

A three-phase flyback current-fed push-pull bidirectional dc-dc converter for dc microgrid application

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Abstract— This paper proposes a new three-phase flyback current-fed push-pull bidirectional dc-dc converter, which in both senses operation of the proposed converter is analyzed and explained even as the DC transfer function in continuous, discontinuous and critical conduction mode has been presented. The proposed converter is suitable for the dc microgrids bus, such as those having fuel cells, PV array and wind turbine as the DC source power supply. Where bidirectional power flow related with battery or supercapacitor bank charge and discharge is necessary.

Keywords - Flyback converter, Three-phase dc-dc converter, Bidirectional, Current-fed push-pull converter

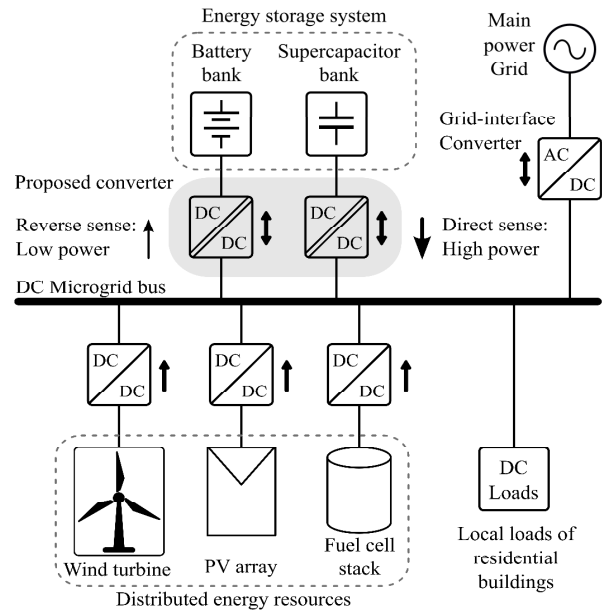
I. INTRODUCTION

The advancing of power device and power electronics makes the dc transmission once again attracting our attention since change of dc voltage level is no longer the problem of the technology. A large number of distributed generation (DG) sources such as photovoltaic generations, fuel cells, wind turbines and gas cogenerations have been installed into utility grids [1-4]. Integrating the renewable energy sources such as solar, wind, and fuel cell are connected together, to a common ac or dc grid through power electronic interfaces gives flexibility in conversion and power level. The microgrid is one of new conceptual power systems for good installation of many DGs, and has become one of the most important research directions in the power area [5-7]. Moreover, dc is chosen over ac because it facilitates integrating most modern electronic loads, and energy storage devices [5].

The Figure 1 shows a schematic view of the dc microgrid system, where this system utilizes a dc bus for distributes power to a residential area and the ac grid through the intermediary of a bidirectional ac-dc grid-interface converter. All the energy resources units and the energy storage system are linked with the dc bus through dc-dc converters, and to control the power flow of the energy storage devices, always is necessary to use bidirectional converters. Furthermore, the microgrid can be used to regulated and stabilize the power flow of the ac commercial grid [8-9]. Electric power storage devices, such as batteries and supercapacitors, can absorb fluctuations of photovoltaic or wind generation and equalize power transmission [10-14].

The literatures that are focused on bidirectional dc-dc converters are mainly concentrated on investigation and application in solar energy, fuel cells and plug-in electric vehicles [15-24]. The proposed isolated dc-dc converter can be used to control the power flow direction and to regulate the dc bus voltage when isolation is required for safety reasons. The storage system accumulates energy during low demand periods and can be later used to supply the microgrid for peak shaving or when increase the number of connected loads. The dc-dc converter is necessary to connect the energy storage system to the microgrid dc bus, once the battery and supercapacitor bank voltage is low and not controlled. Moreover, the proposed converter can by maintaining the supplied current with a low ripple, such as to extend the battery lifetime [25-26].

Figure 1. Typical architecture of dc microgrid system.

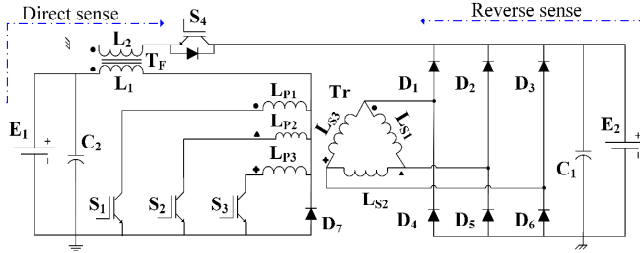


II. PROPOSED BIDIRECTIONAL DC-DC CONVERTER

Fig 2. shows the proposed converter topology. The converter is composed by:

A flyback transformer, primary and secondary winding are L_1 and L_2 respectively; A three-phase transformer, primary windings L_{p1} , L_{p2} , and L_{p3} , secondary windings L_{s1} , L_{s2} and L_{s3} ; Four switches, three (S_1 , S_2 and S_3) for direct sense and one (S_4) in reverse sense; two storage capacitors C_1 and C_2 ; a three-phase full-bridge diode rectifier. By the end, a diode D_7 is used to obtain a DC voltage from the inductor voltage (L_1) when the converter operates in reverse sense.

Figure 2. The proposed converter



A. Operating Principle of The Proposed Converter

The principle of operation is presented considering ideal components. The proposed converter allows bidirectional power flow between power sources E_1 and E_2 . In direct sense, the modulation strategy consists of commanding switches S_1 , S_2 and S_3 by three signals with duty ratio D and shifted by one-third switching period. S_4 commanding signal is applied in reverse sense.

Operation mode in direct sense, the duty ratio can vary from zero to one, hence, there are three different intervals time: one in which the duty ratio is less than $1/3$, a second between $1/3 \leq D \leq 2/3$ and a third interval time, in which the duty ratio is higher than $2/3$.

B. Operation mode in direct sense

In this section, the proposed structure presents different stages when operating in continuous conduction mode (CCM) and in discontinuous conduction mode (DCM). The stages of operation will be described in next section.

1) Operating in the duty ratio range $0 < D < 1/3$

In the 1st, 3rd, and 5th stages, the input source provides energy to the circuit, and part of this energy is stored in the primary winding L_1 . In the 2nd, 4th, and 6th stages, the energy stored in the L_1 is transferred to the load by the internal diode of switch S_4 . Analysis of the 1st and 2nd stages is sufficient to describe the operation stages of the proposed converter. The equivalent circuits for a switching period are shown in table I.

a) *1st Stage [$t_0 \rightarrow t_1$]:* The switch S_1 is conducting at $t = t_0$. The primary winding L_1 stores energy from power source E_1 and input current $i_{E1}(t)$ increases linearly. The voltage across L_1 , L_{p1} and interval time are, respectively, equal to the $E_1 - (E_2/n_T)$, E_2/n_T and $\Delta t_1 = D T_s$. [Fig. 3(a)]

b) *2nd Stage [$t_1 \rightarrow t_2$]:* At the instant t_1 , switch S_1 is turned-off and current $i_{E1}(t)$ decreases linearly. The energy stored in L_1 is transferred to the load through L_2 and the internal diode of switches S_4 . The inductor voltage $v_{L1}(t)$, $v_{Lp1}(t)$ and interval time, are given by equation (1). [Fig. 3(b)]

$$v_{L1}(t) = -E_2 / n_s; \quad v_{Lp1}(t) = -E_2 / n_T; \quad \Delta t_2 = \frac{1-3D}{3} T_s \quad (1)$$

In DCM, nine topological states exist within a switching period. The 1st, 2nd, 3rd, 4th, 5th and 6th topological stages in CCM are similar to the 1st, 2nd, 4th, 5th, 7th, and 8th topological stages of DCM. The only difference is that other stages which the capacitor feeds the load. All the topological stages can be seen in table I.

2) Operating in the duty ratio range $1/3 \leq D \leq 2/3$

a) *1st Stage [$t_0 \rightarrow t_1$]:* At the instant t_0 , switches S_1 e S_3 are turned-on. The primary winding L_1 stores energy from power source E_1 and current $i_{E1}(t)$ increases linearly. The load receives energy from the source through L_{S1} , L_{S3} , D_2 and D_6 . The equivalent circuit of 1st stage is given in Fig. 3(e) The equations of the input current $i_{E1}(t)$, $v_{L1}(t)$, $v_{Lp1}(t)$, and the interval are described in equation (2).

$$v_{L1}(t) = E_1 - v_{Lp1}(t); \quad v_{Lp1}(t) = E_2 / 2n_T; \quad \Delta t_1 = \frac{3D-1}{3} T_s \quad (2)$$

b) *2nd Stage [$t_1 \rightarrow t_2$]:* the switch S_3 is turned-off. The primary winding L_1 is demagnetized and current $i_{E1}(t)$ decreases linearly. The load receives energy from the power source through L_{S1} , D_2 , D_4 . The equivalent circuit of 2nd stage is given in Fig. 3(a). The expressions of inductor voltage $v_{L1}(t)$, $v_{Lp1}(t)$, and the interval time are given by (3).

$$v_{L1}(t) = E_1 - v_{Lp1}(t); \quad v_{Lp1}(t) = E_2 / n_T; \quad \Delta t_2 = (2-3D) T_s / 3 \quad (3)$$

The 3rd and 5th stage are similar to the 1st stage, and the 4th and 6th stage are similar to the 2nd stage. The only difference is that other switches are conducting. The equivalent circuits are illustrated in table I.

To duty ratio $1/3 \leq D \leq 2/3$ and considering DCM operation, the proposed converter has nine topological stages per switching period, table I exposes these stages

3) Operating in the duty ratio range $2/3 \leq D \leq 1$

a) *1st Stage [$t_0 \rightarrow t_1$]:* Starts when switch S_1 , S_2 and S_3 are turned-on. Primary winding L_1 stores energy from power source E_1 and current $i_{E1}(t)$ increases linearly. The diodes of the rectifier bridge are reverse-biased and the load is powered only from the output capacitor C_1 . The equivalent circuit of 1st stage is given in Fig. 3(h). The inductor voltage $v_{L1}(t)$, $v_{Lp1}(t)$ and interval time, are determined by equation (4).

$$v_{L1}(t) = E_1; \quad v_{Lp1}(t) = 0; \quad \Delta t_1 = (3D-2) T_s / 3 \quad (4)$$

b) *2nd Stage [$t_1 \rightarrow t_2$]:* At $t = t_1$, switches S_1 and S_3 continue conducted and S_2 is turned-off. Primary winding L_1 is demagnetized and current $i_{E1}(t)$ decreases linearly. The load receives energy from the source through L_{S1} , L_{S3} , D_2 and D_6 . The equivalent circuit of 2nd stage is shown in Fig. 3(e). The expression of inductor voltage $v_{L1}(t)$, $v_{Lp1}(t)$ and interval time can be given by (5).

$$v_{L1}(t) = E_1 - (E_2 / 2n_T); \quad v_{Lp1}(t) = E_2 / 2n_T; \quad \Delta t_2 = (1-D) T_s \quad (5)$$

The 3rd and 5th stage are similar to the 1st stage and the 4th and 6th stage are similar to the 2nd stage. The only difference is that other switches are conducting. The equivalent circuits are shown in table I

To duty ratio $D \geq 2/3$ and considering DCM operation, the proposed converter has nine topological stages per switching period, table I exposes these stages.

C. Operation mode in reverse sense

In reverse sense and considering CCM operation, the proposed converter has two topological stages that can be described as follows.

a) *1st Stage* [$t_0 \rightarrow t_1$]: This stage starts at $t = t_0$, when the switch S_4 is turned-on and the diode D_7 is reverse-biased. Secondary winding L_2 stores energy from power source E_2 and the load is powered only from the output capacitor C_2 . The equivalent circuit of 1st stage is given in Fig. 3(j). The inductor voltage $v_{L2}(t)$, capacitor current $i_{C2}(t)$, dc source current $i_{E2}(t)$ and interval time, are given by

$$v_{L2}(t) = E_2; \quad i_{E2}(t) = i_{L2}(t); \quad \Delta t_1 = D T_s; \quad v_{C2}(t) = i_2 \quad (6)$$

b) *2nd Stage* [$t_1 \rightarrow t_2$]: At $t = t_1$, S_4 is turned-off and the diode D_7 is forward-biased. Primary winding L_1 transfers energy to the load through D_7 , and no energy is supplied from the dc input source E_2 . The equivalent circuit of 2nd stage is given in Fig. 3(k). The inductor voltage $v_{L2}(t)$, time interval and capacitor current $i_{C2}(t)$ can be expressed via (7) as:

$$v_{L2}(t) = -E_1 \cdot n_s; \quad \Delta t_2 = (1 - D) T_s; \quad v_{C2}(t) = i_{L2}(t) - i_2 \quad (7)$$

In DCM, a switching period is composed of three stages. The 1st and 2nd stage are the same as in CCM, where energy is stored in the inductor (L_2) during the switch is turned-on, and transferred to the load during the switch is turned-off. In DCM, however, all of the energy in the inductor transfers to the load during 2nd stage. The 3rd stage begins when the energy in L_1 is depleted, and it terminates at the end of the switching period (Fig. 3(l)).

III. MATHEMATICAL ANALYSIS

In this section, the DC transfer function, input inductor value and output capacitor of proposed converter are presented in both directions.

A. DC transfer function for direct sense

The principle of inductor volt-second balance states that the average value of voltage applied across an ideal inductor winding (L_1) must be zero. From equation analysis (8), the expression of DC transfer function in direct sense for CCM is described by (9). As can be seen, the DC transfer function is two-thirds of that of the three-phase flyback/current-fed push-pull dc-dc converter with Y-Δ connected transformer [27].

$$V_{L1} = \frac{3}{T_s} \int_0^{\Delta t_1} v_{L1}(t) dt + \int_0^{\Delta t_2} v_{L1}(t) dt = 0 \quad (8)$$

Where n_T turns ratio of three-phase transformer (T_r), n_s turns ratio of coupled inductor (L_1/L_2). D is the duty ratio of the switches S_1 , S_2 and S_3 . The turns ratio n_T and n_s are defined from equation (10). Where n_{L1} and n_{L2} are the winding turns in the primary and secondary sides of the coupled inductor. n_{Lp1} and n_{Ls1} are the winding turns in the primary and secondary sides of the three-phase transformer (T_r).

$$\frac{E_2}{E_1} = \begin{cases} \frac{3D \cdot n_s \cdot n_T}{3D(n_s - n_T) + n_T} & 0 < D < 1/3 \\ \frac{2}{3} \frac{n_T}{(1-D)} & 1/3 \leq D \leq 2/3 \\ \frac{2}{3} \frac{n_T}{(1-D)} & 2/3 \leq D \leq 1 \end{cases} \quad (9)$$

$$n_T = n_{Ls1} / n_{Lp1} \quad n_s = n_{L2} / n_{L1} \quad (10)$$

The DC transfer function of the proposed converter operating in DCM and CrCM is presented by equations (11), (12) and (13).

$$\begin{cases} q_{DCM} = \frac{3D^2 \cdot n_T}{n_T \cdot \bar{i}_1 + 3D^2} \\ q_{CrCM} = \frac{\left(1 \pm \sqrt{1 - 12\bar{i}_1 \cdot n_s}\right) n_T \cdot n_s}{\left(1 \pm \sqrt{1 - 12\bar{i}_1 \cdot n_s}\right) (n_s - n_T) + 2n_T} \end{cases} \quad 0 < D < 1/3 \quad (11)$$

$$\begin{cases} q_{DCM} = \frac{2n_T \cdot (3D - 1)^2 + 12\bar{i}_1 \cdot n_T^2}{(3D - 1)^2 + 12\bar{i}_1 \cdot n_T} \\ q_{CrCM} = \frac{4n_T}{3 \pm \sqrt{1 - 24\bar{i}_1 \cdot n_T}} \end{cases} \quad 1/3 \leq D \leq 2/3 \quad (12)$$

$$\begin{cases} q_{DCM} = \frac{(3D - 2)^2 + 6\bar{i}_1 \cdot n_T}{3\bar{i}_1} \\ q_{CrCM} = \frac{4n_T}{1 \pm \sqrt{1 - 24\bar{i}_1 \cdot n_T}} \end{cases} \quad 2/3 \leq D \leq 1 \quad (13)$$

The normalized output current is defined by equation (14).

$$\bar{i}_1 = \frac{2\bar{i}_1 \cdot L_1 \cdot f_s}{E_1} \quad (14)$$

B. DC transfer function for reverse sense

When the converter operates in reverse sense, the average value of the inductor voltage (L_2) must be equal to zero. Upon equating the average voltage value to zero, we obtain

$$V_{L2} = \frac{1}{T_s} \int_0^{\Delta t_1} v_{L2}(t) dt + \int_0^{\Delta t_2} v_{L2}(t) dt = 0 \quad (15)$$

Which after some mathematical manipulations yields

$$\frac{E_1}{E_2} = \frac{D}{n_s(1-D)} \quad (16)$$

Where D is the duty ratio of the active switches S_4 . As can be seen, the DC transfer function in reverse sense of the proposed converter is equal of that of the conventional flyback converter.

DC transfer function in reverse sense for DCM and CrCM is defined in terms of normalized output current value and duty ratio as is given in equation (17).

$$\begin{cases} q_{DCM} = \frac{D^2}{\bar{i}_2} \\ q_{CrCM} = \left(n_s \pm \sqrt{n_s^2 - 4n_s \cdot \bar{i}_2} \right)^2 / 4n_s^2 \cdot \bar{i}_2 \end{cases} \quad (17)$$

The normalized output current in reverse sense is defined by equation (18).

$$\dot{i}_2 = \frac{2L_2 \cdot f_s \cdot i_2}{E_2} \quad (18)$$

$$L_2 = \frac{E_1 \cdot n_s \cdot (1 - D)}{\Delta i_{E2} \cdot f_s} \quad (20)$$

The following are the main equations which can be used to determine the inductance value (L_1) and output capacitor in both senses for CCM, where the value of L_1 for direct and reverse sense are given in equations (19) and (20), respectively.

$$L_1 = \begin{cases} \frac{E_2 \cdot (1 - 3D)}{3n_s \cdot f_s \cdot \Delta i_{E1}} & D < 1/3 \\ \frac{E_2 \cdot (2 - 3D) \cdot (3D - 1)}{6n_T \cdot f_s \cdot \Delta i_{E1}} & 1/3 \leq D \leq 2/3 \\ \frac{E_2 \cdot (1 - D) \cdot (3D - 2)}{2n_T \cdot f_s \cdot \Delta i_{E1}} & 2/3 \leq D \leq 1 \end{cases} \quad (19)$$

The output capacitor C_1 is calculated from equation (5). Then, the expression for C_2 given in Equation (14).

$$C_1 = \begin{cases} \frac{i_1 \cdot D \cdot (1 - 3D) \cdot (n_s - n_T)}{f_s \cdot \Delta E_2 \cdot 3D \cdot (n_s - n_T) + n_T} & D < 1/3 \\ \frac{i_1}{f_s \cdot \Delta E_2} \cdot \frac{(2 - 3D) \cdot (3D - 1)}{9(1 - D)} & 1/3 \leq D \leq 2/3 \\ \frac{i_1}{3f_s \cdot \Delta E_2} \cdot (3D - 2) & 2/3 \leq D \leq 1 \end{cases} \quad (21)$$

$$C_2 = \frac{D \cdot i_2}{f_s \cdot \Delta E_1} \quad (22)$$

Figure 3. Topological stages of proposed converter

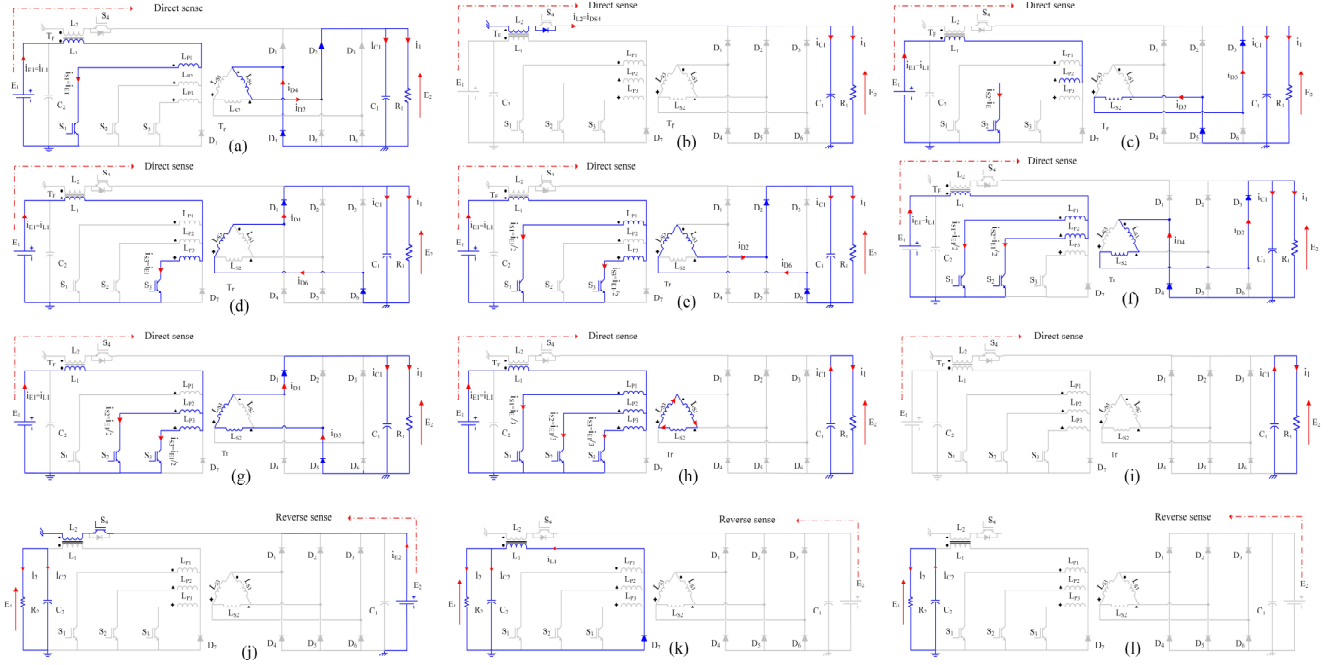


TABLE I. TOPOLOGICAL STAGES OCCURRENCES IN BOTH MODES FOR DIRECT AND REVERSE SENSE

Duty ratio	Direct sense			Reverse sense
	$0 < D < 1/3$	$1/3 < D < 2/3$	$2/3 < D < 1$	$0 < D < 1$
Continuous Conduction Mode (CCM)	1 st Stage: fig. 3(a) 2 nd Stage: fig. 3(b) 3 rd Stage: fig. 3(c) 4 th Stage: fig. 3(b) 5 th Stage: fig. 3(d) 6 th Stage: fig. 3(b)	1 st Stage: fig. 3(e) 2 nd Stage: fig. 3(a) 3 rd Stage: fig. 3(f) 4 th Stage: fig. 3(c) 5 th Stage: fig. 3(g) 6 th Stage: fig. 3(d)	1 st Stage: fig. 3(h) 2 nd Stage: fig. 3(e) 3 rd Stage: fig. 3(h) 4 th Stage: fig. 3(f) 5 th Stage: fig. 3(h) 6 th Stage: fig. 3(g)	1 st Stage: fig. 3(j) 2 nd Stage: fig. 3(k)
Discontinuous Conduction Mode (DCM)	1 st Stage: fig. 3(a) 2 nd Stage: fig. 3(b) 3 rd Stage: fig. 3(i) 4 th Stage: fig. 3(c) 5 th Stage: fig. 3(b) 6 th Stage: fig. 3(i) 7 th Stage: fig. 3(d) 8 th Stage: fig. 3(b) 9 th Stage: fig. 3(i)	1 st Stage: fig. 3(e) 2 nd Stage: fig. 3(a) 3 rd Stage: fig. 3(i) 4 th Stage: fig. 3(f) 5 th Stage: fig. 3(c) 6 th Stage: fig. 3(i) 7 th Stage: fig. 3(g) 8 th Stage: fig. 3(d) 9 th Stage: fig. 3(i)	1 st Stage: fig. 3(h) 2 nd Stage: fig. 3(e) 3 rd Stage: fig. 3(i) 4 th Stage: fig. 3(h) 5 th Stage: fig. 3(f) 6 th Stage: fig. 3(i) 7 th Stage: fig. 3(h) 8 th Stage: fig. 3(g) 9 th Stage: fig. 3(i)	1 st Stage: fig. 3(j) 2 nd Stage: fig. 3(k) 3 rd Stage: fig. 3(l)

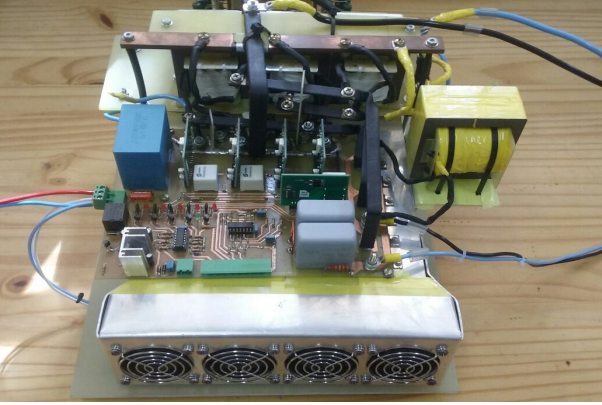
IV. EXPERIMENTAL RESULTS

In order to verify the aforementioned analysis, a prototype of proposed converter was constructed. The main parameters of converter are shown in Table II. The prototype, illustrated in Fig. 4, was developed to prove bidirectional operation between power source and load. In direct sense, the converter is implemented to operates in CCM and at 3kW; for the reverse sense it operates in DCM and at 1kW.

TABLE II. CONVERTER SPECIFICATIONS

Description	Direct sense	Reverse sense
Input voltage	150 V	400 V
Output voltage	400 V	150 V
Nominal power	3 kW	1 kW
Duty ratio	0.595	0.486
Switching frequency	40 kHz	40 kHz
Input inductance L_1/L_2	78.6 μ H / 472.6 μ H	
Turns ratio n_S	2.45	
Turns ratio n_T	1.62	

Figure 4. Photo of the designed converter



➤ Duty ratio

The duty ratio in direct sense are computed using (9) which represents the DC transfer function in CCM.

$$D = \frac{3(E_2 / E_1) - 2n_T}{3(E_2 / E_1)} = \frac{4.76}{8} = 0.595 \quad (23)$$

The duty ratio in reverse sense are calculated from equation (9) which defines the DC transfer function in DCM.

$$D = \sqrt{(E_1 / E_2) \cdot \frac{2L_2 \cdot f_s \cdot i_2}{E_2}} = \sqrt{(E_1 / E_2) \cdot \frac{2L_2 \cdot f_s \cdot i_2}{E_2}} = 0.375 \quad (24)$$

A. Operating in direct sense

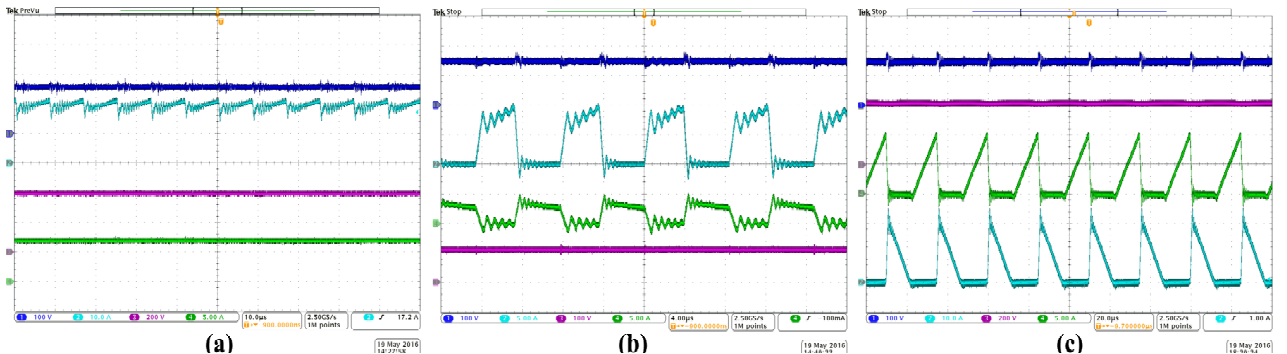
Fig. 5 (a) depict the resultant waveforms of inductor current (L_1) and load current, as well as input and output voltage for direct sense. It's observed that the converter operating in CCM and the frequency of input current ripple is three times the switching frequency.

The proposed converter was also tested for 12 % duty ratio; Fig. 5 (b) shows the current in the coupled inductor (L_1/L_2), input and output voltage. The ratio of output and input voltage was confirmed to the theory (CCM) and it is observed that the converter operated as a step-down converter.

B. Operating in reverse sense

In Fig. 5 (c), the current across coupled inductor (L_1/L_2) are shown together with input and output voltage for reverse sense. It has been observed that the converter is operating in DCM, and the stored energy in L_2 is transferred to the load through the winding L_1 . The experimental waveforms and DC transfer function in this sense are in accordance with the theoretical analysis.

Figure 5. Experimental waveforms of the proposed converter; (a) output current, inductor current L_1 , output and input voltage for CCM in direct sense; (b) inductor current cross L_1 and L_2 , output and input voltage for CCM in direct sense; (c) inductor current cross L_1 and L_2 , output and input voltage for DCM in reverse sense



V. CONCLUSION

This paper proposes a new three-phase flyback current-fed push-pull bidirectional dc-dc converter in order to prove a bidirectional power flow between dc microgrids bus and

energy storage systems. From the theoretical analysis and the experimental results, it can be concluded that proposed converter has the following features:

In direct sense, the frequency of input current ripple, output voltage and current is three times higher than the switching frequency in the direct sense. The converter is a step-up converter, which corresponds to the duty ratio range from 1/3 to 1, and it is a step-up/step down converter when it operates with duty ratio less than 1/3. In the reverse sense, the proposed converter has the same features of the conventional flyback converter, and provides power transfer with the same coupled inductor and one additional switch S_4 .

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