Appendix A

Single-Phase Modified Type 1 SLC-ZSI

A.1 Description and Operation of Modified Type 1 SLC-ZSI

A single-phase modified Type 1 SLC-ZSI is shown in Fig. A.1(a)**.** It is derived from Type 1 SLC-ZSI by rearranging the elements between input DC source and HB circuit. It also has three states; shoot-through, power and zero states. For investigating its operation easily, circuit operation in the three states is explained in non-shoot-through and shoot-through operations as same as the Type 1 SLC-ZSI. The HB circuit with a second-order low pass filter ($L_f C_f$) is replaced by a parallel combination of a switch (S_{inv}) and an equivalent resistance (R_{ac}) as shown in Fig. A.1(b). The operation of modified Type 1 SLC-ZSI is explained in subsequent sections.

(a) Shoot-Through Operation of Modified Type 1 SLC-ZSI

For this shoot-through operation, the equivalent circuit of modified Type 1 SLC-ZSI is shown in Fig. A.2(a). During this operation, switches (S and S_{inv}) are turned-on. Meanwhile diodes (D_1 and D_3) are forward biased and diodes (D_a, D_b and D_2) are reverse biased. The capacitor C is discharged whereas the inductors (L_1 and L_2) store energy from the input DC source through S and S_{inv}. The corresponding KCL and KVL are given in (A.1).

$$\left.\begin{array}{c} v_{L1} = v_{dc} + v_C \\ v_{L2} = v_{dc} + v_C \\ i_C = -i_{L1} - i_{L2} \\ v_{inv} = 0 \\ i_{st} = i_{L1} + i_{L2} \end{array}\right\} \tag{A.1}$$

(b) Non-Shoot-Through Operation of Modified Type 1 SLC-ZSI

For this non-shoot-through operation, the equivalent circuit of modified Type 1 SLC-ZSI is shown in Fig. A.2(b)**.** During this operation, S and S_{inv} are turned-off. Diodes (D_1 and D_3) are reverse biased and diodes (D_a, D_b and D_2) are forward biased. The capacitor C is charged and the inductors (L_1 and L_2) are discharged. The corresponding KCL and KVL equations are given in (A.2)

$$\left.\begin{array}{c} v_{L1} + v_{L2} = v_{dc} - v_C \\ i_C = i_{L1} - i_{inv} \\ v_{inv} = v_C \end{array}\right\} \tag{A.2}$$

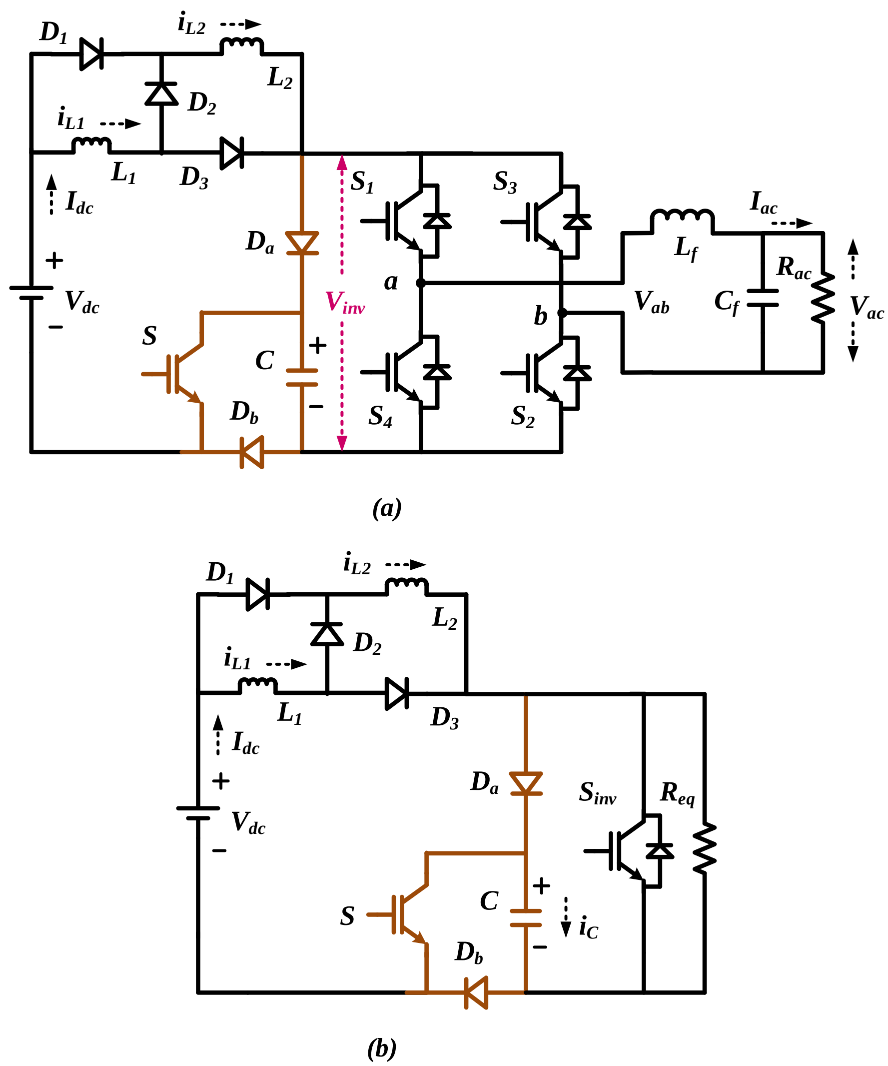


Fig. A.1. Single-phase modified Type 1 SLC-ZSI **(a)** actual circuit diagram **(b)** simplified circuit diagram.

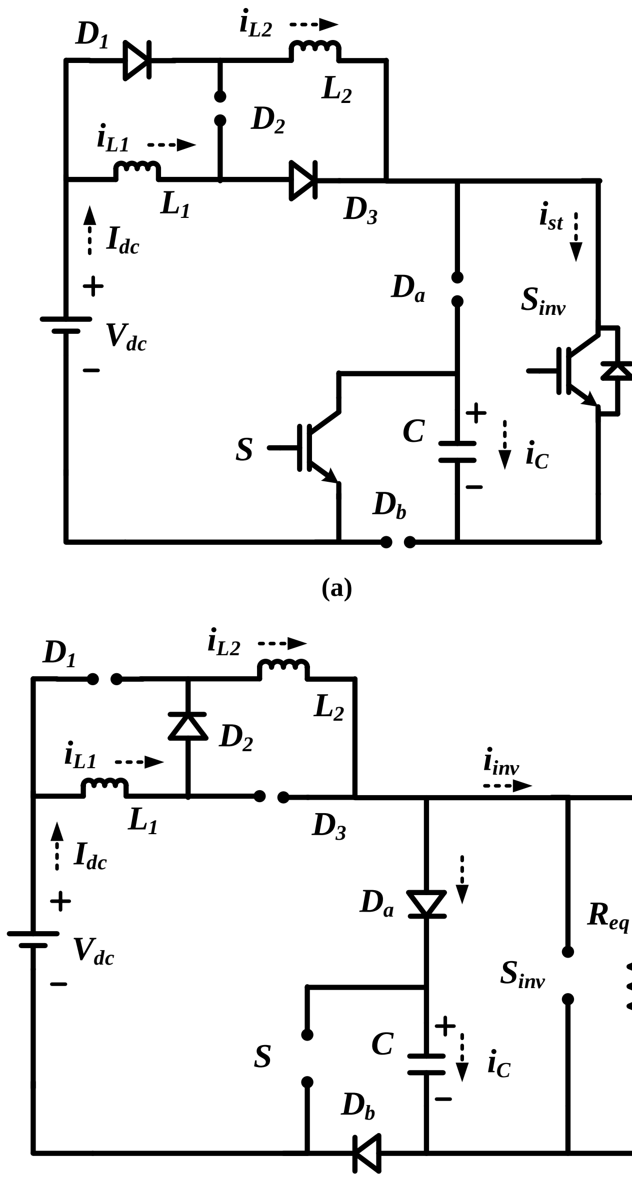
A.2 Steady-State Analysis of Modified Type 1 SLC-ZSI

By applying volt-second balance principle to L_1 and L_2 over a switching period T_s, the obtained steady-state voltage across C is given in (A.3)

$$V_C = \frac{1+D_{st}}{1-3D_{st}} V_{dc} \tag{A.3}$$

The booting voltage (V_{inv}) appeared across the HB is same as that of V_C and its expression is given in (A.4).

$$V_{inv} = \frac{1+D_{st}}{1-3D_{st}} V_{dc} = BV_{dc} \tag{A.4}$$



(b)

Fig. A.2. Equivalent circuits of modified Type 1 SLC-ZSI **(a)** during shoot-through operation **(b)** during non-shoot-through operation.

where B is boosting ability of modified Type 1 SLC-ZSI and defined as a ratio of V_{inv} and V_{dc}. The mathematic expression of B is given in (A.5).

$$B = \frac{1+D_{st}}{1-3D_{st}} \tag{A.5}$$

The fundamental peak AC output voltage of modified Type 1 SLC-ZSI is determined and given in (A.6).

$$V_{ac(pk)} = MV_{inv} = MBV_{dc} \tag{A.6}$$

The voltage gain G of modified Type 1 SLC-ZSI is obtained and given in (A.7).

$$G = MB = M\frac{1+D_{st}}{1-3D_{st}} \quad \text{(A.7)}$$

It can be said from (A.5) and (A.7) that boosting ability and voltage gain of modified Type 1 SLC-ZSI is the same as that of Type 1 SLC-ZSI. Moreover, maximum current and voltage stresses on the elements of modified Type 1 SLC-ZSI are given in Table A.1.

Table A.1. Maximum current and voltage stresses on the elements of modified Type 1 SLC-ZSI.

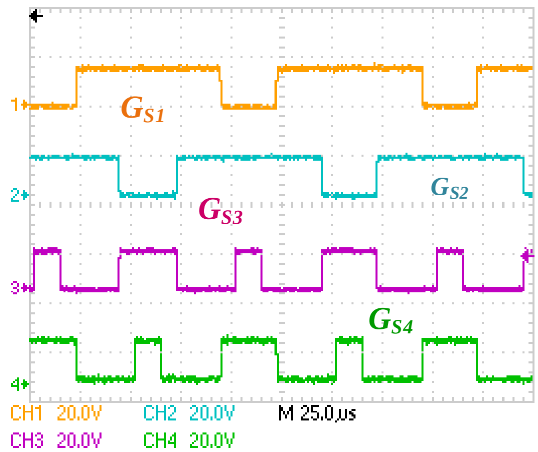
Elements	Voltage stress	Current stress
L_1, L_2	$\frac{2(1-D_{st})}{1-3D_{st}}V_{dc}$	I_{dc}
C	$\frac{1+D_{st}}{1-3D_{st}}V_{dc}$	I_{dc}
D_1, D_3	$\frac{-2D_{st}}{1-3D_{st}}V_{dc}$	$\frac{1}{2}I_{dc}$
D_2	$\frac{-2(1-D_{st})}{1-3D_{st}}V_{dc}$	I_{dc}
D_a, D_b	$\frac{1+D_{st}}{1-3D_{st}}V_{dc}$	I_{dc}
S	$\frac{1+D_{st}}{1-3D_{st}}V_{dc}$	I_{dc}
$S_1 - S_4$	$\frac{1+D_{st}}{1-3D_{st}}V_{dc}$	I_{dc}

A.3 Experimental Results of Modified Type 1 SLC-ZSI

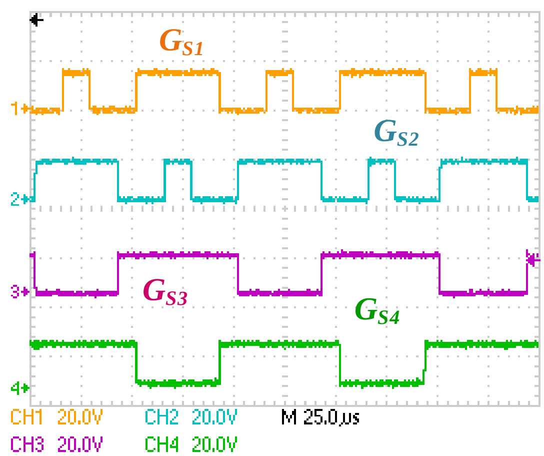
The experimental validation of modified Type 1 SLC-ZSI is carried out on a 100 W laboratory prototype for the specifications; V_{dc} = 48 V, D_{st} = 0.268, M = 0.732, f_S = 10 kHz and f_{line} = 50 Hz, resistive loading (R_{ac} = 229 Ω) and inductive loading (R_{ac} = 65.85 Ω and L_{AC} = 106.4 mH) respectively. The gating signals of modified Type 1 SLC-ZSI for positive and negative half cycles of AC output are shown in Fig. A.3.

The experimental results of modified Type 1 SLC-ZSI are shown in Fig. A.4**,** where Figs. A.4(a)-A.4(e) are for resistive load and Fig. A.4(f) is for inductive load. It can be observed from Fig. A.4(a) that average voltage across capacitor C, V_C = 300.3 V, fundamental output AC voltage $V_{ac(rms)}$ = 149.6 V and AC current $I_{AC}(rms)$ = 0.66 A for input voltage V_{in} = 48 V. Fig. A.4(b) shows a harmonic spectrum of load current. It can be observed from Fig.

A.4(b) that the THD is obtained as 2.17%. Fig. A.4(c) shows voltage across switch S, $V_S =$ 300.4 V along with the gating pulse G_S of S, V_C and V_{in}. It can be noticed from Fig. A.4(d) that the maximum voltage appearing across HB circuit $V_{inv} =$ 300.5 V and the maximum shoot-through current flowing through HB circuit $I_{st} =$ 9.84 A. Fig. A.4(e) shows the maximum voltages appeared across diodes (D_a, D_b and D_2) $V_{Da} = -$ 300.4 V, $V_{Db} = -$ 300.6 V and $V_{D2} = -$ 338.7 V. Fig. A.4(f) shows experimental results of modified Type 1 SLC-ZSI at the inductive loading. It can be observed from Fig. A.4(f) that $V_C =$ 285 V, $V_{ac(rms)} =$ 143 V and $I_{ac(rms)} =$ 1.84 A and $V_{in} =$ 48 V.



(a)



(b)

Fig. A.3. Gating pulses of modified Type 1 SLC-ZSI **(a)** during positive half cycle of AC output **(b)** during negative half cycle of AC output

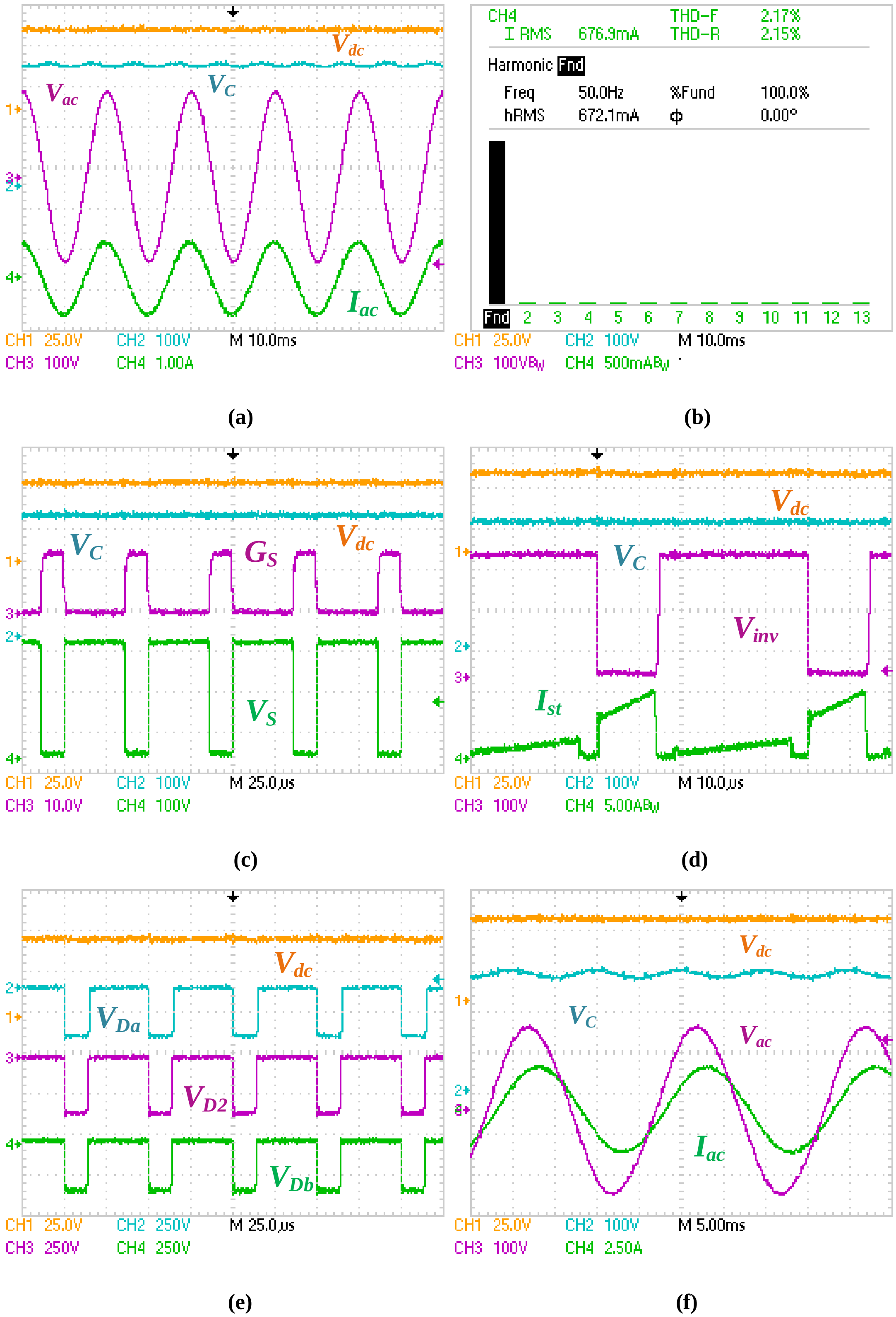


Fig. A.4. Experimental results of modified Type 1 SLC-ZSI.

Appendix B

Extendable Single-Phase Type 1 SLC-ZSI

The Type 1 SLC-ZSI can be modified further to achieve even higher voltage gain using many SL cells in a cascaded manner as shown in Fig. B.1, named as extendable single-phase Type 1 SLC-ZSI. It can be observed from Fig. B.1 that the extendable Type 1 SLC-ZSI has SL cells in a cascaded manner, which are placed at the top right-hand side. The n^{th} SL cell consisting of three diodes D_{3n-2} , D_{3n-1} and D_{3n} and one inductor L_{n+1}. The operation of extendable Type 1 SLC-ZSI is as same as Type 1 SLC-ZSI. In shoot-through operation, HB circuit is shorted, S_a is turned-on and S_b is turned-off. Meanwhile, diodes (D_{3n-2} and D_{3n-1}) are forward biased and diodes (D_a and D_{3n}) are reverse biased. Further, all inductors from L_1 to L_{n+1} are connected in parallel and charged by DC input source V_{in} and capacitor C during shoot-through operation. In non-shoot-through operation, S_a is turned-off and S_b is turned-on. The HB circuit is operated either in power or in zero states for achieving AC output. Meanwhile, diodes (D_a and D_{3n}) are forward biased and the diodes (D_{3n-2} and D_{3n-1}) are reverse biased. The inductors from L_1 to L_{n+1} are connected in series to discharge their stored energy and C is charged.

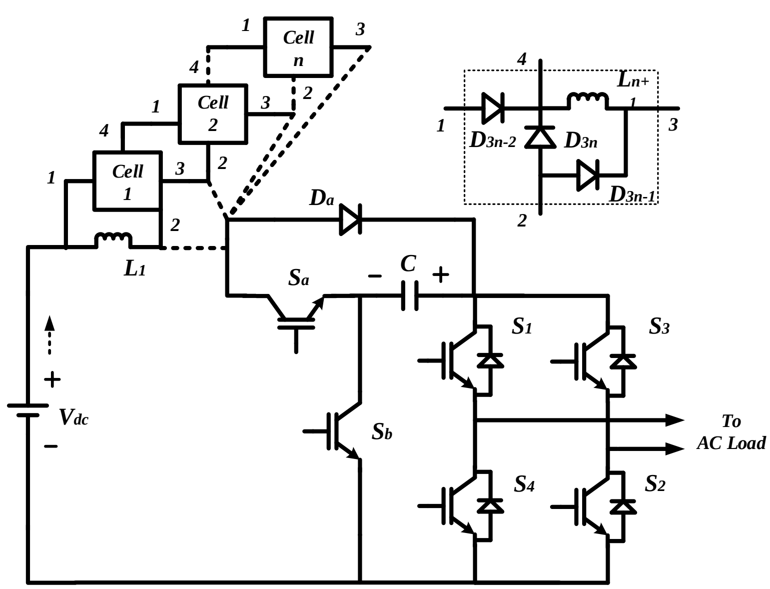


Fig. B.1. Extendable single-phase Type 1 SLC-ZSI.

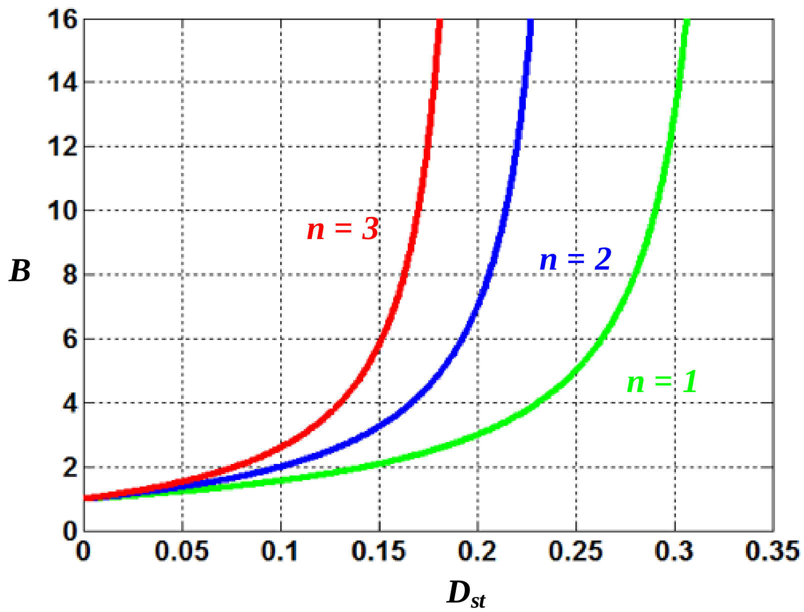


Fig. B.2. Boosting ability of extendable Type 1 SLC-ZSI, B versus D_{st}.

The obtained steady-state relations of extendable Type 1 SLC-ZSI are given in (B.1).

$$\left.\begin{aligned} V_{inv} &= \frac{1+nD_{st}}{1-(n+2)D_{st}} V_{dc} = BV_{dc} \\ B &= \frac{1+nD_{st}}{1-(n+2)D_{st}} \end{aligned}\right\} \tag{B.1}$$

where n denotes number of SL cells. Fig. B.2 shows boosting ability (B) of extendible Type 1 SLC-ZSI with respect to D_{st}.

Appendix C

Components Used for the Experimental Verification of Proposed Converters

Table C.1 gives the components used for the experimental verification of proposed converters.

Table C.1. List of components used for the experimental verification of proposed converters.

Components	Manufacturer's IC number
Switches	IRG7PH42UPBF (Infineon) FGH40T65UPD (ON semi) IRFP260N (Infineon) IXKH70N60C5 (IXYS)
Diodes	RURG5060 (Fairchild) 40EPF06 (Vishay) IN4007
Gate Drivers	FOD3184 (Fairchild)
Capacitors	Keltron
Inductors	PCV-2-564-08L (Coil craft)
FPGA Board	Artix -7 Nexys DDR 4 (Digilent)
Voltage Regulator	LM7815