Efficient Multi-Port Bidirectional Converter With Soft-Switching Capability for Electric Vehicle Applications

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ABSTRACT In this paper, to solve the hard-switching operation problem and the lack of existing a bidirectional power flow path from output to the energy storage device of the conventional three-port converter, a new soft-switched bidirectional multi-port converter is proposed. A large number of switches, different power flow paths which vary in each operating mode, and changing the outputs and their power levels are some of the challenges to provide soft-switching conditions in multi-port converters. In the proposed converter, by changing the topology of the conventional three-port converter, the bidirectional power exchangeability between ports is provided. Moreover, a soft-switching cell is added, which can operate independently from the output power levels. Less number of components with low volume is one of the important features of this multi-port converter. Due to the soft-switching operation of the proposed converter, the size of passive components and heat-sink is reduced. In addition, by the use of coupled inductors in the soft-switching cell, only one magnetic core is used and thus, single-stage power conversion is achieved and conduction loss is reduced. In this paper, the converter operating modes are presented, and design considerations are discussed. Finally, a 200 W-200 V prototype is implemented, and the theoretical analysis is validated by the experimental results.

INDEX TERMS Multi-port converter, dc-dc converter, soft-switching, electric vehicle, hybrid power systems.

I. INTRODUCTION

Developments in technologies of power sources and energy storage devices and the demand to utilize varieties of sources in a specific system have led to the emergence of hybrid energy systems. Also, clean and renewable energies have received much more attention in recent years due to the problems associated with fossil fuels cause. In this regard, the usage trend of electric vehicles (EV) is rapidly growing. In the design of electric vehicles, the concepts of hybrid energy systems are used such that some sources with the ability of absorbing/generating power are utilized, and the sources exchange power with each other [1], [2].

In an electric vehicle, an energy generation source (EGS) like fuel cell, the energy storage systems (ESS) like battery and super-capacitor and a source with the ability to regenerate energy like regenerative braking system are utilized together. The power management between sources is handled by the power converters. Thus, a unidirectional converter for transferring power from EGS to load, and for transferring power from/to each of ESS and regenerate energy source (RES), a distinct bidirectional converter is needed [3].

By increasing the number of sources, more power converters must be employed, which leads to a higher number of components. Instead of using a dedicated converter for
each input source, a multi-port converter can be used [4], [5]. In this type of converters, different converters are integrated to reduce the number of components. For integration, some parts of the converter should be shared between different operating modes.

Multi-port converters operate in different operating modes. Depending on each operating mode, a port can act as an input or act as an output. Due to the use of different types of sources in EV applications, the inputs and outputs of the power converter in each operating mode are changed. Thus, the power flow paths are changed in each operating mode. Fig. 1 shows the different operating modes of a multi-port converter utilized in the EV application. The converter has six operating modes as briefly described below:

**Mode I:** In this mode, the generated power of EGS is more than load power demand, and ESS needs to be charged. Thus, a part of EGS generated power is transferred to the load, and the remaining power is transferred to ESS.

**Mode II:** In this operating mode, ESS is fully charged, and the load is supplied by EGS.

**Mode III:** Load does not need to receive power, and EGS charges ESS.

**Mode IV:** The generated power of EGS is not enough to supply the load demand power, and ESS is used to compensate the lack of power.

**Mode V:** This operating mode happens when the load power demand increases instantaneously, and due to the faster response of the ESS than EGS, ESS supplies the load independently.

**Mode VI:** In this mode, the output port acts as a regenerative energy source and the generated power of this source is used to charge ESS.

In electric vehicle applications, the size and weight of the converter are very important factors. In most power converter topologies, inductors and heat-sinks have the most portion of the occupied volume and weight of the converter. Thus, the converter topologies must be utilized with the minimum number of inductors and small-size heat-sinks.

According to Fig. 1, to implement each operating mode separately, the number of required inductors increases drastically. Thus, sharing converter inductors by different operating modes is a promising method to reduce the volume of the multi-port converters. Besides, by increasing the switching frequency, the size of passive components can be reduced. However, switching loss increases and imposes larger size heat-sinks to dissipate the heat [6], [7]. To meet the high switching frequency and mitigating the switching loss, soft-switching methods must be employed [8]. However, implementing soft-switching methods in multi-port converters is not a straightforward method [9], [10]. Different operating modes, changing the direction of the power flow paths, sharing the components, and large number of switches with different switching patterns are the challenges of implementing soft-switching techniques.

In literature, many non-isolated multi-port DC-DC converters are introduced, which have attempted to overcome some of the mentioned challenges. In [11], a family of integrated multi-port DC-DC converters with a reduced number of switches is presented. In this paper, the derived multi-port converter uses three switches, but three inductors are used that increase the converter volume. In addition, some switches operate under soft-switching condition in some operating modes, and fully soft-switching operation is not achieved. In [12], a three-port converter with the capability of charging ESS from EGS and output is presented. In this converter, all energies from various sources are accumulated in a DC-link and through a bidirectional converter, ESS is charged. In this converter, no components are shared such that three inductors are used that increase the size and volume of the converter. Also, power conversion is accomplished in more than one stage, which increases the conduction loss. In addition, the converter has four switches operating under the hard-switching conditions, which degrades the converter efficiency.

In [13]–[17], some power converters are introduced for utilizing in electric vehicle and hybrid electric vehicle applications. In [13], a multi-port converter is introduced that uses a simple switch-diode structure to add input sources. Also, through a single-inductor bidirectional converter, all sources can exchange power together. This converter uses three switches, but in order to extend the number of operating modes, three extra relays are utilized. In this converter, ESS cannot directly receive power from EGS and the switches operate under hard switching condition. In [15], [16], in order to derive a dual-input single-inductor converter, the bridge arrangement is used. In this arrangement, one switch and one of the input sources are placed in series which establish a branch. Then, the branches can be placed in series or parallel to derive a multi-input converter. In this method, all the power flow paths are shared between the input sources. The EV power systems normally use metal chassis and frames as the current return path. This requires most of the sources and loads to have a common ground port which the presented converters lack and do not meet the EV power systems requirements. Also, the mentioned converters do not operate under soft-switching. The multi-port converters introduced in [14], [17] dedicate a complete converter to transfer power from each input to the output. Thus, the component counts of these converters are high. In [14], four inductors and five switches and in [17], four inductors and six switches are used, which increase the design complexity of the converters. In [14], energy storage devices cannot be charged from other input sources, and the switches of both converters operate under hard-switching condition.

In [18], three boost converters are integrated to derive a multi-input converter. In this converter, one EGS and one ESS are used which the power flow paths from these inputs to the output are shared. Thus, a single inductor converter is achieved that reduces the converter size, and also the power conversion is done in a single stage for every operating mode. However, this converter does not have the ability to transfer power from the output to the ESS and thus, it is not applicable.
R. Faraji et al.: Efficient Multi-Port Bidirectional Converter With Soft-Switching Capability

FIGURE 1. Different operating modes of a multi-port converter in EV application.

FIGURE 2. Conventional three-port converter (TPC).

to EV applications. The topology of this converter is shown in Fig. 2.

The topology of the introduced converter in [18] has been used as the base of many converters to derive a multi-input converter [19]–[23]. In [19], [20], the structure of conventional three-port converter (TPC) is changed to enhance the voltage gain. And to reduce the voltage stress on main switches, passive clamp circuits are used, but the switching loss still exists. In [21]–[23], some improvements are applied to the conventional TPC converter to provide soft-switching condition. A simple auxiliary resonant circuit is used in [21] to provide the soft-switching condition for the main switch and the switch in the ESS charging path. The auxiliary resonant circuit is integrated into the ESS charging path in which the resonance energy is recovered and sent to ESS. This converter has two inductors, and the converter volume is increased. Moreover, the switch in the input side operates under hard-switching condition. A passive lossless snubber circuit is presented in [22] to solve the hard-switching problem of the conventional TPC converter. In this converter, the pair of coupled-inductors along with an auxiliary inductor is used to provide turn-ON zero voltage switching (ZVS) and turn-OFF zero current switching (ZCS) conditions for the main switch. Also, the switch in the ESS charging path operates under ZCS. The hard-switching operation of the input switch and adding an extra magnetic core are the disadvantages of this converter. In [23], the TPC converter structure is changed and an active clamp circuit is added to provide soft-switching condition. In addition, the hard-switching problem of the input switch is solved, but the proper operation of the active clamp circuit is lost at low output power conditions and in some operating modes, soft-switching operation is missed. All of the introduced converters in [18]–[23] do not have the ESS charging capability from the output which limits their applications.

In this paper, to overcome the problems associated with the conventional TPC, including the hard-switching operation and disability of ESS charging from the output, a new soft-switched bidirectional multi-port DC-DC converter is proposed. To add the ESS charging ability from the output, a bidirectional power flow path is integrated into the TPC converter. And, to enhance the efficiency, a soft-switching cell with the minimum number of switches is added to the converter such that soft-switching condition for all switches in all operating modes is provided. By the use of coupled inductors in the soft-switching cell, the converter benefits from one magnetic core and all power conversions are done in a single-stage. As a result, both switching and conduction losses are reduced. The paper is organized in seven sections. The proposed converter and operating modes are described in section II. The converter design considerations are presented in section III. The experimental results are discussed in Section IV. In section V, efficiency and loss breakdown analysis are presented and the proposed topology is compared with some novel counterparts in section VI. Finally, the drawn conclusions from this manuscript are presented in section VII.

II. PROPOSED CONVERTER TOPOLOGY AND OPERATING MODES

The topology of the proposed soft-switched bidirectional multi-port converter (BTPC) is shown in Fig. 3. In this
The soft-switching cell consists of coupled inductors \( (N_1, N_2) \) and the leakage inductance \( (L_{LK}) \), \( C_4 \) and the auxiliary switches \( S_{a1} \) and \( S_{a2} \). The magnetizing inductance \( (L_M) \) in coupled inductors acts as the main inductor of the converter and \( n = N_2/N_1 \). The leakage inductance in the soft-switching cell acts as the snubber inductor and provides ZCS turn-ON condition for \( S_{a1} \) and \( S_{a2} \). Also, \( D_3 \) is added to deliver the discharging energy of \( C_2 \) and provide ZVS turn-ON condition for \( S_2 \).

In the proposed converter, \( V_{in1} \) is dedicated to energy generation sources like fuel cell, \( V_{in2} \) port is connected to an energy storage system like the battery or super-capacitor such that \( V_{in2} > V_{in1} \). When \( S_1 \) is ON, \( D_1 \) is reverse biased and current just flows from \( V_{in2} \) and when \( S_1 \) is OFF, \( D_1 \) conducts and \( V_1 \) supplies the load. Through this simple switch-diode structure, power management between input sources can be easily done. And output port can be connected to a regenerative energy source or DC-link.

According to the power status of each source, the proposed multi-port converter has different operating modes indicated in Fig. 1. To simplify the converter analysis, it is assumed that the voltage of all sources is constant, all semiconductor components are ideal and the converter is at steady-state condition.

### A. MODE I

In this operating mode, EGS supplies the required power of ESS and the output simultaneously. In other words, some amount of \( V_{in1} \) generated power is transferred to \( V_{out} \), and the remaining power is delivered to \( V_{in2} \). This operating mode has thirteen distinct operating intervals in each switching cycle. The key waveforms and the equivalent circuit of each interval are shown in Figs. 4 and 5, respectively. Prior to the first interval, it is assumed that all switches are OFF.

1) INTERVAL I \( (t_0 - t_1) \) [SEE FIG. 5(a)]

At the beginning of this interval, the body diode of \( S_4 \) conducts, and the stored energy in the magnetizing inductance is transferred to the output.

2) INTERVAL II \( (t_1 - t_2) \) [SEE FIG. 5(b)]

Before the switches turn ON, the corresponding snubber capacitors must be discharged. Thus, to provide ZVS turn-ON condition for the TPC switches, the soft-switching cell is activated. In this interval, \( S_{a1} \) is turned ON under ZCS condition due to leakage inductance. As a result, a constant positive voltage is applied to the leakage inductance through the coupled inductors, and its current \( (i_{LK}) \) increases linearly.

3) INTERVAL III \( (t_2 - t_3) \) [SEE FIG. 5(c)]

At \( t_2 \), the leakage inductance current becomes more than the output current and thus, the body diode of \( S_4 \) turns OFF. Then, a resonance begins between the leakage inductance and \( C_2-C_4 \) snubber capacitors. Thus, \( v_{C2} \) and \( v_{C3} \) decrease, and \( v_{C4} \) increases.
4) INTERVAL IV (t3 – t4) [SEE FIG. 5(d)]
This interval starts when C4 is fully charged, and C2 and C3 are fully discharged. Therefore, the body diode of S2 and S3 conduct. During this interval, the direction of the input current is reversed, and a resonance occurs between leakage inductance and C1 which causes C1 to discharge. During this interval, ILK starts to decrease.

5) INTERVAL V (t4 – t5) [SEE FIG. 5(e)]
When the body diode of S3 is conducting, S3 can turn ON under ZVS condition. In the meantime, VC1 reaches zero, and the body diode of S1 conducts. Through the proposed soft-switching method and by the use of the ESS power flow path, the soft-switching energy is recovered and transferred to the ESS.

6) INTERVAL VI (t5 – t6) [SEE FIG. 5(f)]
At t5, the direction of the input current becomes positive. Thus, the body diode of S1 turns OFF, and the C1 snubber capacitor is charged.

7) INTERVAL VII (t6 – t7) [SEE FIG. 5(g)]
This interval begins when C1 is charged, and D1 starts to conduct. Therefore, the magnetizing inductance is charged through Vin1.

8) INTERVAL VIII (t7 – t8) [SEE FIG. 5(h)]
At t7, the leakage inductance current reaches zero, and Sd1 turns OFF under ZCS condition. In this interval, the current in LM continues to increase.

9) INTERVAL IX (t8 – t9) [SEE FIG. 5(i)]
In the previous intervals, a part of the stored energy in Cn is discharged, and in order to keep the voltage of this capacitor constant, Sd2 is turned ON under ZCS condition due to LKL. In this interval, a negative voltage is applied to the leakage inductance and iLK decreases.

10) INTERVAL X (t9 – t10) [SEE FIG. 5(j)]
In order to charge ESS, S1 is turned OFF under ZVS condition due to the snubber capacitor. Then, VC3 increases.

11) INTERVAL XI (t10 – t11) [SEE FIG. 5(k)]
At t10, VC3 reaches Vin2 and D2 conducts. Because the C2 snubber capacitor was discharged during interval IV, S2 is turned ON under ZVS condition. And the stored energy in LM is transferred to ESS. Due to the induced voltage by the coupled inductors, iLK decreases toward zero during this interval.

12) INTERVAL XII (t11 – t12) [SEE FIG. 5(l)]
At the beginning of this interval, iLK reaches zero, and Sd2 is turned OFF under ZCS condition while ESS is charged by Vin1.

13) INTERVAL XIII (t12 – t13) [SEE FIG. 5(m)]
At t12, S2 is turned OFF under ZVS due to C2. Then, the voltage of C2 and C3 increase, and the voltage of C4 decreases. At the end of this interval, C4 is fully discharged, and the body diode of S4 conducts. This interval is the last interval in a switching cycle in Mode I.

B. MODE II
In this operating mode, EGS just supplies the output demand power. The converter operation is approximately similar to Mode I, with the difference that S2 never turns ON in this mode. Therefore, converter operation starts from intervals I to IX, then ends in Interval XIII (Figs. 5(a)-(i) plus Fig. 5 (m)).

C. MODE III
In this mode, all the generated power by EGS is used to charge ESS. This operating mode is similar to Mode I with the difference that S2 is always ON and no power is transferred to the output port. By switching S3, the power flow is controlled and similar to other operating modes, Sd1 is activated before S3 is turned ON and Sd2 is activated after S3 is turned-OFF to provide soft-switching condition for the S3 switch.
D. MODE IV

In this operating mode, both input sources supply the output load simultaneously. And, S1 is switched such that the harvested energy from each input is controlled. This operating mode has thirteen distinct intervals in each switching cycle. The key waveforms and the equivalent circuit of each interval are shown in Figs. 6 and 7, respectively. Prior to the first interval, it is assumed that S1, S3 and Sα1 are ON and S2, S4 and Sα2 are OFF, and the leakage inductance current is decreasing.

1) INTERVAL I (t0 − t1) [SEE FIG. 7(a)]

In this interval, S1 and S3 are ON, and $L_M$ is being charged by $V_{in2}$. 
2) INTERVAL II (t₁ - t₂) [SEE FIG. 7(b)]
To receive power from \( V_{in} \), \( S₁ \) is turned OFF under ZVS due to \( C₁ \) snubber capacitor, and \( v_{C₁} \) is increased.

3) INTERVAL III (t₂ - t₃) [SEE FIG. 7(c)]
At t₂, the \( C₁ \) voltage reaches the difference of input voltage sources, and \( D₁ \) starts to conduct. Thus, \( L_M \) is being charged by \( V_{in} \).

4) INTERVAL IV (t₃ - t₄) [SEE FIG. 7(d)]
In this interval, \( S₄₂ \) is turned ON to charge \( C₄ \). The \( S₄₂ \) turn-ON operation is under ZCS condition due to the leakage inductance.

5) INTERVAL V (t₄ - t₅) [SEE FIG. 7(e)]
At the beginning of this interval, \( S₃ \) is turned OFF under ZVS condition. Then, the voltage of \( C₂ \) and \( C₃ \) increase, and the voltage of \( C₄ \) decreases through a resonance with the leakage inductance.

6) INTERVAL VI (t₅ - t₆) [SEE FIG. 7(f)]
At \( t₅ \), \( v_{C₄} \) reaches zero and the body diode of \( S₄ \) starts to conduct. The magnetizing inductance is supplying energy to the load. Also, the current through the leakage inductance decreases.

7) INTERVAL VII (t₆ - t₇) [SEE FIG. 7(g)]
At \( t₆ \), \( i_{LK} \) reaches zero, and \( S₄₂ \) is turned OFF under ZCS condition.

8) INTERVAL VIII (t₇ - t₈) [SEE FIG. 7(h)]
To discharge the \( C₁ - C₃ \) snubber capacitors and to provide ZVS turn-ON condition, \( S₄₁ \) is turned ON. Since the \( S₄₁ \) current rate is restricted by the leakage inductance, this switch is turned ON under ZCS condition. Also, due to the positive voltage induced on \( L_{LK} \), \( i_{LK} \) is increasing.

9) INTERVAL IX (t₈ - t₉) [SEE FIG. 7(i)]
This interval begins when \( i_{LK} \) becomes more than the output current, and the body diode of \( S₄ \) turns OFF under ZCS condition. Then, a resonance occurs between the leakage inductance and \( C₂ - C₄ \), and \( v_{C₂} \) and \( v_{C₃} \) decrease and \( v_{C₄} \) increases.

10) INTERVAL X (t₉ - t₁₀) [SEE FIG. 7(j)]
At the beginning of this interval, \( C₂ \) and \( C₃ \) are fully discharged, and the corresponding body diodes start to conduct. During this interval, the input current direction becomes negative, and \( D₁ \) turns OFF. Then, the voltage of \( C₁ \) decreases through a resonance with \( L_{LK} \).

11) INTERVAL XI (t₁₀ - t₁₁) [SEE FIG. 7(k)]
At the beginning of this interval, \( S₃ \) is turned OFF under ZVS and \( C₁ \) is discharged, and the body diode of \( S₁ \) turns ON.

12) INTERVAL XII (t₁₁ - t₁₂) [SEE FIG. 7(l)]
When the body diode of \( S₁ \) is conducting, \( S₁ \) can be turned OFF under ZVS condition.

13) INTERVAL XIII (t₁₂ - t₁₃) [SEE FIG. 7(m)]
At \( t₁₂ \), the input current direction is reversed, and at \( t₁₃ \), the current through \( S₄₁ \) becomes zero. Thus, \( S₄₁ \) can be turned OFF under ZCS condition.

**E. MODE V**
In this operating mode, ESS supplies the output load independently. The converter operation in this mode is similar to Mode IV with the difference that \( S₁ \) is always ON and \( D₁ \) is always OFF. In this mode, just \( S₃ \) is switched. Similar to other operating modes, \( S₄₁ \) and \( S₄₂ \) are switched such that the soft-switching condition for \( S₃ \) is provided.

**F. MODE VI**
In the previous operating modes, the output port acted as the power sink and absorbed power from the other ports. However, in mode VI, the output port acts as a power source and the generated power in this port is used to charge ESS. This operating mode has eleven distinct operating intervals in each switching cycle. The key waveforms and the equivalent circuit of each interval are shown in Figs. 8 and 9, respectively. Prior to the first interval, it is assumed that \( S₁ \), \( S₄ \) and \( S₄₂ \) are ON and other switches are OFF and the leakage inductance current is decreasing.

1) INTERVAL I (t₀ - t₁) [SEE FIG. 9(a)]
This interval starts when the leakage inductance current reaches zero. During this interval, the magnetizing inductance is charged by \( V_{out} \).
2) INTERVAL II \((t_1 - t_2)\) [SEE FIG. 9(b)]
In this interval, to charge \(C_a, S_{a1}\) is turned ON at ZCS due to series \(L_{LK}\).

3) INTERVAL III \((t_2 - t_3)\) [SEE FIG. 9(c)]
At \(t_2, S_4\) is turned OFF under ZVS condition, and its corresponding snubber capacitor is charged. In the meantime, \(C_2\) and \(C_3\) are discharged in a resonance interaction with the leakage inductance.

4) INTERVAL IV \((t_3 - t_4)\) [SEE FIG. 9(d)]
At \(t_3, v_{C2}\) and \(v_{C3}\) reach zero, and the body diodes of \(S_2\) and \(S_3\) start to conduct. During this interval, \(i_{LK}\) is decreasing.
5) INTERVAL V (t4 – t5) [SEE FIG. 9(e)]
In this interval, \( i_{LM} \) is still decreasing, and \( i_{LM} \) passes through the body diode of \( S_3 \).

6) INTERVAL VI (t5 – t6) [SEE FIG. 9(f)]
At t6, the leakage inductance current reaches zero, and \( S_a1 \) is turned OFF under ZCS condition.

7) INTERVAL VII (t6 – t7) [SEE FIG. 9(g)]
To provide soft-switching condition for \( S_4 \), \( S_a2 \) is turned ON. Then, \( i_{LK} \) increases in the reverse direction.

8) INTERVAL VIII (t7 – t8) [SEE FIG. 9(h)]
In this interval, the current through \( N_1 \) becomes more than \( i_{LM} \) and in a resonance process between \( C_2 - C_4 \) with \( L_{LK} \), \( v_{C2} \) and \( v_{C3} \) increase, and \( v_{C4} \) decreases.

9) INTERVAL IX (t8 – t9) [SEE FIG. 9(i)]
When \( v_{C4} \) reaches zero, the body diode of \( S_4 \) conducts and \( i_{LK} \) decreases.

10) INTERVAL X (t9 – t10) [SEE FIG. 9(j)]
When \( S_4 \) body diode is conducting, \( S_4 \) can be turned ON under ZVS condition.

11) INTERVAL XI (t10 – t11) [SEE FIG. 9(k)]
At t10, the coupled inductors primary side current becomes lower than \( i_{LM} \). This interval ends when \( i_{LK} \) becomes zero and \( S_a2 \) is turned OFF under ZCS condition.

### III. CONVERTER ANALYSIS AND DESIGN CONSIDERATIONS

In this section, the analysis of the proposed bidirectional TPC is investigated, and the voltage gain, inductor design, and soft-switching conditions are discussed. To simplify the analysis, it is assumed that the voltage across \( C_m \) is constant, all circuit elements are ideal, and the converter operates under steady-state condition. In this section, \( d_{S1}, d_{S2}, d_{S3} \) and \( d_{S4} \) are used to indicate the duty cycle of switches \( S_1, S_2, S_3 \) and \( S_4 \), respectively.

In Fig. 10, the operating modes selection of the proposed converter is illustrated.

#### A. VOLTAGE GAINS

According to the operating modes shown in Fig.1, the proposed converter has six different voltage gains:

1) **MODE I**
In this mode, \( V_{in1} \) supplies the demand power of \( V_{in2} \) and \( V_{out} \) simultaneously. Using the volt-second balance principle on the magnetizing inductance as (1), the voltage gain can be achieved by (2):

\[
d_{S3}V_{in1} = d_{S2}(V_{in2} - V_{in1}) + (1 - d_{S2} - d_{S3}) \times (V_{out} - V_{in1})
\]

\[
V_{out} = \frac{1}{1 - (d_{S2} + d_{S3})[V_{in1} - d_{S2}V_{in2}]}
\]  \( \text{(1)} \)

2) **MODE II AND MODE V**
In these operating modes, each of \( V_{in1} \) and \( V_{in2} \) supplies output power separately. By considering \( V_{in1} = V_{in2} = V_{IN} \), the voltage gains of mentioned operating modes are the same. Equation (3) indicates the magnetizing volt-second balance principle applied on magnetizing inductance which results the voltage gain presented by equation (4).

\[
d_{S3}V_{IN} = (1 - d_{S3})(V_{out} - V_{IN})
\]

\[
\frac{V_o}{V_{IN}} = \frac{1}{1 - d_{S3}}
\]  \( \text{(3)} \)


3) **MODE III**
The whole generated power of \( V_{in1} \) is transferred to \( V_{in2} \). Thus, \( V_{in2} \) in this mode acts as the output. By applying the volt-second balance principle on \( L_M \) (5), the voltage gain is achieved (6).

\[
d_{S3}V_{in1} = (1 - d_{S3})(V_{in2} - V_{in1})
\]

\[
\frac{V_{in2}}{V_{in1}} = \frac{1}{1 - d_{S3}}
\]  \( \text{(5)} \)

4) **MODE IV**
In this mode, \( V_{in1} \) and \( V_{in2} \) contribute to the volt-second balance principle calculation of magnetizing inductance (7), results in the voltage gain can be calculated by (8).

\[
d_{S1}V_{in2} + (d_{S3} - d_{S1})V_{in1} = (V_{out} - V_{in1})(1 - d_{S3})
\]  \( \text{(7)} \)
FIGURE 9. Proposed converter equivalent circuit in each interval for Mode IV. (a) Interval I \([t_0, t_1]\), (b) Interval II \([t_1, t_2]\), (c) Interval III \([t_2, t_3]\), (d) Interval IV \([t_3, t_4]\), (e) Interval V \([t_4, t_5]\), (f) Interval VI \([t_5, t_6]\), (g) Interval VII \([t_6, t_7]\), (h) Interval VIII \([t_7, t_8]\), (i) Interval IX \([t_8, t_9]\), (j) Interval X \([t_9, t_{10}]\), and (k) Interval XI \([t_{10}, t_{11}]\).

5) MODE VI
During this mode, the \(V_{\text{out}}\) acts as the power source, and the generated power of \(V_{\text{out}}\) is transferred to \(V_{\text{in}}\). In this mode, just \(S_4\) is switched. Equation (9) shows the volt-second balance principle of magnetizing inductance and equation (10) indicates the derived voltage gain for this mode:

\[
V_{\text{out}} = \frac{1}{1 - d_{S3}} \times [(1 - d_{S1}) V_{\text{in}1} + d_{S1} V_{\text{in}2}]
\]  

\[
d_{S4}(V_{\text{out}} - V_{\text{in}2}) = (1 - d_{S4}) V_{\text{in}2}
\]  

\[
\frac{V_{\text{in}2}}{V_{\text{out}}} = d_{S4}
\]  

\[
id_{L_M} = \frac{2 \cdot I_o}{1 - d_{S1}}
\]  

Fig. 11 depicts the voltage gain curves of each operating mode.

B. INDUCTOR DESIGN
In the proposed converter, the magnetizing inductance of the coupled inductors is shared between all operating modes. The converter is designed to operate in continuous conduction mode (CCM). Thus, the optimum value of the magnetizing inductance must be selected. The proposed converter in Modes I-V acts as the boost converter. In these modes, the magnetizing inductance value can be calculated as follows:

\[
id_{L_M(\text{avg})} = \frac{2 \cdot I_o}{1 - d_{S1}}
\]
FIGURE 10. Operating modes selection flow chart for the proposed converter.

\[
\Delta L_{LM} = \frac{dS_1 \cdot V_{IN}}{L_M \cdot f_s} \quad (12)
\]

\[
L_M \geq \frac{dS_1 \cdot (1 - dS_1^2) \cdot V_{O\_mode}^2}{2 \cdot f_s \cdot P_{O\_mode(Critical)}} \quad (13)
\]

where \(i_{LM(\text{avg})}\) is the average value and \(\Delta i_{LM}\) is the ripple of \(L_M\) current so that by substituting (12) into (11) and using (1)-(6), the minimum value of \(L_M\) at the boundary of CCM and DCM is achieved (13). In equation (13), \(V_{O\_mode}\) refers to the output voltage of each operating mode, and \(P_{O\_mode(Critical)}\) is the minimum power in which for a specific value of \(L_M\), the converter operates in the boundary of CCM and DCM.

In Mode VI, the proposed converter operates as a buck converter and similar calculations can be done for this mode:

\[
i_{LM(\text{avg})} = \frac{2 \cdot P_{Vin2}}{V_{in2}} \quad (14)
\]

\[
\Delta i_{LM} = \frac{(1 - dS_4) \cdot V_{in2}}{L_M \cdot f_s} \quad (15)
\]

By substituting (15) into (14), the minimum value of magnetizing inductance at the boundary of CCM and DCM is achieved as:

\[
L_M \geq \frac{(1 - dS_4) \cdot V_{in2}^2}{2 \cdot f_s \cdot P_{Vin2(Critical)}} \quad (16)
\]

C. SOFT-SWITCHING CONDITIONS

The principle of soft-switching operation of the proposed converter is investigated in this section. Before main switches become turn ON, the auxiliary switches must be turned ON to provide ZVS condition. At the first step, one of the auxiliary switches is activated, then the summation of output voltage and \(V_{Ca}\) and the secondary side voltage of coupled inductors is drooped on the leakage inductance. Then, the \(i_LK\) starts to increase linearly until it reaches \(i_{out}\). Then, through a resonance process, the snubber capacitors are discharged. Thus, in order to have soft-switching conditions, the following points must be satisfied.

1) PROVIDING ZVS TURN-OFF CONDITION FOR \(S_1, S_2, S_3\) AND \(S_4\)

C1-C4 snubber capacitors provide zero voltage switching condition for their corresponding switches at turn-OFF instant. Therefore, their minimum value can be selected similar to any snubber capacitor as follow [24]:

\[
C_{1-4} \geq C_{\text{min}} = \frac{I_{SW}t_s}{2V_{SW}} \quad (17)
\]

where \(I_{SW}\) is the switch current before switch turn-OFF instant, \(t_s\) is the switch current fall time, and \(V_{SW}\) is the switch voltage after turn-OFF.

2) PROVIDING ZCS TURN-ON CONDITION FOR \(S_{a1}\) AND \(S_{a2}\)

Leakage inductance acts as the snubber inductor at turn-ON instant of the auxiliary switches. The minimum value of snubber inductor can be defined as:

\[
L_{\text{leakage}} \geq L_{\text{leakage, min}} = \frac{V_{SW}t_s}{2I_{SW}} \quad (18)
\]

where \(V_{SW}\) is switch voltage before switch turns ON, \(t_s\) is the switch current rise time, and \(I_{SW}\) is the switch current after switch turns ON.

3) PROVIDING ZVS TURN-ON CONDITION FOR MAIN SWITCHES

To obtain the ZVS condition at turn-ON instant of the TPC switches, the voltage of the switches must reach zero. The soft-switching condition in operating modes I to VI are almost the same. Thus, as an example, just the soft-switching condition for Mode V is investigated in this section. During intervals III and IV, the snubber capacitors through resonance by leakage inductance are discharged. To simplify calculations, it is assumed that the value of all snubber capacitors are the same such that \(C_1 = C_2 = C_3 = C_4 = C_S\), and they are discharged at the same time. The simplified resonance equation is presented as follows (19)–(24), as shown at the bottom of the next page:

To calculate the value of \(V_{Ca}\) some simplifications are necessary; otherwise, the relations would become cumbersome. According to (19)-(24), the first soft-switching condition is achieved as follow:

\[
V_{Ca} \geq V_{IN} - \frac{V_{out}}{4} \quad (25)
\]

Assuming that the resonance time is short enough to omit it in comparison with the switching period. Fig. 12 shows the simplified waveform of \(i_{Ca}\) at the steady-state condition which the average of \(i_{Ca}\) would be zero. Thus, the value of \(V_{Ca}\) can be obtained as follow:

\[
V_{Ca} = V_{out} (n + 1) - nV_{IN} - \frac{I_{LM}L_{LK}}{nt_{3-4}} \quad (26)
\]

where \(t_3-t_4\) is the duration time of interval IV in Fig. 6 which would be adjustable and it can be expressed as follow:

\[
t_{3-4} = \frac{2I_{LM}L_{LK}}{V_{out}(2n + 1) - 2nV_{IN}} \quad (27)
\]
FIGURE 11. Voltage gain graphs in different modes. (a) Modes II, III, and V. (b) Mode IV (VA = VB). (c) Mode I (VA = VB). (d) Mode VI.

FIGURE 12. Simplified waveform of $i_{Ca}$.

Before main switches of the converter would turn ON, auxiliary switches must be turned ON to discharge the snubber capacitors and to provide ZVS condition. Thus, $t_{ZVT}$ is the minimum required time which auxiliary switches must be turned ON before main switches become active and is defined by:

$$t_{ZVT} = \frac{1}{\omega_1} \left[ \cos^{-1} \left( \frac{A_1}{\sqrt{B_1^2 + C_1^2}} \right) + \tan^{-1} \left( \frac{B_1}{C_1} \right) \right]$$

(28)

The $t_{ZVT}$ must be shorter than the OFF time of the main converter switch in each mode:

$$t_{ZVT} \leq \left[ 1 - d_{S, mode} \right] T_{SW}$$  

(29)

4) PROVIDING ZCS TURN-OFF CONDITION

During soft-switching process, the auxiliary switches must be kept ON enough in order to the leakage inductance current reaches zero and ZCS condition achieves. The $t_{ZCT}$ is defined by Equation (30):

$$t_{ZCT} = \frac{I_{LM} (t_4) L_{LK}}{V_O (1 + n) - n V_{IN} - V_{Ca}} + t_{ZVT} + \frac{3 I_{LM} (t_6) L_{LK}}{n V_{IN} + V_{Ca}}$$  

(30)

IV. EXPERIMENTAL RESULTS

To verify the effectiveness of the proposed converter, the prototype of the converter is implemented to supply a 200 W–200 V load. The specifications of the prototype are indicated in Table 1 and the photograph of the converter prototype is shown in Fig. 13. Also, experimental waveforms are shown in Fig. 14. Fig.14 (a)-(c) shows the waveforms of active switches in mode V. As it is shown in Fig. 14(a),

$$v_{CS} (t) = A_1 + B_1 \sin \omega_1 (t - t_1) + C_1 \cos \omega_1 (t - t_1)$$

$$A_1 = \frac{V_{IN} n (1 + n) - V_{Ca} (1 + n) + 3 V_n n^2}{4 n^2 + 2 n + 1}$$

(19)

(20)

$$B_1 = \frac{[I_{LM} (t_{r1-1}) (4 n^2 + 5 n + 1)] - [I_{LM} (t_{r1-1}) (4 n^3 + 5 n^2 + 3 n + 1)]}{Z_1}$$

(21)

$$C_1 = \frac{V_O (n^2 + 2 n + 1) + V_{Ca} (1 + n) - V_{IN} n (1 + n)}{4 n^2 + 2 n + 1}$$

(22)

$$Z_1 = \frac{\sqrt{L_{LK}}}{(4 n^2 + 2 n + 1) \sqrt{3 C_S (4 n^2 + 2 n + 1)}}$$

(23)

$$\omega_1 = \frac{4 n^2 + 2 n + 1}{\sqrt{C_S L_{LK}}}$$

(24)
FIGURE 14. Waveforms of the implemented prototype in different operating modes: (a), (b) and (c) Mode V. (d) and (e) Mode IV. (f) and (g) Mode I. (h) Mode III. (i) Mode VI. [All time scales are 2 μS/div except (c) which is 1 μS/div].

| Symbol | Parameter | Value |
|--------|-----------|-------|
| \( I_M \) | Magnetizing inductance | 650 μH |
| \( N \) | Turns ratio | 0.4 |
| \( C_2 \) | Output capacitors | 10 μF |
| \( C_1, C_3 \) | Snubber capacitors | 3 nF |
| \( D_1, D_2 \) | Diodes | MUR1640 |
| \( S_2, S_3 \) | Switches | IRF250P225 |
| \( S_3, S_4 \) | Switches | TK31N60W |
| \( f_s \) | Switching frequency | 100 kHz |
| \( V_1 \) | EGS (Unidirectional fixed voltage Source) | 70 V |
| \( V_L \) | ESS | 96 V |
| \( V_o \) | Output voltage | 200 V |

the \( S_3 \) main switch operates under ZVS condition. Also, Figs 14 (b)-(c) show that axillary switches operate under ZCS condition. The waveforms of \( S_3 \) in mode II are the same as Fig. 14(a), and for all operating modes, the waveforms of \( S_{a1} \) and \( S_{a2} \) are almost similar to Figs 14 (b)-(c). In mode IV, both EGS and ESS must contribute to supply the load. Thus, \( S_1 \) is switched to control the received power from each source. To provide ZVS condition for \( S_1 \), the soft-switching cell must be able to reverse the direction of the input current. Accordingly, Fig. 14 (d) indicates that the input current direction is reversed. Thus, the \( S_1 \) switch operates under ZVS condition, as shown in Fig. 14 (e). In mode I, some amounts of stored energy in magnetizing inductance must be transferred to the load, and the remained energy must be transferred to ESS. This is done by adjusting the activation time of \( S_2 \) switch which is shown in Fig. 14 (f). In this mode, \( S_2 \) operates under ZVS condition (Fig. 14 (g)). In mode III, EGS charges ESS and \( S_3 \) control this mode. The ZVS operation of \( S_3 \) in this mode is shown in Fig. 14 (h). In mode VI, \( S_4 \) is activated such that how ESS is charged through output. In this mode, \( S_4 \) is switched under the ZVS condition (Fig. 14 (i)).

V. EFFICIENCY AND LOSS BREAKDOWN ANALYSIS

In this section, the experimental results are used to investigate the efficiency of the proposed converter in all operating modes and wide range of output power. Also, the components loss breakdown analysis at full load condition is analyzed. In mode I, half of the EGS generated power is transferred to the output load, and the remaining power is transferred to the ESS. And in mode IV, each input source supplies the load with the same amount of power. In Fig. 15 the efficiency of the proposed converter is compared with the conventional three-port converter (Fig. 2). According to the results, it can conclude that by reducing the switching loss through using the proposed soft-switching method, the efficiency is enhanced in a wide range of the output power. Also, the detailed loss analysis of the main components is shown in Fig.16 which
TABLE 2. Features comparison of multi-port converters with the proposed converter.

| Converters   | Converter topology type | No. of switches | No. of diodes | No. of Magnetic Cores | Six modes & Fully soft-switched | Operating modes (N/A: Not available, Soft Switching: ✓, Hard switching: ✗) |
|--------------|-------------------------|-----------------|---------------|-----------------------|----------------------------------|--------------------------------------------------------------------------------|
| [9]          | Other                   | 4               | 5             | 2                     | ✗                                | ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                                 |
| [12]         | Other                   | 4               | 4             | 3                     | ✗                                | ✓ ✗ ✓ ✓ ✗ ✗ N/A                                                                |
| [17]         | Other                   | 6               | 2             | 4                     | ✗                                | ✓ ✗ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| [19]         | TPC-based               | 3               | 5             | 2                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| [20]         | TPC-based               | 3               | 8             | 1                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| [21]         | TPC-based               | 3               | 5             | 2                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| [22]         | TPC-based               | 3               | 7             | 2                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| [25]         | TPC-based               | 4               | 5             | 1                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| [26]         | Other                   | 5               | 0             | 2                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| [27]         | Other                   | 3               | 2             | 5                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| [28]         | Other                   | 4               | 3             | 1                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| [29]         | Other                   | 6               | 0             | 2                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |
| Proposed     | TPC-based               | 6               | 6             | 1                     | ✓                                | ✓ ✓ ✓ ✓ ✓ ✓ ✓ N/A                                                             |

FIGURE 15. Efficiency curves. (a) Hard-switched conventional converter (with the bidirectional power flow path from output to the ESS). (b) Proposed converter.

indicates that by reducing switching loss, the conduction loss is the dominated loss in the proposed converter.

VI. COMPARISON

In Table 2, the proposed converter is compared with different multi-port converters. At first, in comparison with [9], [19]–[22], [25]–[28], the proposed converter has a bidirectional power flow path to charge ESS from the output. Moreover, the converters introduced in [12], [17], [19]–[22], [28] do not operate under fully soft-switching conditions. In the introduced converter in [21], [22], the switch

in the input side of the TPC converter operates under hard-switching condition. And, in [28], the active clamp circuit technique is used to provide soft-switching conditions, and due to the dependency of this technique to output power, the soft-switching condition is missed in Mode III. In the proposed converter, only one magnetic core is used to provide six different operating modes in which, in all of them, the switches operate under soft-switching conditions. However, in [9], [12], [17], [19], [21], [22], [26], [27], [29], more than one magnetic cores are used to have fewer number of operating modes or operate under hard-switching conditions which caused the volume and weight of the converters to be increased.

VII. CONCLUSION

In this paper, a bidirectional multi-port converter with soft-switching capability is proposed. At first, the ESS charging ability from the output port is provided for the conventional three-port converter. Then, a soft-switching cell is used to solve the hard-switching operation of the three-port converter switches which are placed in different power flow paths. Although the power flow paths are changed during different operating modes and each switch has a distinct switching pattern, but the proposed soft-switching conditions are
elaborately provided for all switches under different modes. As a result, by reducing switching loss, the efficiency of the proposed converter is improved in the wide range of the output power. Realizing six distinct operating modes, one-stage power conversion, and soft-switching operation by utilizing only one magnetic core are the prominent advantages in comparison with other counterparts.

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