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Review of High Efficiency Bidirectional dc-dc Topologies with High Voltage Gain

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Abstract— **A review of high voltage gain, high efficiency bidirectional dc-dc topologies is presented. Each converters primary benefit is highlighted, and a summary of all the converters is presented. It is observed that voltage gains higher than 20 is only achieved with topologies using a transformer. The average efficiency of the topologies is slightly lower for isolated topologies. Different strategies are utilized in most of the topologies in order to achieve the high voltage gain, and high efficiency, for example charge pumps, resonant circuits, coupled inductors, and switching cells.**

Index Terms-- **Bidirectional dc-dc converter, energy storage, high efficiency, high-voltage gain.**

I. Introduction

Green and renewable energy sources, like solar and wind power, are in increasing demand from both consumers, producers and policy makers. Green energy sources produce fluctuating power levels throughout the day and year, which does not necessarily match the power consumption of consumers [1]. This can lead to stability and reliability issues in the power grid [2]. For this reason, research into storing the energy in periods with high power production and using the stored energy in periods with low energy production, has been conducted in recent years [3]. Two storage systems that are currently in use are battery systems and fuel cell/electrolysis systems. A setup where a battery is charged from a dc bus is depicted in Fig. 1. Both batteries and fuel cells has a voltage requirement (input and output) for a few cells of around 12 V [4], [5], while the voltage on the dc bus is commonly around 400 V [6]. Therefore, an interface is needed to convert the 400 V to 12V in order to connect the dc bus to the battery or fuel cell system. Once the battery is charged and the power is needed in the dc bus the converter should be bidirectional, so that the power can be delivered back [7].

Several parameters are interesting when investigating bidirectional converters. Depending on the application of the converter one parameter might be more interesting than another. A common parameter is the efficiency (η) [8] of converter, and is given as the output power (Pout) divided by the input power (Pin). The efficiency is a number that describes how much energy is lost in the conversion, and includes both switching losses and conduction losses. Generally the efficiency varies with changes in the power level it has to convert, and with the direction of the power flow.

In fuel cell/battery to grid applications the achievable voltage gain of the converter is an important parameter. In this case a voltage gain around 30 is needed in order to

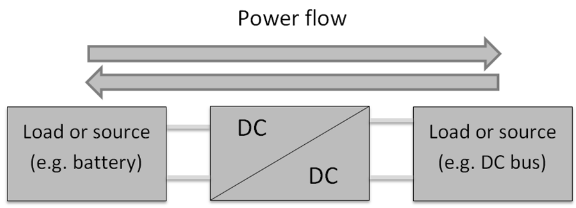

Fig. 1. Basic power flow for a bidirectional dc-dc converter.

converter the battery voltage of 12 V to the dc bus voltage of around 400 V [7]. With a high gain one side of the converter will have a low voltage, while the other has a high voltage. Since the power is ideally the same for both sides of the converter current will be high in the low voltage side, and low in the high voltage side.

One way to achieve a high gain is with a transformer, where the turns ratio can be used to achieve the desired gain [9]. The transformer can also be placed in such a way that galvanic isolation is achieved, which gives a safety in case of converter malfunction [10]. Since the transformer only lets alternating current pass through a switch short circuiting will not affect the other side of the circuit, and therefore the transformer provides galvanic isolation, meaning no physical connection from one side of the circuit to the other.

Another important parameter is how many switches are used in the converter, since the complexity of the control circuit, physical size of the converter and cost of the converter are all tied to the number of switches used. On the other hand more switches are able to reduce the amount of voltage and/or current that a single switch needs to handle. Therefore a trade-off between complexity and component stress has to be made [11], [12].

Section II first has some general comments regarding the different topologies, before a brief summary of each topology is presented. In Section III a comparison of the presented topologies is presented and a conclusion is presented in Section IV.

II. High Voltage Gain Topologies

The basic working principle of all the converters are the same: dc comes in from one side, gets chopped into ac, and rectified back to dc on the other side, and somewhere along the way it is stored in an inductor or capacitor or both. While it is turned into an ac form it might be passed through a transformer, which can help boost the voltage gain along with the galvanic isolation. As will be seen later the topologies achieving gains above 20 are all with transformers.

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Very few of the topologies have overlapping in how they obtain the high-voltage gain, and therefore the following will highlight the main points of each topology, along with the maximum efficiency in step-up and step-down will be mentioned.

A. Buck-Boost Using a Coupled Inductor

A topology using three active switches along with three diodes is used in [3]. The converter works in a buck and boost state to achieve the bidirectional dc-dc conversion. The converter uses a mixture of zero-current-switching (ZCS) and ZVS to reduce losses, along with few switches. A 2 kW prototype has a step-up efficiency of 96.3% and a step-down efficiency of 95.3%.

B. Isolated Dual Active Half Bridge (DAHB)

The dual active half bridge of [4] is working at 200 kHz. The transformer is used both for isolation and for achieving the large voltage gain of 31. The low voltage side switches are operated as synchronous rectifiers, and a total of four switches are used. The direction and magnitude of power flow is controlled by selecting the appropriate phase-shift angle between the high voltage bridge and the low voltage bridge. Zero-voltage-switching (ZVS) is achieved for all the switches, resulting in an efficiency of 88% in both charging and discharging mode for a 256 W prototype.

C. LCL Resonant dc/dc Converter

In [13] a LCL resonant circuit is used as the heart of the dc/dc converter. A half-bridge boost converter is used from the low voltage side with a resonant LCL tank, which is followed by a voltage doubler to get the high voltage. Going from the high voltage side the voltage is first divided by the voltage doubler, before a buck half-bridge is achieving the final voltage step-down. The switches are turned-on under zero-voltage condition, while the diodes are turned-on and off under zero-current conditions. This results in an efficiency for boost operating mode of 95.5% and buck operating mode of 95% for a 350 W rated prototype.

D. Dual Active Half Bridge Combined with a Buck-Boost

A new topology is proposed in [14], where the equivalent circuit can be drawn as a buck-boost and a dual active half bridge converter. The two converters share the low voltage switches, and stacks the high voltage switches on top of them to reduce the component stress on the switches. A total of four switches are used for the converter, where two are used for the low voltage side and two are used for the high voltage side. The buck-boost converter supplies the voltage to the dual active half bridge, making it possible for the dual active half bridge to have voltage matching. ZVS is achieved for both buck-boost and dual active half bridge due to their sharing of the low voltage switches. For a 1 kW converter an efficiency of 95% is achieved.

E. Dual Active Bridge (DAB) and Three-State Switching Cell (3SSC)

A three port bidirectional dc-dc converter using two dual active bridges and a three-state switching cell is proposed in [15]. One of the bridges is directly linked to the low voltage side, while the other bridge is coupled to the low voltage side with an inductor. Due to the use of two bridges a total of eight switches are used. For specific values of duty cycle soft switching is achieved for all switches for any value of phase-shift, while for other values of the duty cycle this is soft switching capability is lost. A 2 kW prototype is developed and tested between two ports, where an efficiency of 95.5% and 96% is achieved for charging and discharging, respectively.

F. Isolated Dual Active Bridge Converter with Tap Changer

In [16] an approach with four DAB at the low voltage side is chosen. The four bridges share the high current at the low voltage side. Between the high and low voltage side a tap changer is placed to combine the power from the four low voltage side bridges or some of the bridges. The tap changer consists of eight lanes with switches that can combine any number of the low voltage dual active bridge to the single high voltage dual active bridge. Having a total of five dual active bridges and a tap changer with eight channels and two switches per channel brings the switch count up to 36. Even with 36 switches the efficiency for a 10 kW prototype is 96%.

G. Boost Half Bridge Converter with an Auxiliary Circuit

The converter proposed in [17] consists of half bridge boost converter on the low voltage side, while an auxiliary circuit consisting of a capacitor, inductor and two switches are used on the high voltage side. ZVS is achieved for all switches for turn-on, while only some switches have zero-current conditions for turn-off. The prototype made use an interleaved version of the converter, which reduces the stress on the components, but doubles the amount of components needed, resulting in a need for eight switches. The prototype of the converter was made for nominal power of 5 kW, and reached an efficiency of 97.9% and 97.7% for forward and reverse modes, respectively.

H. Two Stacked Boost Converters

In [18] two inductors in parallel at the low voltage side split the high current in two, thus making the current handling requirement for each component in the low voltage side lower. A 160 W prototype with an efficiency of 98.5% and 95.5% for step up and down, respectively, is presented.

I. Isolated Full Bridge Boost

Planar magnetics are used in [19], both to handle the high currents of low voltage side and to reduce the losses in the magnetic components. A loss analysis of the converter topology is presented, including the control and driver circuits. It is concluded that the main losses occur as switching losses in the semiconductors. A 6 kW prototype is produced and shows and efficiency of 97.8% and 96.5% for step up and step down, respectively.

J. Interleaved Switched-Capacitor

A different approach is used in [20], where they theoretically propose to only use the stray inductance as inductance (in practice they use some air coils in order to achieve the desired inductance). In order to obtain the desired voltage gain of 6 and power rating of 1.5 kW they use a total of 36 switches, and 18 capacitors (and in theory no inductors). In the control there is only two states in both forward and reverse modes, which reduces the complexity of the control scheme, even though drivers are still needed for all 36 switches. The 1.5 kW prototype has an efficiency of 96.9% and 97.8% for step-up and step-down, respectively.

K. SEPIC Derived

Three coupled inductors are used in [21] to reduce the input and output current ripple. Along with the reduced input current ripple the electromagnetic noise is reduced. Only three switches are used, and two states in both forward and reverse mode, making the control easy as a single signal can be used. The proposed converter was designed for 100 W and achieved a maximum efficiency of 94.4%.

L. Buck-Boost with Built-In dc-Transformer

A combination of a buck-boost and a dual active half bridge converter is presented in [22]. The buck-boost is used to insure a constant input voltage to the half bridge, while sharing switches with the half bridge. At the same time the switches are connected in series in order to reduce the switch stresses. The topology achieves almost the same efficiency for step-up and step-down, and an equal efficiency across the different input voltages. A 1 kW prototype was built and had an maximum efficiency of 96.6% for both step and step down.

M. Isolated Resonant Two Inductor Boost Converter

Two inductors are used at the low voltage side to reduce the current ripple through the battery in [23]. While one of the low side inductors is charging, the other one is discharging. ZVS is achieved for some of the switches, by using the parasitic capacitance of the switches along with an inductor to open the switch's body diode, and switch at that time. A 2 kW prototype was made to demonstrate the functioning and an efficiency of around 96% was achieved for both step up and down.

N. Full Bridge with CLLC Tank

Adding an extra capacitor to the unidirectional LLC converter a bidirectional converter with a resonant tank is made in [24]. The proposed converter uses the resonance to achieve ZCS for the rectifying switches, while ZVS is used for the clipper switches. One of the arguments for using the topology is that MOSFETs can be used for all switches, thus allowing low on resistance and well known switches to be used. An efficiency of 96% is achieved for both step up and down for a 500 W prototype.

O. Half Bridge and Push-Pull

In [25] a simple bidirectional converter using four switches, and two diodes is proposed. For operation in step down mode the body diodes of low voltage switches are employed to rectify the voltage, while the same is though in step up mode for the body diodes of the high voltage switches. Thereby only two switches are operated actively at any given time. The prototype is designed for 100 W in step up mode, while 300 W can be processed in step down mode. The efficiencies in step up and down mode are 90% and 86.6%, respectively.

P. Three State Switching Cell

A magnetically coupled topology is suggested in [26]. The coupling does not provide isolation, but is used for achieving a high voltage gain and low component stress. In both boost and buck mode only two control signals are active at the same time, since the switches are only actively used during either boost or buck mode. A 500 W prototype was made and achieved and efficiency of 92% in boost mode, and 86% in buck mode.

Q. Buck-Boost with Resonant Network

At a switching frequency of 1 MHz the proposed topology in [27] has the highest switching frequency. Along with the highest switching frequency the proposed topology also has the lowest voltage gain. By implementing an auxiliary circuit that the is coupled to the inductor in a buck-boost converter zero-voltage and zero-current switching is almost achieved for both switches, through a resonance between the parasitic of the switches and the auxiliary circuit. The 250 W prototype has an efficiency of 92.99% in step up mode, and 93.98% in step down mode.

R. Isolated Winding-Coupled Bidirectional Converter

Interleaving on the low voltage side is used to reduce the current in each branch in [28]. The windings in each interleaved branch is then coupled to two series-connected windings in the high voltage side to divide the voltage between the windings. The low voltage side has large ripple in each branch, but they are opposite in each branch, reducing the ripple on the battery side. The control of the inverter is done with PWM plus phase-shift, which makes them able to achieve ZVS for all the power switches. The efficiency of the 1 kW prototype is 96% for both buck and boost mode.

S. Switched Capacitor with Coupled-Inductor

By the combination of switched capacitors and coupled-inductors the voltage and current ripples are reduced in [29]. This and the coupling of the capacitors lead to a reduced current and voltage rating of the associated switches. The 1 kW prototype achieves an efficiency of 96.4% and 94.5% for boost and buck mode, respectively.

T. Resonant Half Bridge Buck with Current Doubler

Two inductors are used on the low voltage side in [30] to reduce the high current running through the inductors and switches. On the high voltage side a dc blocking capacitor is placed after the transformer, which is used to half the voltage on the transformer, thus helping with the voltage gain. The prototype is made for 200 W and has an efficiency of 96.3% and 95.6% in step down and step up mode, respectively.

U. Buck/Boost with Coupled Inductor

Only two states are used in both step up and step down mode in [31]. Along with using three switches, this is one of the simplest control converters found. By the use of a coupled inductor the voltage and current stresses on the switches are reduced compared to a conventional boost/buck converter. The coupled-inductors are charged in series and discharged in parallel for step down mode, while they are charged in parallel and discharged in series for step up mode, both in order to increase the voltage gain in the respective modes. A 200 W prototype was made, and achieved and efficiency of 96.2% and 96.7% in step-up and step-down mode, respectively.

V. SEPIC with Tapped Inductor

Only one switch is actively switched during boost mode in the topology suggested in [32], and a complementary pair of switching signals are used in buck mode. The known SEPIC topology is modified to include both a tapped inductor and a charge pump, which enhances the gain, but also makes it necessary to add a regenerating snubber to recycle the leakage energy. The 400 W prototype demonstrates an efficiency of 96.4% in boost mode, and 95.0% in buck mode.

W. Cascaded Buck/Boost and Series Resonant Converter

The cascade of a buck/boost and a series resonant converter is done in [33], where the buck/boost converter handles the voltage gain, and the series resonant converter provides isolation. The series resonant converter is controlled with frequency tracking, which is used to extend the load values that can achieve ZVS. For the 5 kW prototype only the efficiency in step up mode is reported as 96.5%.

X. Cascaded Switched Capacitor

A modular switched capacitor converter is presented in [34]. The converter can achieve a gain of an integer number of the low voltage, which is due to the way the converter is built. The converter consists of several cells that can contain a number of switched capacitors. The cells are then further cascaded with other cells that can also contain a number of switched capacitors, and in this way the desired gain is achieved. The 100 W prototype achieves a step up efficiency of 95.5%, while the step down efficiency is not mentioned.

Y. Two-Stage Isolated dc-dc Converter with Current Ripple Reduction Technique

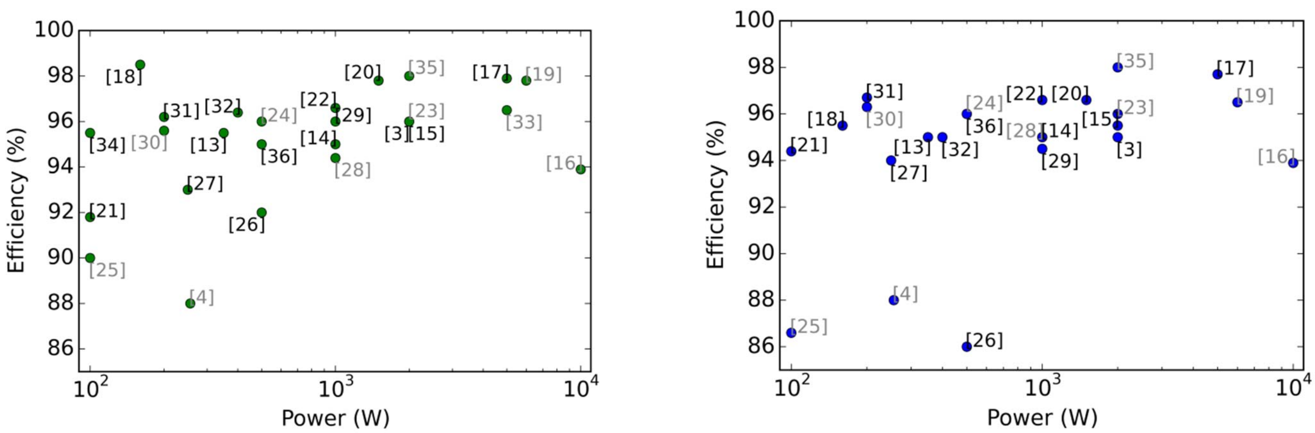
A two-stage resonant converter is proposed in [35]. The converter uses three bridges, where two of them is used for a static gain and isolation, and the last is used for bidirectional control. The transformer is connected between capacitors and the switches, and the capacitors are chosen so that the stage resonant is resonant, and achieves ZVS. The efficiency curves of step up and step down are almost equal, which is seen seldom. The 2 kW prototype achieves and efficiency of 98% in both step up and step down mode.

Z. Unregulated Level Converter Cascaded with Interleaved Buck-Boost

A capacitor in one of the interleaved branches is used to reduce the voltage stress on the switches in [36]. Cascading an unregulated level converter with the buck-boost converter also reduces the stress on each component, along with a reduction in voltage gain for the second stage converter. The reduction in voltages across semiconductors is used in order to use lower on-resistance MOSFETs. The duty cycle of the buck-boost stage can also be kept lower in a narrower span around 0.5 than without the unregulated level converter. An efficiency of 95% in step up mode and 96% in step down mode is achieved for a 500 W prototype.

III. Comparison of the Presented Topologies

A visual comparison of the efficiency of the proposed converters in step down and step up mode are shown in Fig. 2a and Fig. 2b, respectively. The black references use a non-isolated topology, while the grey references use an isolated topology. The average efficiency in step up and step down mode are 95.2% and 94.6%, respectively. Considering the isolated and non-isolated topologies separately the efficiency of the non-isolated topologies in this study has a higher average than the isolated topologies. Looking at the



(a) (b)

Fig. 2. Reported efficiency of the converters found in the literature in step up mode (a), and step down mode (b). The references in gray use an isolated topology, while those in black uses a non-isolated topology.

efficiencies shown in Fig. 2, it is clear that [4] and [26] are the highest contributors to the difference in average.

A comparison of all the topologies achieved voltage-gain is visualized in Fig. 3. Isolated topologies are shown in grey, and non-isolated topologies are shown in black. The highest gain is achieved by the isolated topologies, which is attributed to the transformer turns ratio available to achieve the gain.

Converters of both topologies have been made for many different power levels, so the power level does not seem to play an important part in what kind of gain or efficiency is desired.

The main parameters of all the mentioned topologies are summarized in Table I. As can be seen the power level varies widely between the topologies, along with the voltage gain. The efficiency is generally above 90%, and the number of switches is often between three and eight. For both parameters extremes are observed, such as a topology using a total of 36 switches or having an efficiency of 98.5%. The switching frequency is usually between 25 kHz and 200 kHz, but a single topology manages to get it up to 1 MHz. The low voltage varies between 10 V and 200 V, while the high voltage is between 120 V and 700 V. As witnessed by the

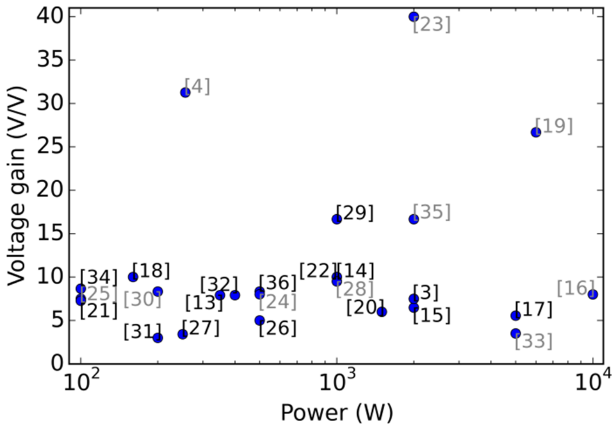


Fig. 3. The calculated voltage gain of the converters found as V_{high}/V_{low}, where the highest and lowest reported voltages has been used, respectively. The references in gray use an isolated topology, while those in black uses a non-isolated topology.

TABLE I
COMPARISON OF TOPOLOGIES

Ref.	Topology	Power (W)	Efficiency η (%) Step up	Step down	V_{low} (V)	V_{high} (V)	Gain (V_{high}/V_{low})	Switching frequency (kHz)	Number of switches	Isolation
[3]	Buck-Boost Using a Coupled Inductor	2000	96.3	95.3	48	360	7.50	100	3	N
[4]	Isolated Dual Active Bridge	256	88.0	88.0	12.8	400	31.25	200	4	Y
[13]	LCL Resonant dc/dc Converter	350	95.5	95.0	48	380	7.92	105	4	N
[14]	Dual Active Half Bridge Combined with a Buck-Boost	1000	95.0	95.0	40	400	10.00	100	36	N
[15]	Dual Active Bridge and Three-State Switching Cell	2000	96.0	95.5	48	311	6.48	30	8	N
[16]	Isolated Dual Active Bridge Converter with Tap Changer	10000	93.9	93.9	50	400	8.00	100	20	Y
[17]	Boost Half Bridge Converter with an Auxiliary Circuit	5000	97.9	97.7	72	400	5.56	30	8	N
[18]	Two Stacked Boost Converters	160	98.5	95.5	25	250	10.00	30	4	N
[19]	Isolated Full Bridge Boost	6000	97.8	96.5	30	800	26.67	40	8	Y
[20]	Interleaved Switched-Capacitor	1500	97.8	96.6	50	300	6.00	120	36	N
[21]	SEPIC derived	100	91.8	94.4	24	180	7.50	66	3	N
[22]	Buck-Boost with Built-In dc-Transformer	1000	96.6	96.6	40	400	10.00	100	4	N
[23]	Isolated Resonant Two Inductor Boost Converter	2000	96.0	96.0	10	400	40.00	20	4	Y
[24]	Full Bridge with CLLC Tank	500	96.0	96.0	48	400	8.33	-	8	Y
[25]	Half Bridge and Push-Pull	100	90.0	86.6	55	400	7.27	100	4	Y
[26]	Three State Switching Cell	500	92.0	86.0	24	120	5.00	25	6	N
[27]	Buck-Boost with Resonant Network	250	93.0	94.0	14	48	3.43	1000	4	N
[28]	Isolated Winding-Coupled Bidirectional Converter	1000	94.4	95.0	40	380	9.50	100	6	Y
[29]	Switched Capacitor with Coupled-Inductor	1000	96.0	94.5	24	400	16.67	200	8	N
[30]	Resonant Half Bridge Buck with Current Doubler	200	95.6	96.3	24	200	8.33	50	4	Y
[31]	Buck/Boost with Coupled Inductor	200	96.2	96.7	14	42	3.00	50	3	N
[32]	SEPIC with Tapped Inductor	400	96.4	95.0	48	380	7.92	50	4	N
[33]	Cascaded Buck/Boost and Series Resonant Converter	5000	96.5	-	200	700	3.50	-	10	Y
[34]	Cascaded Switched Capacitor	100	95.5	-	20	173	8.67	100	12	N
[35]	Two-Stage Isolated dc-dc Converter with Current Ripple Reduction Technique	2000	98.0	98.0	18	300	16.67	90	6	Y
[36]	Unregulated Level Converter Cascaded with Interleaved Buck-Boost	500	95.0	96.0	48	385	8.02	20	8	N

topology naming, most of the topologies used are different, and a one-to-one comparison is therefore impossible.

IV. Conclusion

There are many different ways of making a high gain, high efficiency bidirectional dc-dc converter as evidenced by the summary presented here. For a gain above 20 only topologies with transformers has been found. With regards to power level, efficiency, switching frequency and number of switches any of the presented topologies is suitable. Based on the study only the isolated resonant two inductor boost converter and the isolated full bridge boost has shown a gain above 20 and a high efficiency is required for an application.

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