, switch Q1 turn on and Q2 remain off and it works as buck converter and in backward power flow mode it works as boost converter with Q2 turn off. Coupling of inductor L1 and L2 can reduce the voltage output ripple and voltages rating stress on switches.

3.1.5 Switched Capacitor Bidirectional dc to dc Converter

Fig. 2 (b) shows the switched capacitor bidirectional dc-dc converter which is used when ICs (integrated Circuits) are to use in dc-dc converter circuits[30]–[32]. Since no magnetic devices are present in non- isolated dc-dc converter, integrating of ICs are quite simpler. But theses converters suffer from high ripple current in output due to large number of passive component that leads to electromagnetic interference (EMI). These problems can be resolved by control scheme such as current control and voltage control techniques but this will increase the complexity and cost of the circuit.

3.1.6. Interleaved Non-isolated Bidirectional dc to dc Converter

Interleaved converter is the parallel combination of two or more than two converters with relative phase shift $360^0/n$. Interleaved converters have some the advantages: current splitting (I/n), cancellation of ripples in output current, higher efficiency of system, high-power density and, higher thermal capacity. Due to the current splits in parallel paths, conduction losses decrease with less number of switches. With the interleaving method in dc-dc converter, the ripple of the input current and the output voltages decreases without increasing the switching losses which leads to higher system efficiency [33].

3.1.6.1 2-phase Interleaved Non-Isolated Bidirectional dc-dc converter

2-ø interleaved converter contains two output stages which is 180 degrees out of phase. Conduction losses (i^2r) are reduced by dividing the current into two paths which are connected parallel. More over overall efficiency increases as compared to 1-ø converter. Due to 2-phase combines at the capacitor which is connected at output, effective ripple frequency becomes doubled which reduces ripple in output voltage. Also, power pulses coming from the input capacitor are stumbled and reduces ripple in current. In Fig. 2(c) basic circuit of 2-phase interleaved dc-dc converters is discussed. Interleaved half bridge converter is the mostly used topology [19][34]–[36]. Theses converter facilitates higher voltage conversion with smaller size of converter. The switching losses also decreases [37]. Hence these converters can be employed to interface ultra-capacitor/battery hybrid energy system for automotive applications like hybrid electric vehicle. Interleaved converter are designed as follows [38]:

- Decide the duty ratio
- Decide the number of phases
- Choose proper Inductor values
- Choose a power semiconductor switch
- Design of filter

These converters have some issue such as: high in cost due to the increased number of component and complex the control strategy.

3.2 Isolated Bidirectional dc to dc Converter

NIBDC are not capable to provide the safety standards of galvanic isolation. Hence in many applications, IBDC is used in place of NIBDC. In IBDC, high frequency transformer is used to provide galvanic isolation. Galvanic isolation is necessary in many applications for safety of source in overload condition, for noise reduction, for voltage matching between conditions. This converter works in two stages [39]. In first stage dc is converted to ac and second stage ac is converted into dc and both the stages are connected through high frequency transformer. The basic circuit of isolated bidirectional dc-dc converter is shown in Fig. 2(d). Since transformer can work only at There are many topologies of isolated converters such as forward-flyback IBDC, dual push-pull IBDC, dual flyback IBDC, Dual-CUK IBDC, Dual half bridge IBDC and Dal active full bridge IBDC [40]–[46]. But half bridge and full bridge are widely used because of their high efficiency [47]–[50].

3.2.1 Dual Half Bridge (DHB)-Isolated Bidirectional Dc to Dc Converter (IBDC)

Dual Half Bridge (DHB) isolated ZVS bidirectional dc-dc converters[51] achieve high power density, soft switching and easy control hence are used in EV applications. Fig. 2(e) shows the topology. Its efficiency is 92 to 94%.

3.2.2 Dual Active Full Bridge (DAFB)-Isolated Bidirectional dc to dc Converter

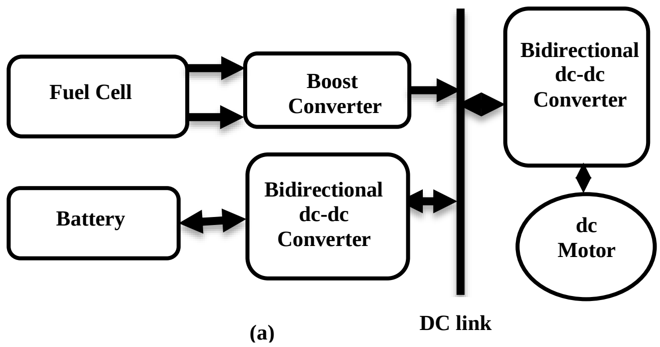
Full bridge isolated bidirectional dc-dc converters are more suitable choice in hybrid energy system because of the high-power density and high efficiency [52]. Fig. 2(f) shows the DAFB-IBDC. The power capacity with the switches so the above discussed DAFB-IBDC has higher power capacity than another topology. Its efficiency is 95%. Hence in high power application like hybrid energy system, this converter is most suitable.

4. Control Technique for Isolated Bidirectional dc to dc converter

For power flow in isolated bidirectional dc-dc converter, phase shift technique is used such as single-phase shift technique (SPS), extended phase shift (EPS) technique, double technique (DPS) and triple phase shift (TPS) technique. Single phase shift is widely used method in DAFB-IBDC [53]–[57]. SPS technique has advantages: small inertia, high dynamics and ease of soft switching but power flow suffers from the leakage inductance of transformer. EPS [58], DPS [53], [59], TPS [60] are modified form of SPS.

5. Switching Techniques

Hard switching is the main cause for the switching [45], [54]. Hence researchers have developed the soft switching techniques so that switching losses can be minimized. But to achieve soft switching, passive component has to be used which makes the system bulky and complex. Table No. 2 shows the comparison of soft and hard switching.



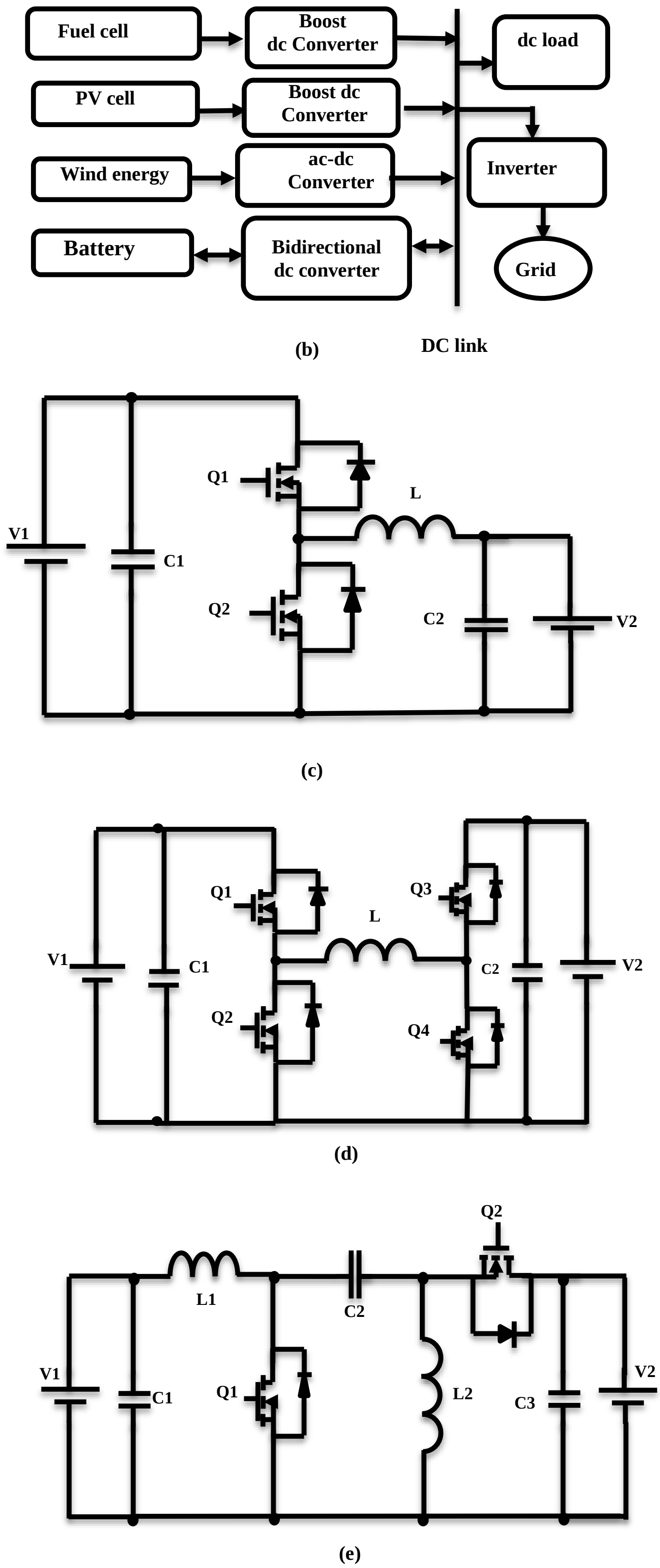


Fig.1:. (a) Fuel Cell powered Electric Vehicle, **(b)** Hybrid Energy System with Battery Interface using Bidirectional dc-dc Converter, **(c)** Bidirectional dc to dc Buck-Boost Converter, **(d)** Cascaded Bidirectional Buck-boost Converter, **(e)** Bidirectional CUK Converter

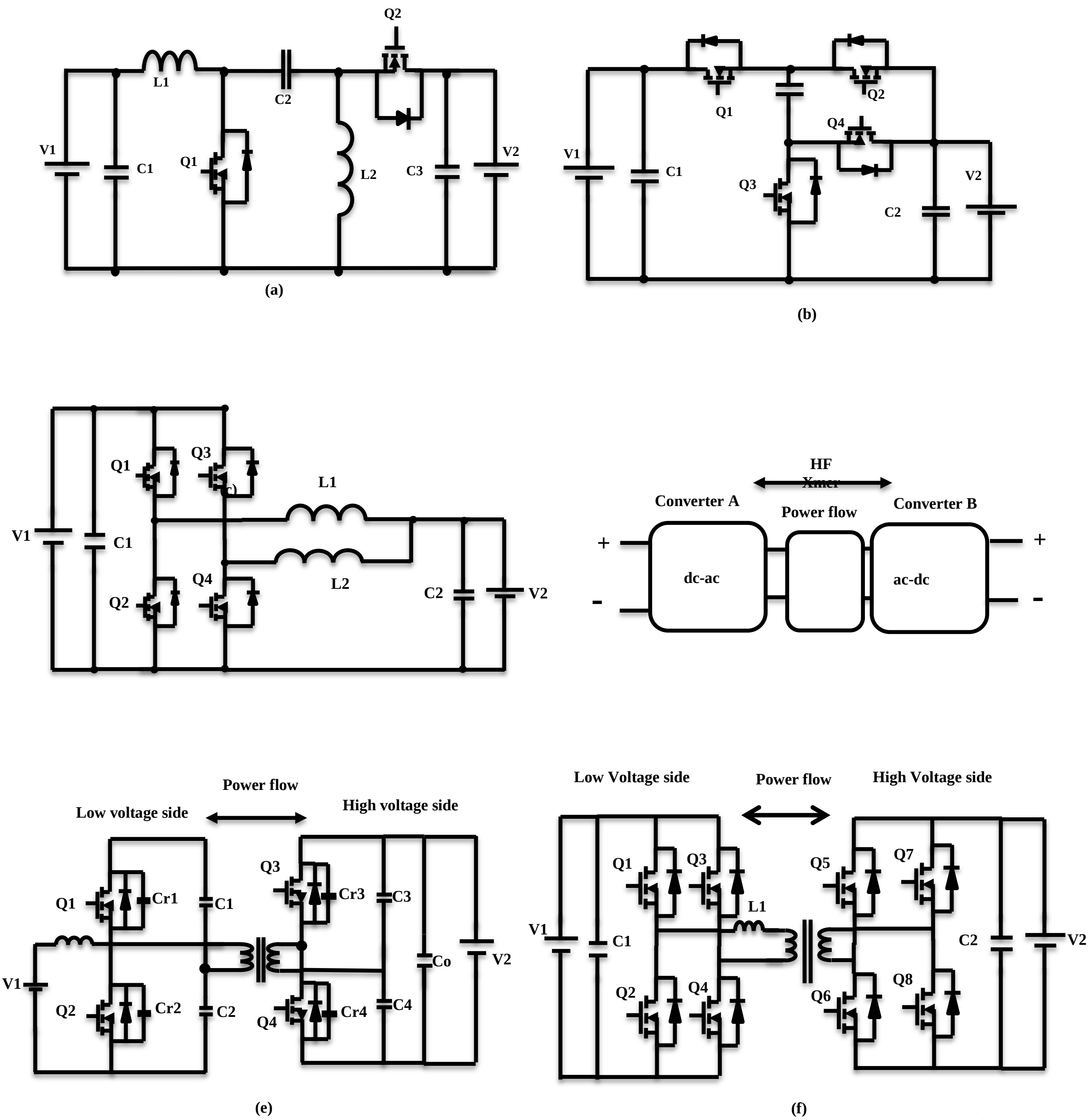


Fig.2.: **(a)** Bidirectional SEPIC-ZETA dc-dc Converter, **(b)** Switched Capacitor Bidirectional dc to dc Converter, (**c**) 2-phase interleaved half bridge Bidirectional dc-dc converter, **(d)** Basic Structure of Bidirectional dc-dc Converter, **(e)** Dual Half Bridge (DHB) Isolated Bidirectional dc-dc (IBDC), **(f)** DAFB-IBDC

Table 1: Comparison between Soft and Hard Switching

Hard switching	**Soft switching (ZVS and ZCS)**
Large switching losses	Near zero switching losses
High EMI due to high di/dt and dv/dt	Low EMI loss
Limited range of switching frequency	High range of switching frequency
Low power density	High Power Density
Low efficiency	High Efficiency
Easy control	Complex Control
Low cost	High cost due to more number of switches

6. Conclusion

From the above discussion it can be concluded that the isolated bidirectional dc-dc converters are large in size and heavier in weight due to presence transformer so theses converters seem to unfit for electric vehicles and non-isolated interleaved bidirectional dc-dc converter are more suitable in electric vehicles. But in high power palpation where galvanic isolation is necessary, IBDC are more suitable for hybrid energy system. Soft switching scheme should be used in place of hard switching because it reduces the switching the losses. In IBDC controlling scheme is used according to complexity of the circuit and application.

Acknowledge

The authors acknowledge Dr. lini Mathew, NITTTR Chandigarh Dr. Paulson Samuel, MNNIT Allahabad, Bandi Mallikarjna Reddy MNNIT Allahabad for their direction and support. The authors also acknowledge Professor Dinesh Chandra for his support.

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