

Introduction to High Gain DC-DC Converter and its control Techniques

Dr. SIJA GOPINATHAN

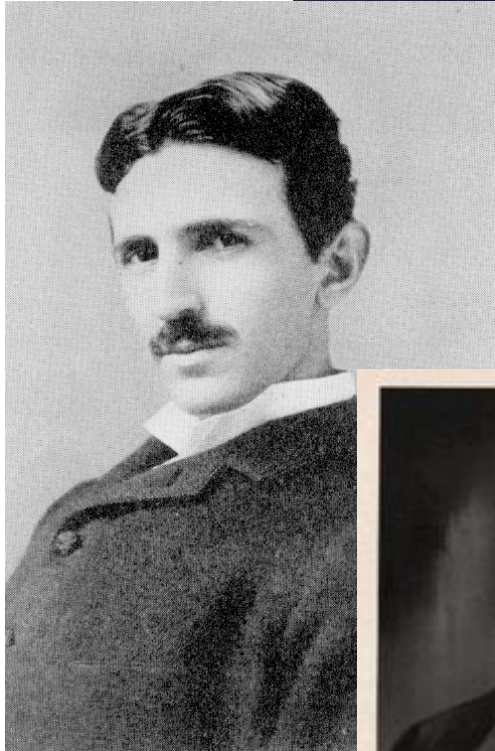
**Associate Professor,
Department of Electrical & Electronics Engineering,
Mar Athanasius College of Engineering, Kothamangalam**

Agenda

1. Introduction to High Gain DC-DC Converter
2. Controller Design

AC

DC

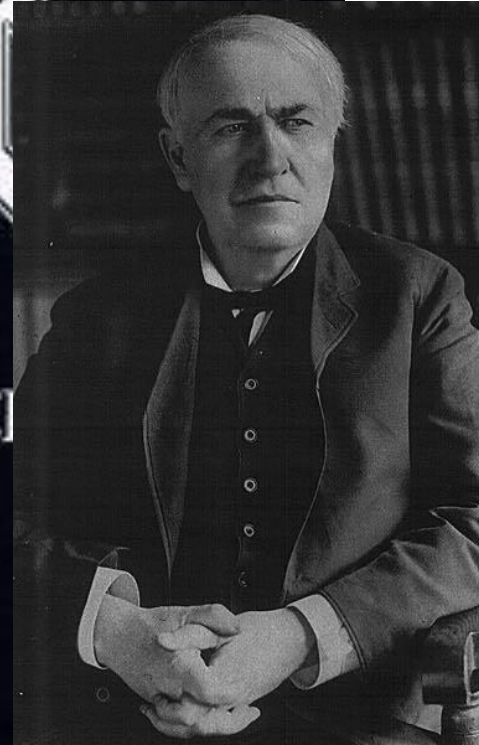


Tesla

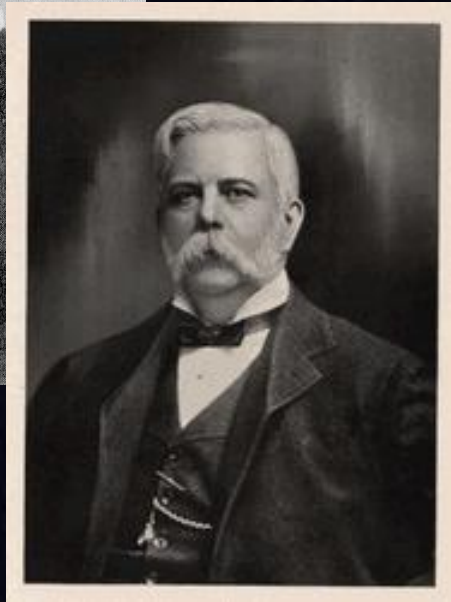
AC/DC

IN BLACK

vs.

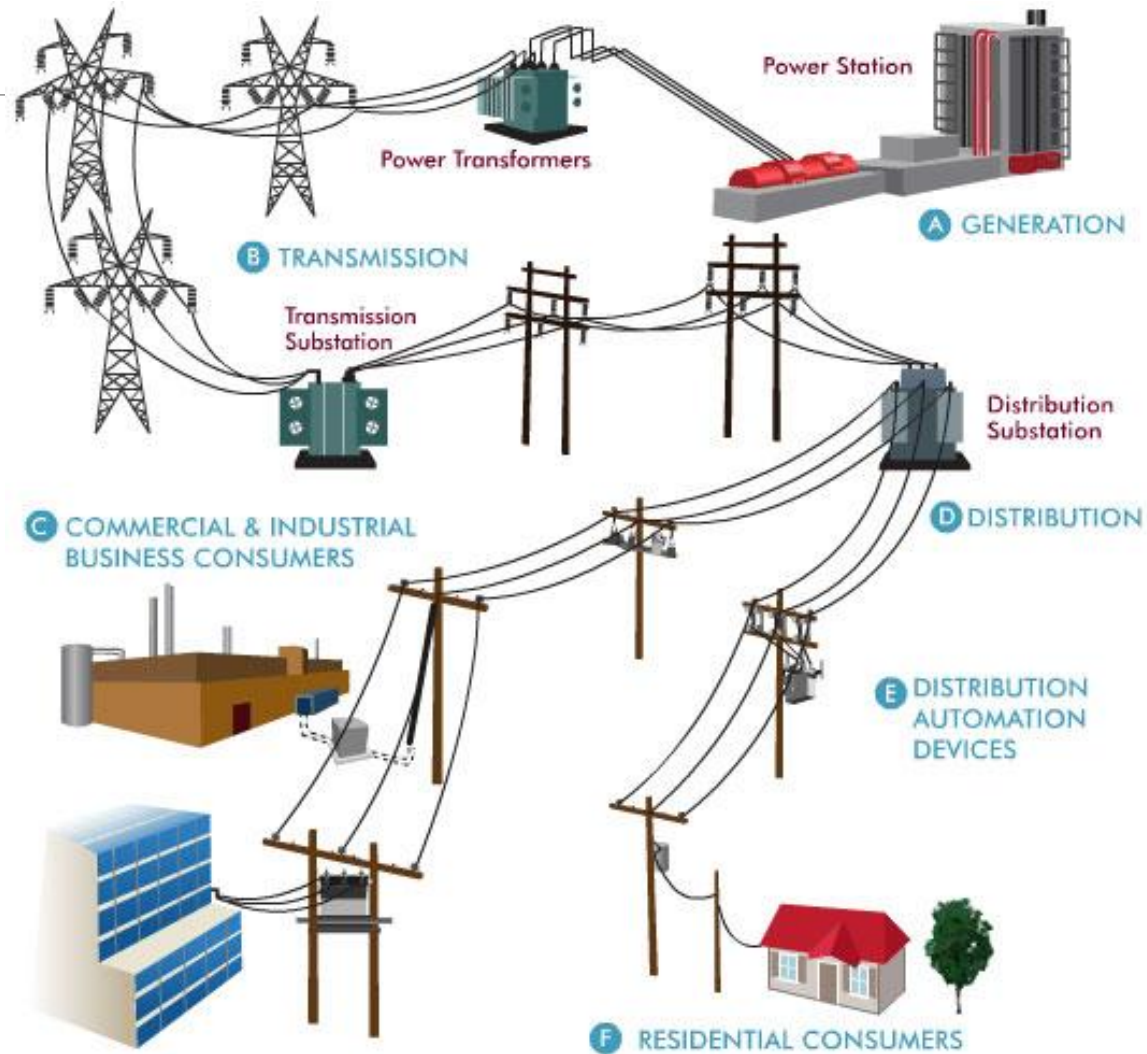


Edison

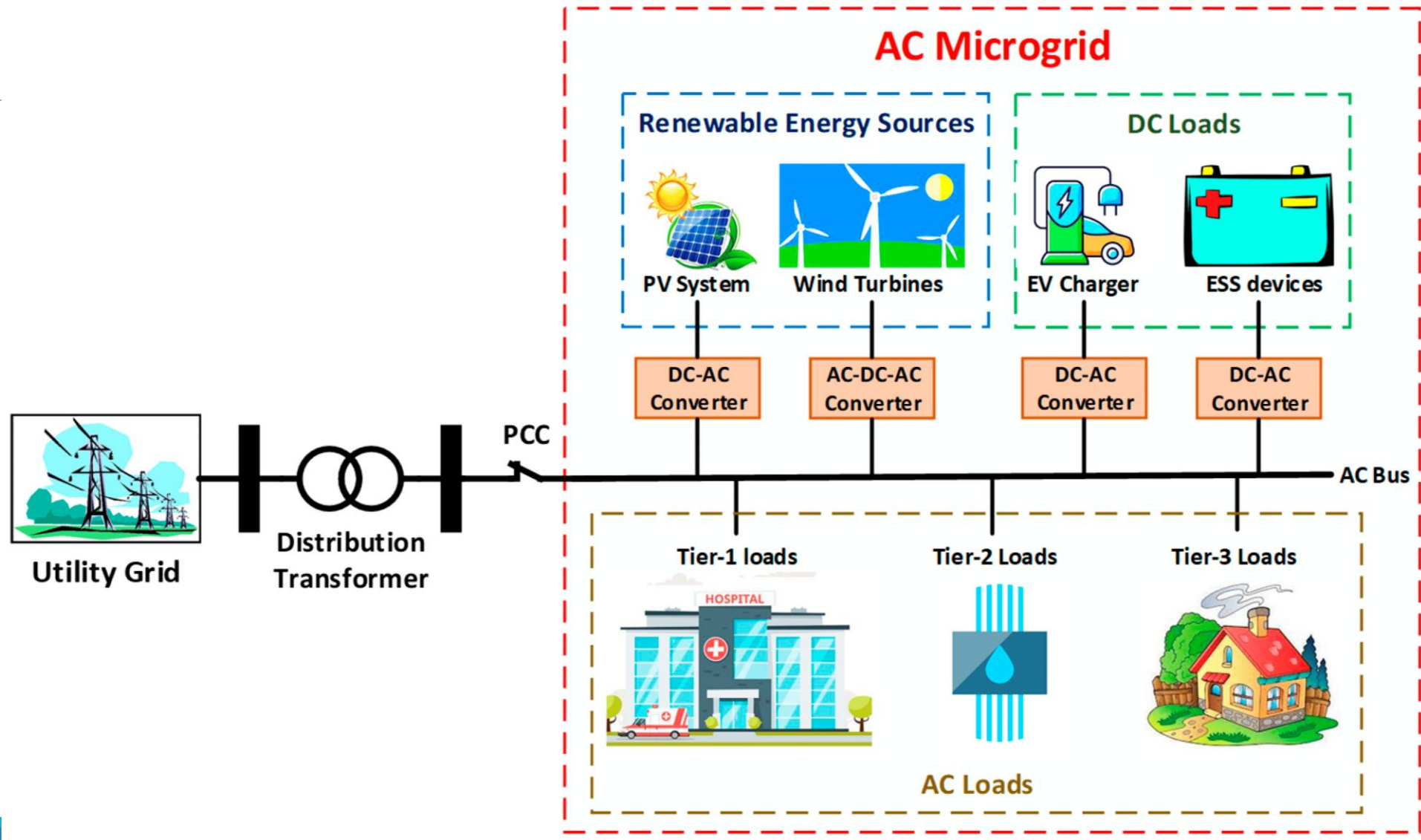


Westinghouse

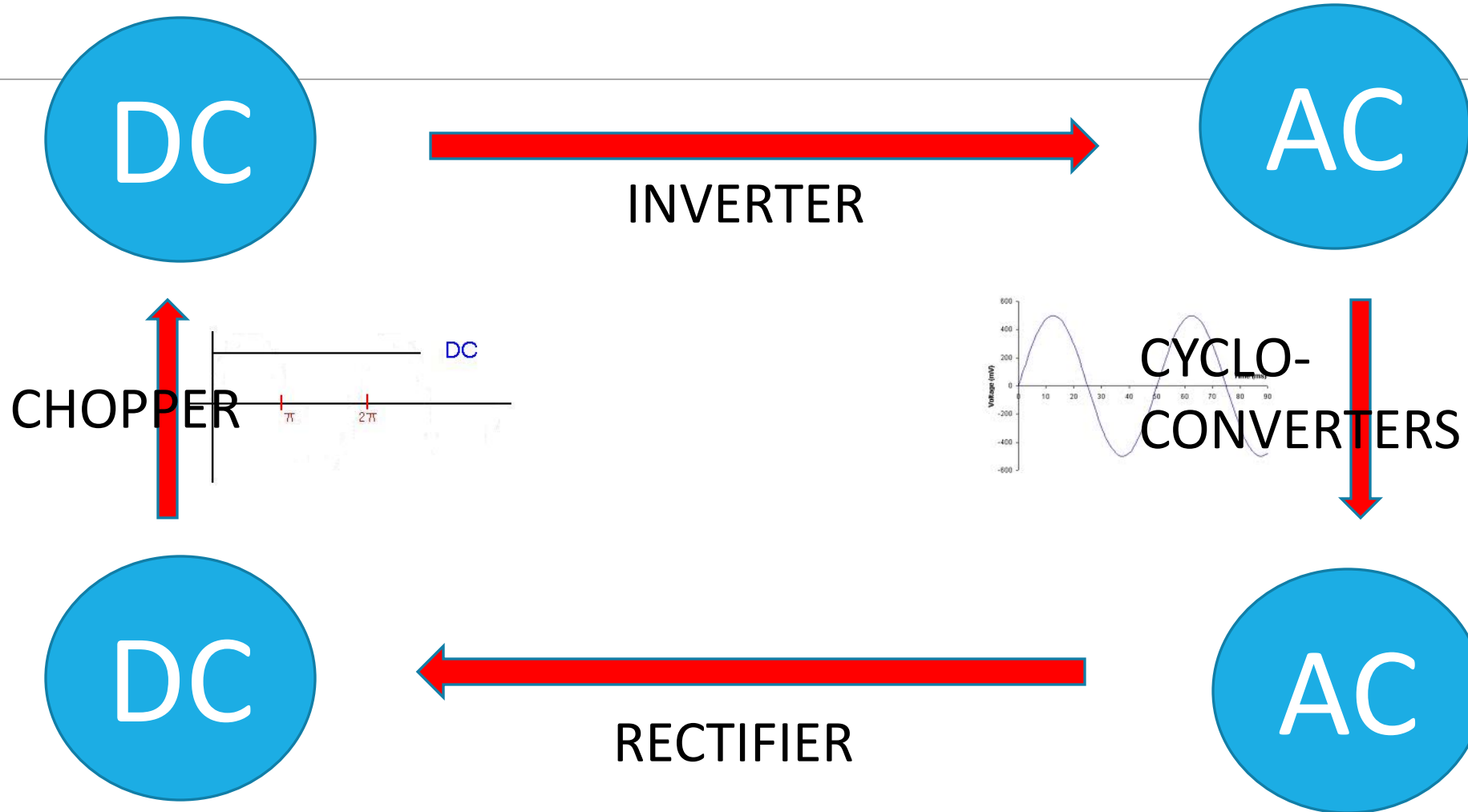
Structure of Present Power System



Structure of Microgrid

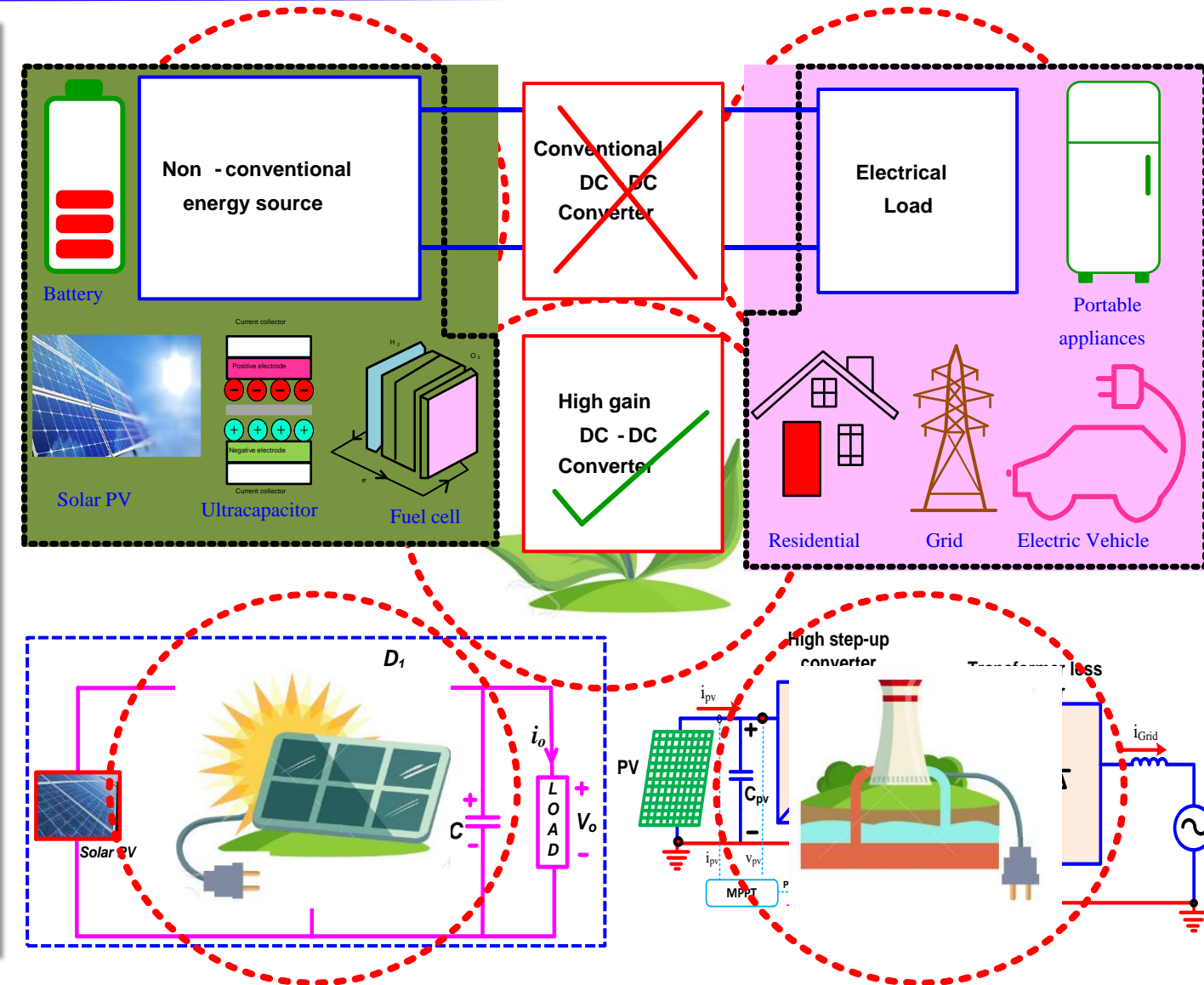


Power Converter

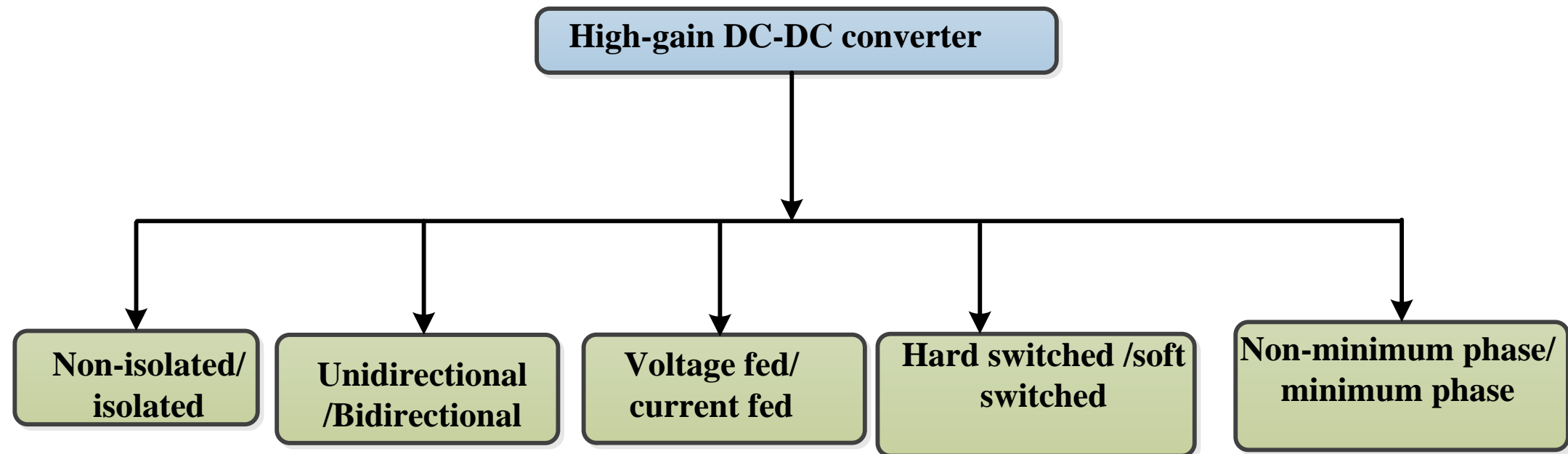


INTRODUCTION

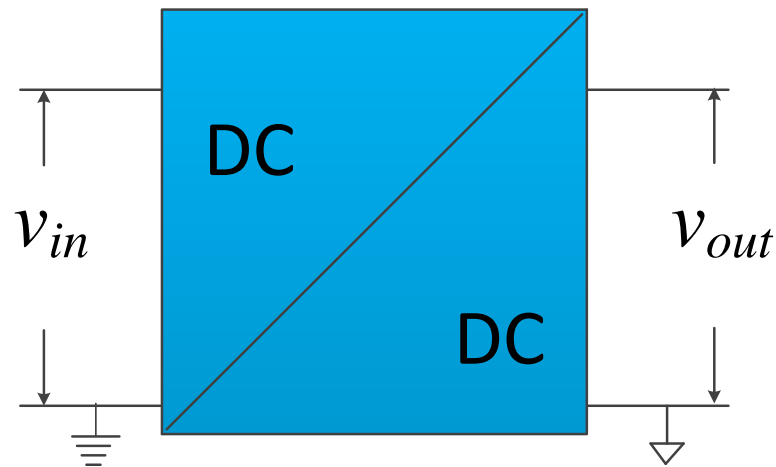
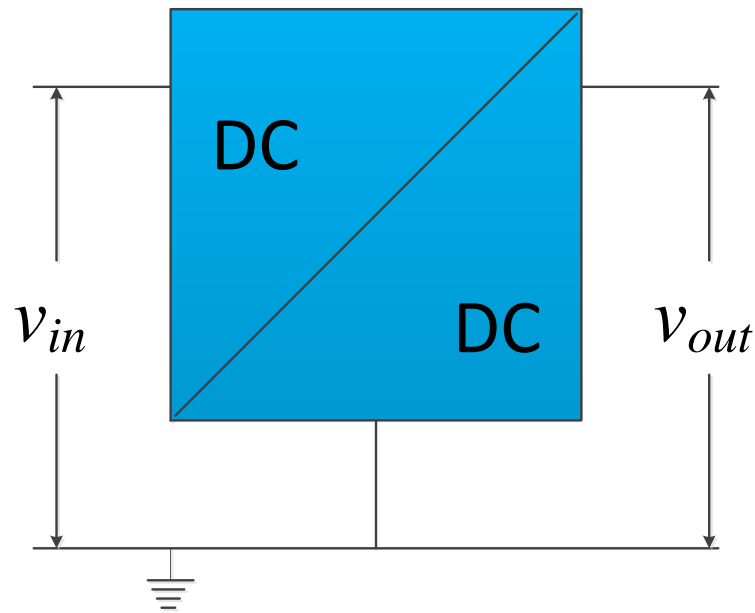
- ❖ The power generation based on the nonconventional energy sources
- ❖ Due to highly intermittent nature of these renewable sources, proper integration of these sources, with same or distinct voltage-current characteristics, are required.
- ❖ DC-DC converters for integration
- ❖ The performance of overall system can be improved by the use of **high gain converters**.
- ❖ The Boost converters are having a Non-minimum phase characteristics.
- ❖ Need to design a **closed-loop controller** to improve the dynamic performance under all operating conditions.



CLASSIFICATION

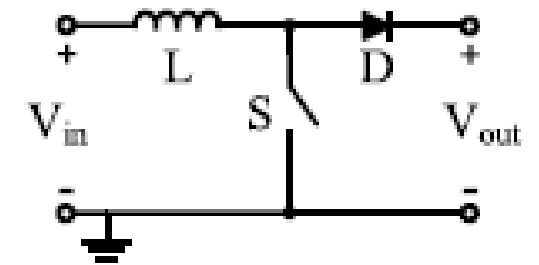


CLASSIFICATION-Non-isolated / Isolated



Introducing a shared connection between the input and output of non-isolated DC-DC converters in transformerless grid-connected PV systems serves to reduce energy losses, enhance overall system efficiency, and optimize performance.

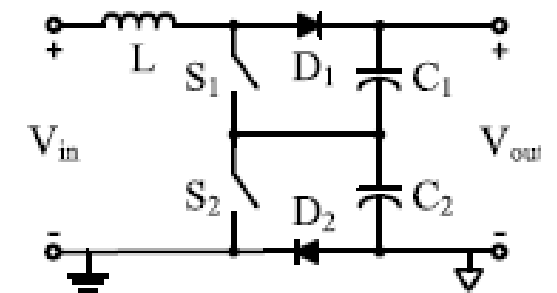
PWM Boost converter



Applications in which a common ground between the input source and load is not necessary, the output of non-isolated dc-dc converters can also be floated

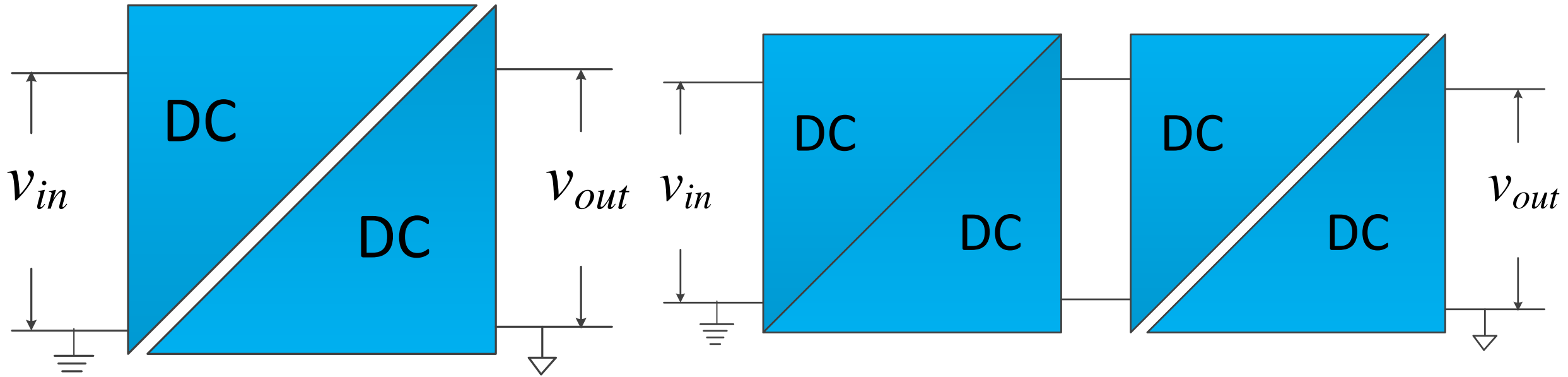
Three level Boost converter

Can be with/without magnetic coupling



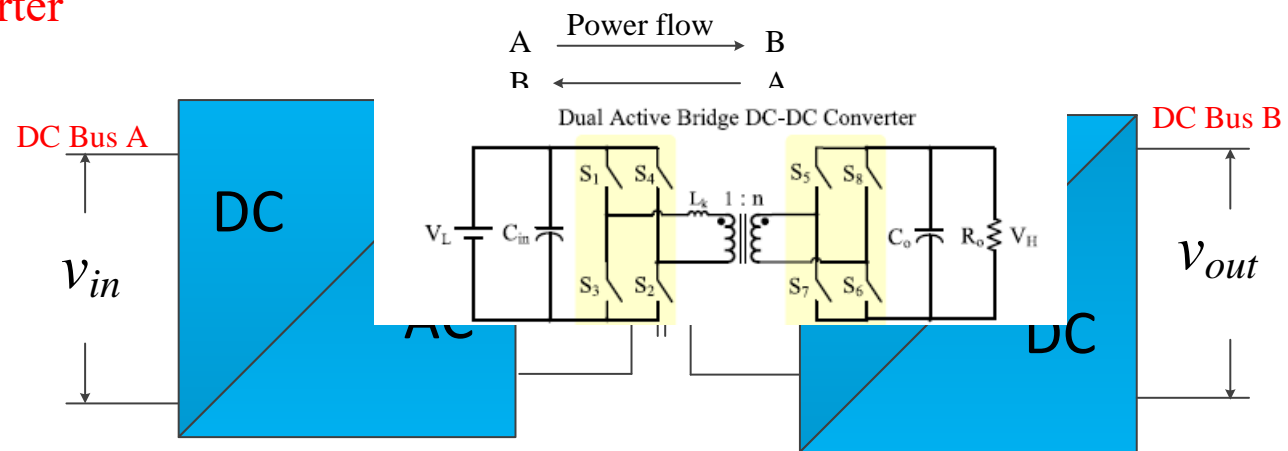
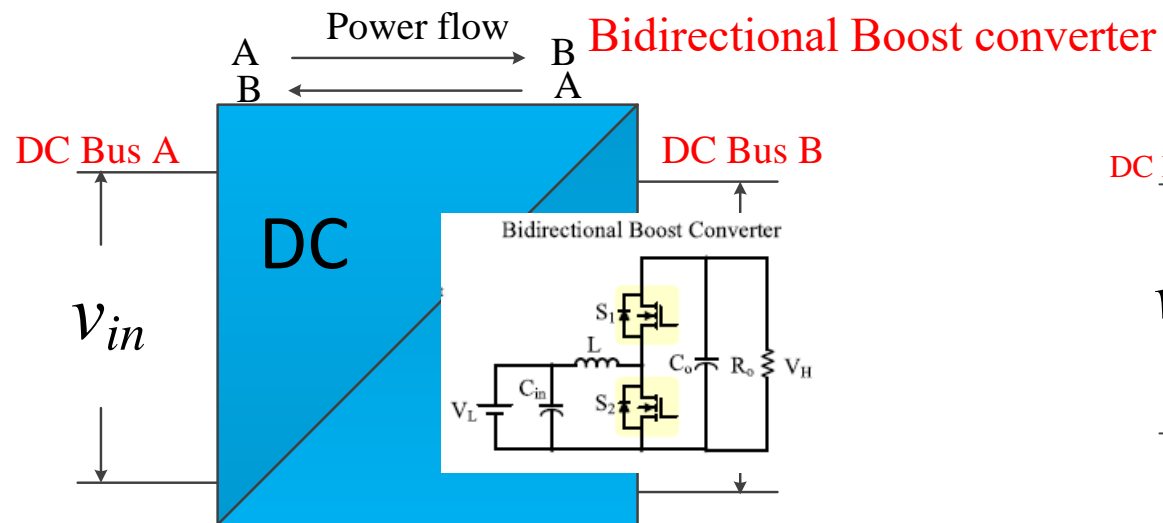
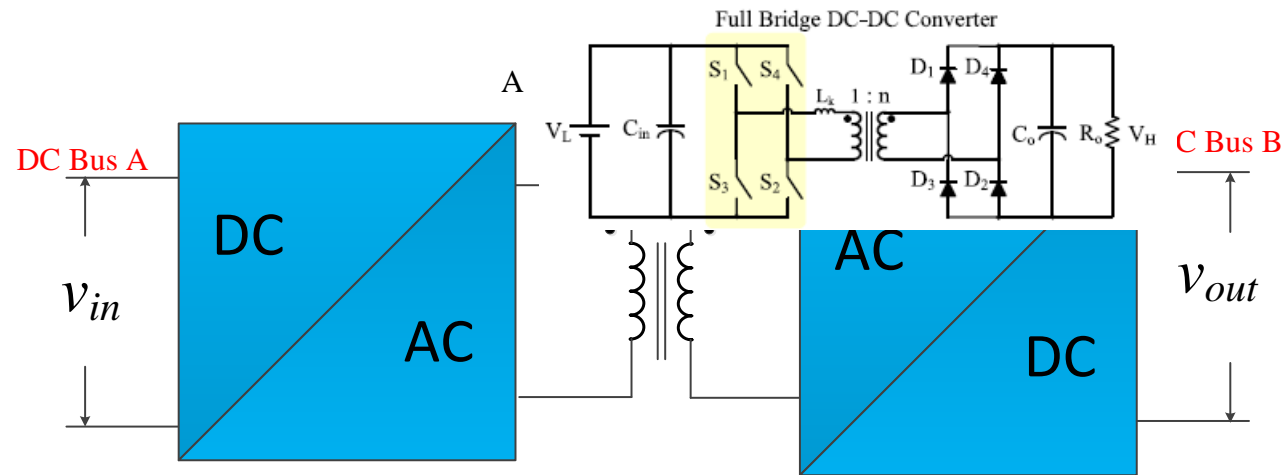
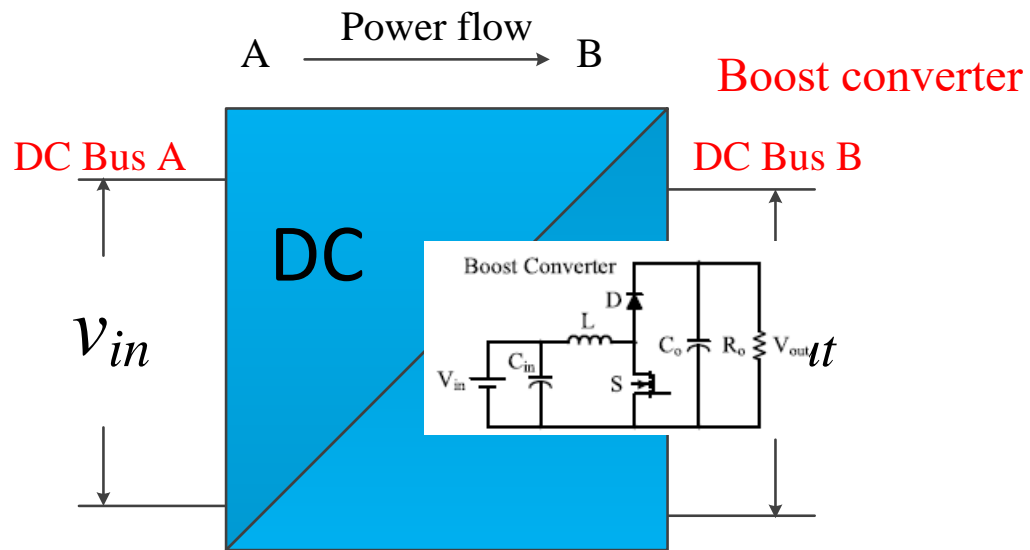
CLASSIFICATION-Nonisolated/Isolated

Electrical isolation is an important feature for grid-tied dc–dc converters and for some other applications that require reliable power transfer with low noise and reduced EMI.



Can be achieved by means of either transformer or coupled inductor

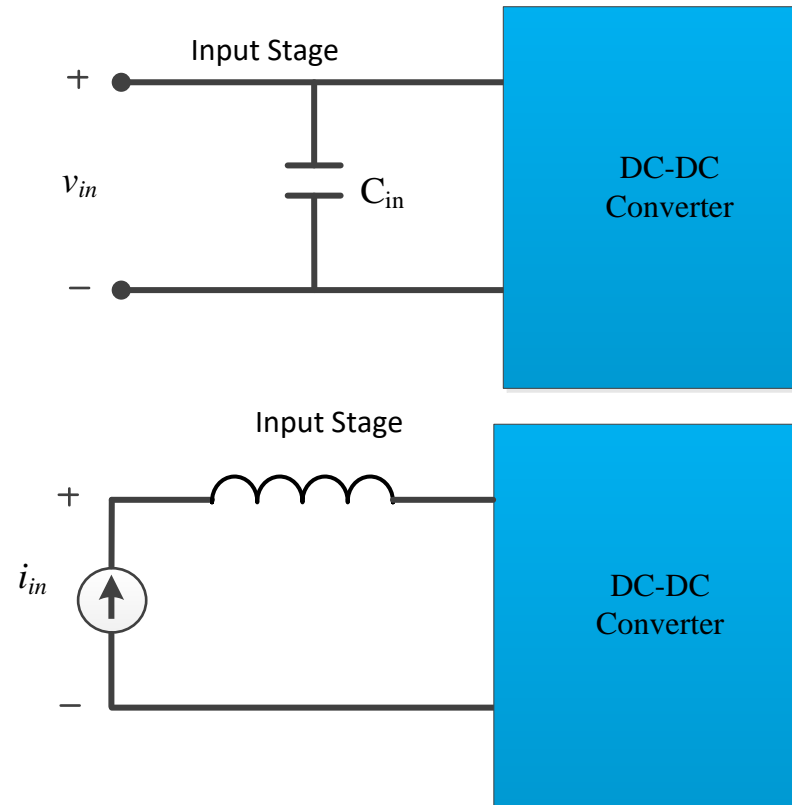
CLASSIFICATION-*Unidirectional/Bidirectional*



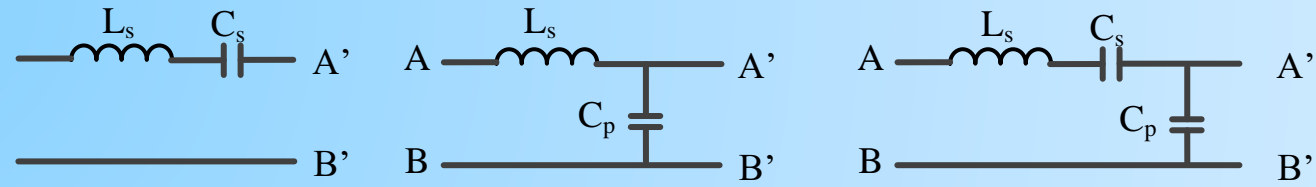
CLASSIFICATION-*Voltage-Fed/Current-Fed*

Depending on their input circuitry, step-up dc-dc converters can be classified as either voltage- or current-fed converters.

Current-fed dc-dc converters are very popular for low-voltage renewable energy applications such as photovoltaics (PVs) and fuel cells (FCs) because their input inductors can provide a continuous input current, typically with low ripple. This feature reduces the negative impacts of high ripple current on low voltage high-current sources.



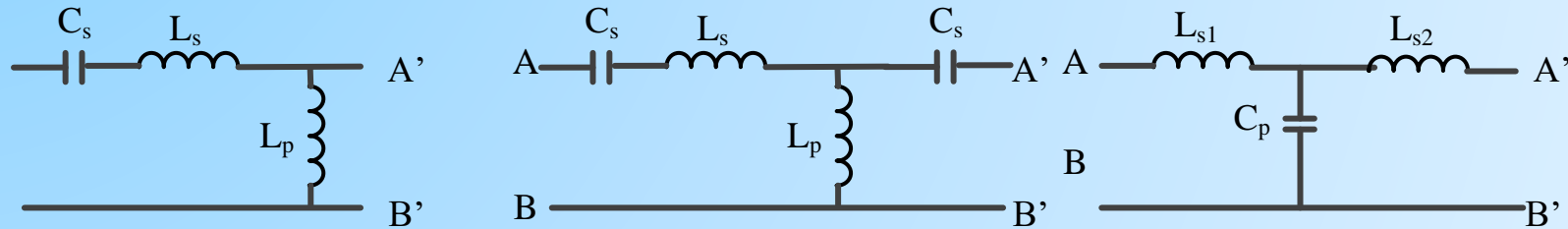
CLASSIFICATION-*Hard Switched/Soft Switched*



Series

Parallel

Series-Parallel

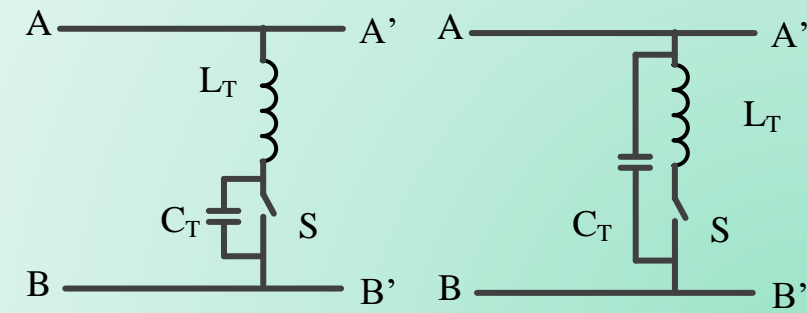


LLC

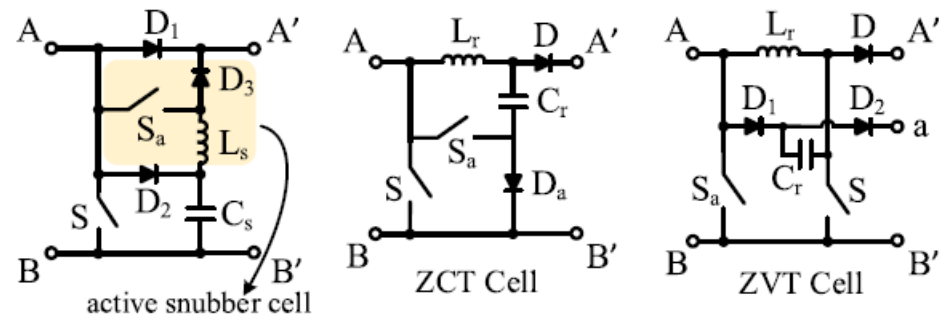
CLLC

LCL

General resonant tank networks



Quasi-resonant switch cells



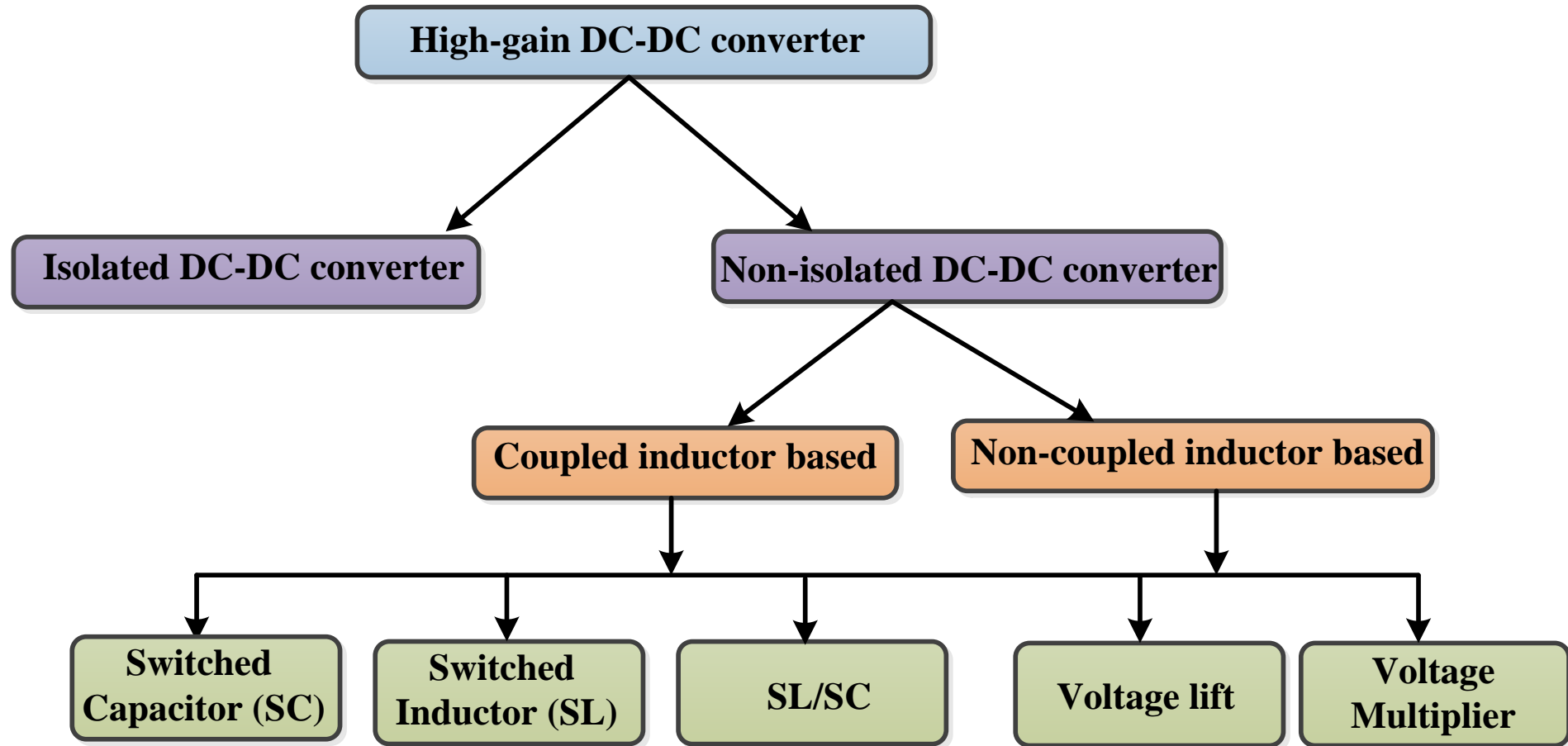
Auxillary Circuits

CLASSIFICATION-NMP/Minimum Phase

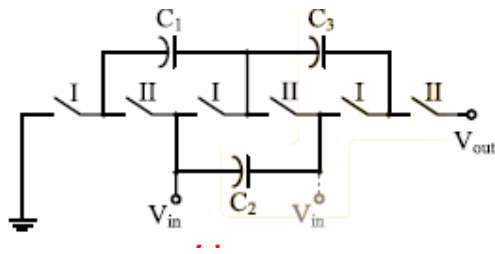
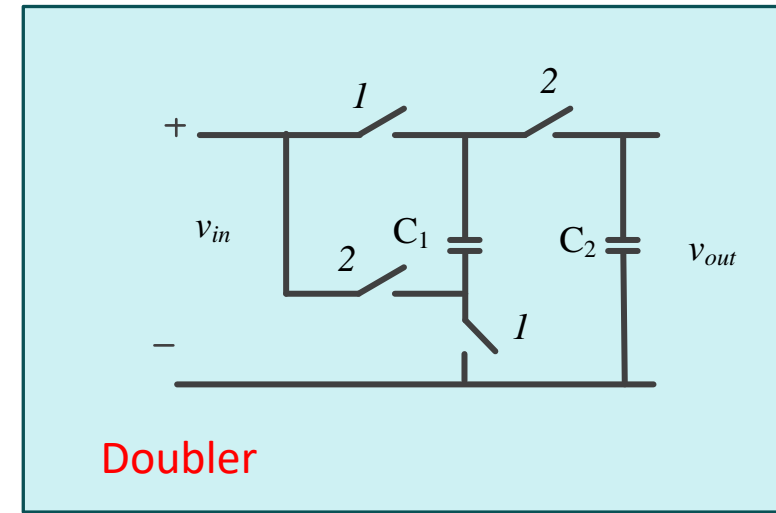
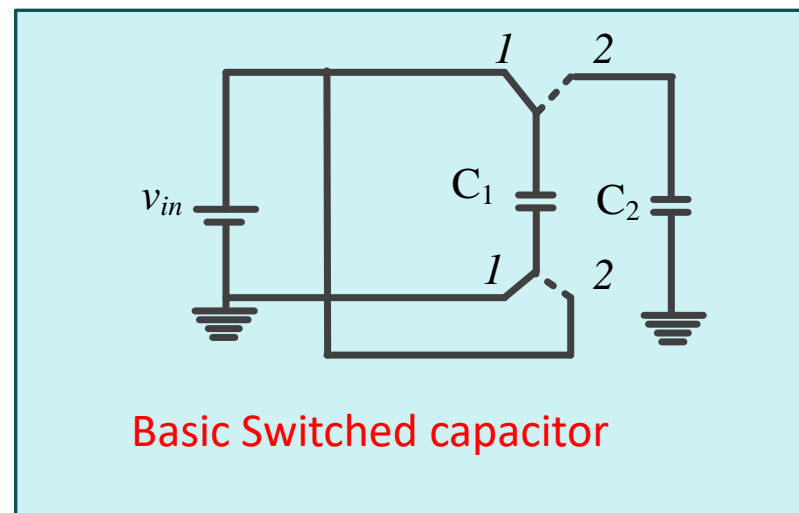
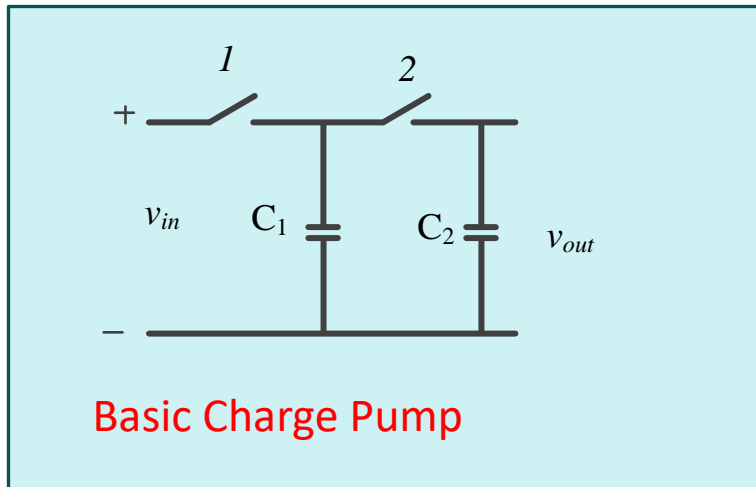
- Systems with RHP zeros are called Non-Minimum Phase systems (NMP).
- Controllers for these NMP systems are more difficult to design because, as the gain increases in a conventional controller, the closed-loop poles will be attracted to the RHP.
- Reducing the inductor value does not eliminate the RHP zero, it pushes it further from the origin and thus reduces the NMP effect.
- operating in the DCM allows for very stable dynamics without RHP zero
- New boost converters with additional active switches are introduced tristate boost converters eliminate the RHP zero in the control to output transfer function and can be used in applications in which fast-response boost action is needed.

KY converter

CLASSIFICATION



Voltage Boosting Techniques- Switched Capacitor(Charge Pump)



Dickson

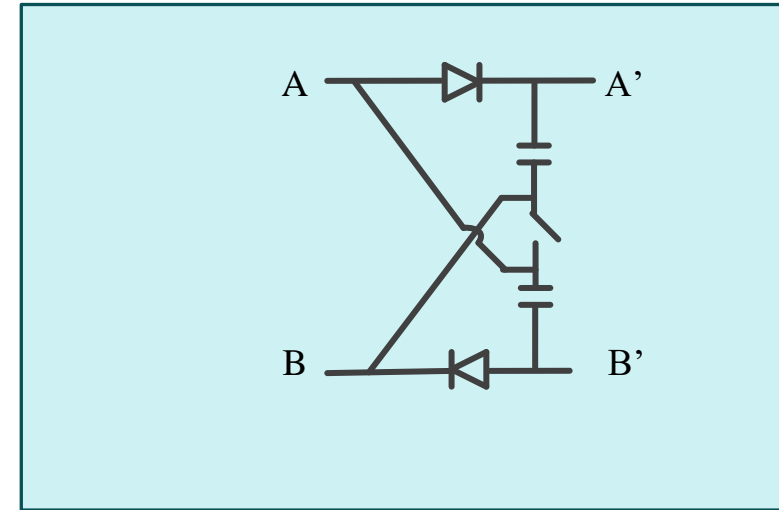
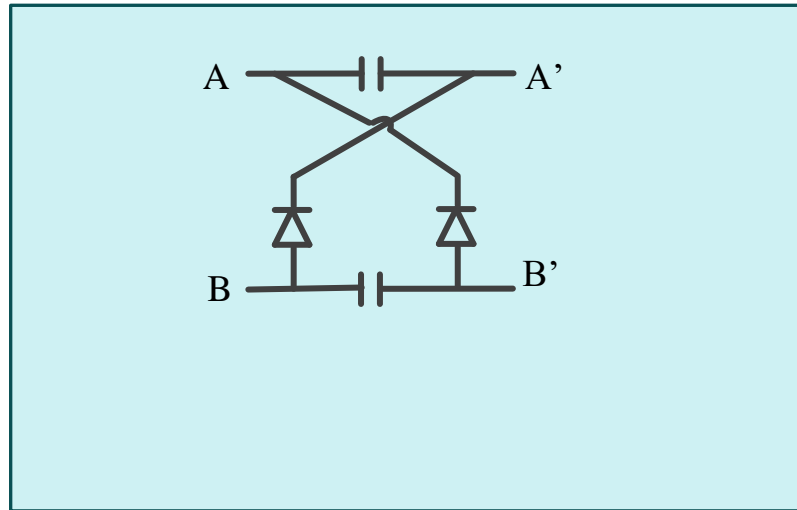
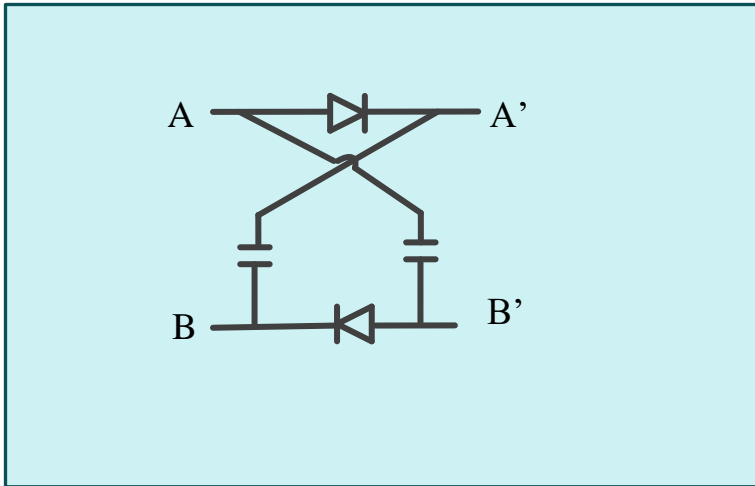
Makowski/Fibonacci

- Cheap and Light weight
- Small size and higher power density
- Easy to be integrated
- Fast dynamic response

- Inrush current at startup
- ESR of capacitor
- Lack of output voltage regulation

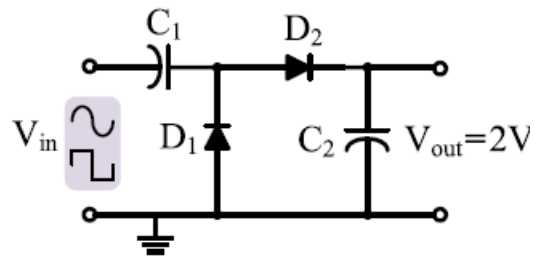
- Energy Harvesting
- Automotive and vehicular applications
- High gain DC-DC applications

Voltage Boosting Techniques- Voltage Multiplier

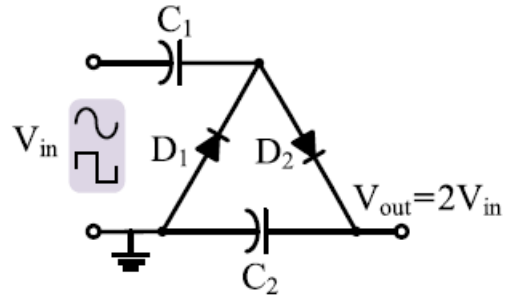


Voltage Multiplier Rectifiers

Half-wave:

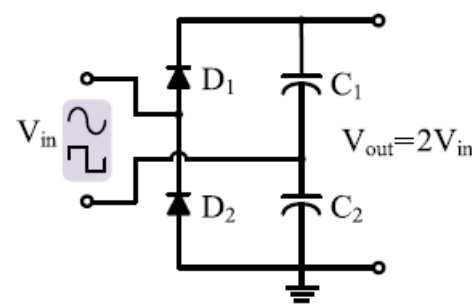


Greinacher Voltage Doubler

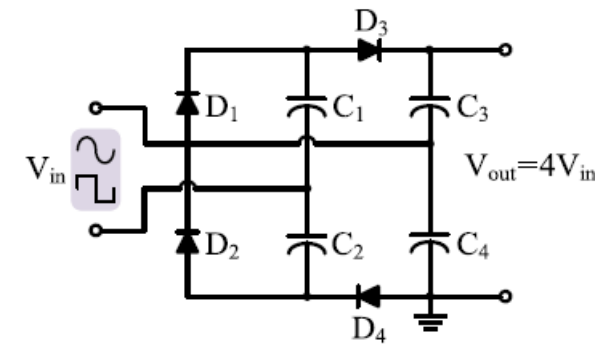


Cockcroft-Walton Voltage Doubler

Full-wave:



Voltage Doubler Rectifier



Voltage Quadrupler Rectifier

Voltage Boosting Techniques- Voltage Multiplier

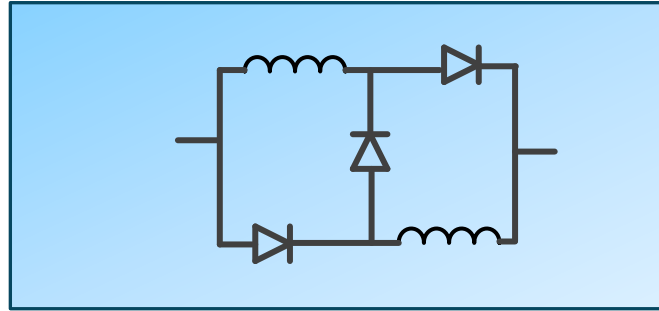
- Very high voltage ability with simple topology
- Cell based structure
- Can be integrated to various structures

- Medical
- Military(high power laser)
- Physics(Plasma accelerator)

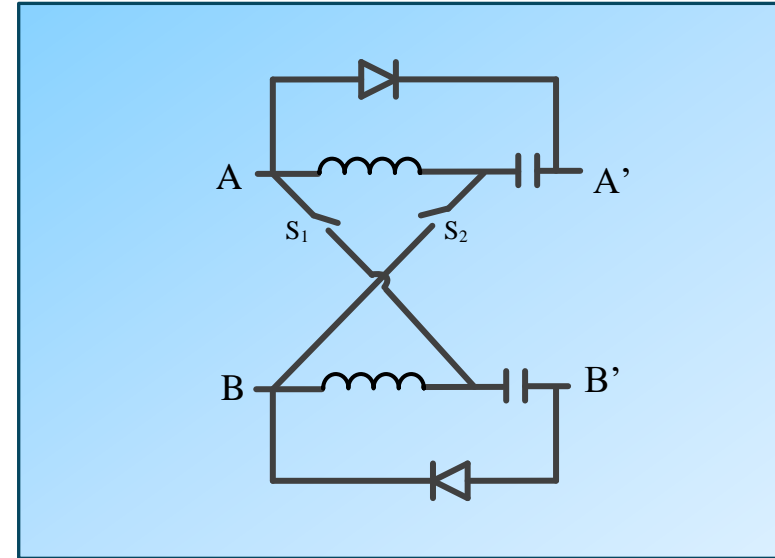
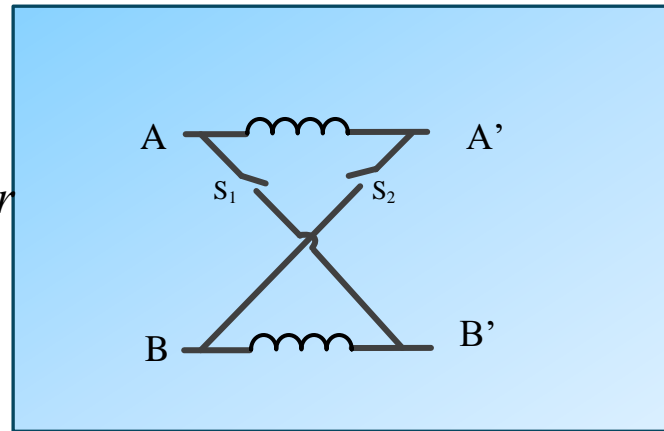
- High voltage stress on components
- Need several cells with high voltage ratings for high power applications

Voltage Boosting Techniques- Switched Inductor and Voltage Lift

Passive switched inductor

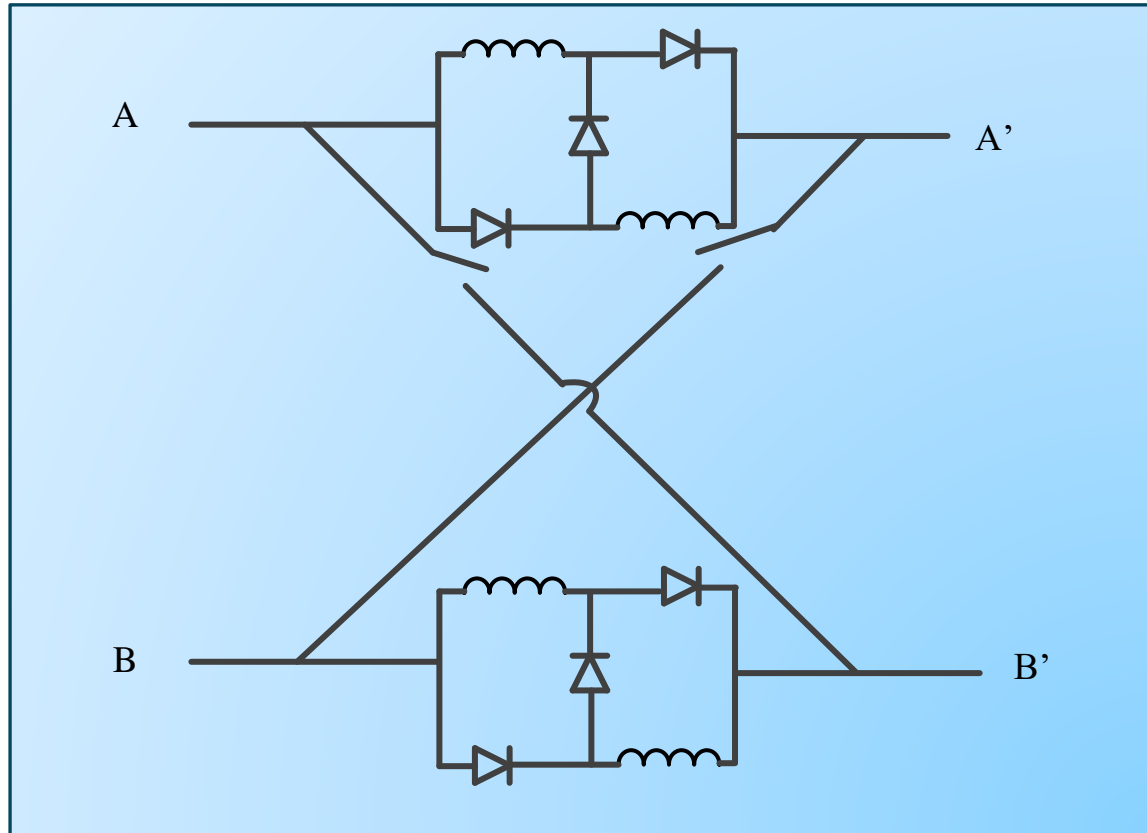


Active switched inductor



Voltage Boosting Techniques- Switched Inductor and Voltage Lift

Hybrid A-SL



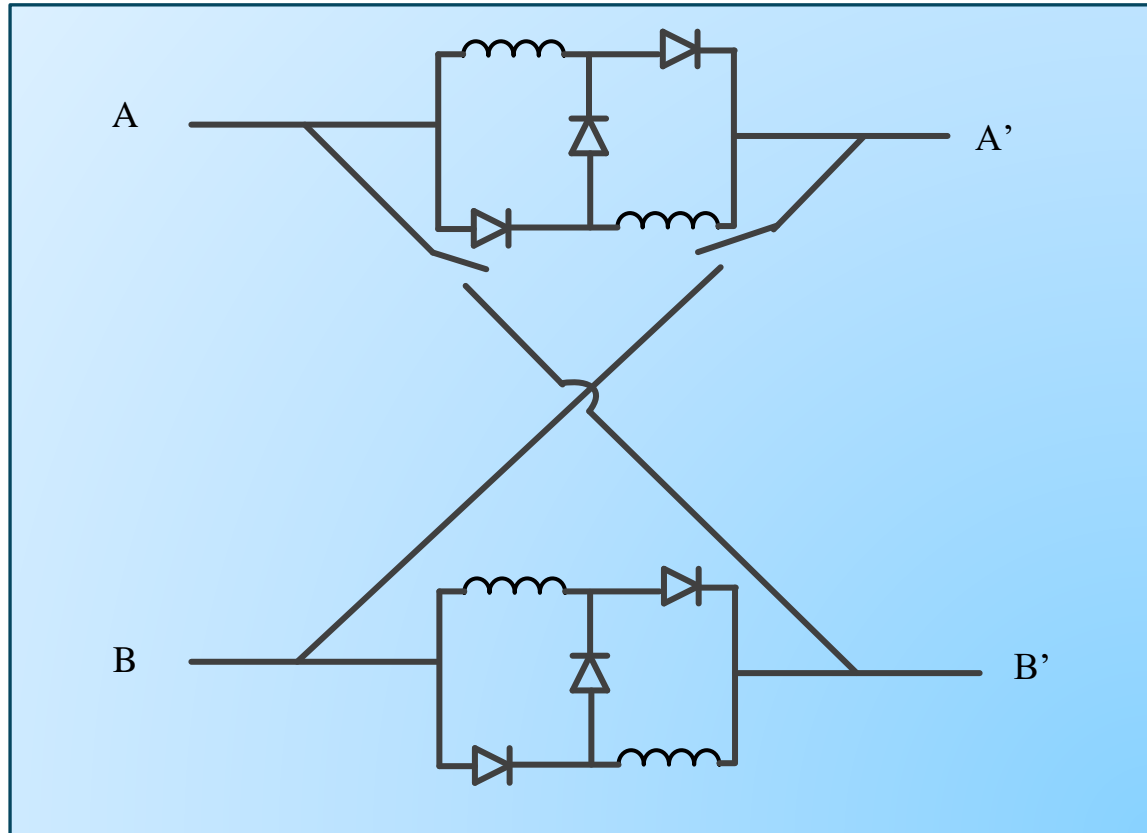
- High boost ability
- Amenable in many converters

- Need more passive components
- Not suitable for high power applications

- Mid-range DC-DC converters
- High gain DC-DC converter applications

Voltage Boosting Techniques- Switched Inductor and Voltage Lift

Hybrid A-SL



- High boost ability
- Amenable in many converters

- Need more passive components
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- Mid-range DC-DC converters
- High gain DC-DC converter applications

Voltage Boosting Techniques- Magnetic Coupling

1) Transformer:

a) *Isolated transformers:*

b) *Built-in transformers:*

2) Coupled Inductor:

a) *Tapped inductor/autotransformer:*

b) *Magnetically coupled-based converters*

- High power/voltage DC supply
- High voltage applications
- CCPS for capacitive loads
- DC Microgrids
- Bidirectional

- High design freedom
- Versatile in boost ability
- Switch can be implemented in low voltage side help to reduce conduction loss
- High efficiency in soft switched type

- Negative effect of leakage inductance
- Need precise coupled magnetic design
- Relatively bulky

Voltage Boosting Techniques- Multistage/-Level

1) *Cascaded:* a) *Quadratic boost:*

b) *Hybrid cascaded:*

2) *Interleaved:*

3) *Multilevel:*

a) *Modular (single dc source):*

b) *Cascaded (multiple dc source):*

- Modularity structure
- High power capability
- Reliable and efficient
- High voltage or current level

- Large amount of components
- Relatively heavy, bulky and costly
- Efficiency decrease with number of stages/levels

- HVDC Transmission
- High power DC supply
- EV, FC-EV, HEV
- DC Microgrid

Applications

Renewable
Energy

Transportation

Avionic space

Telecom

Gadgets/
appliances

Lighting

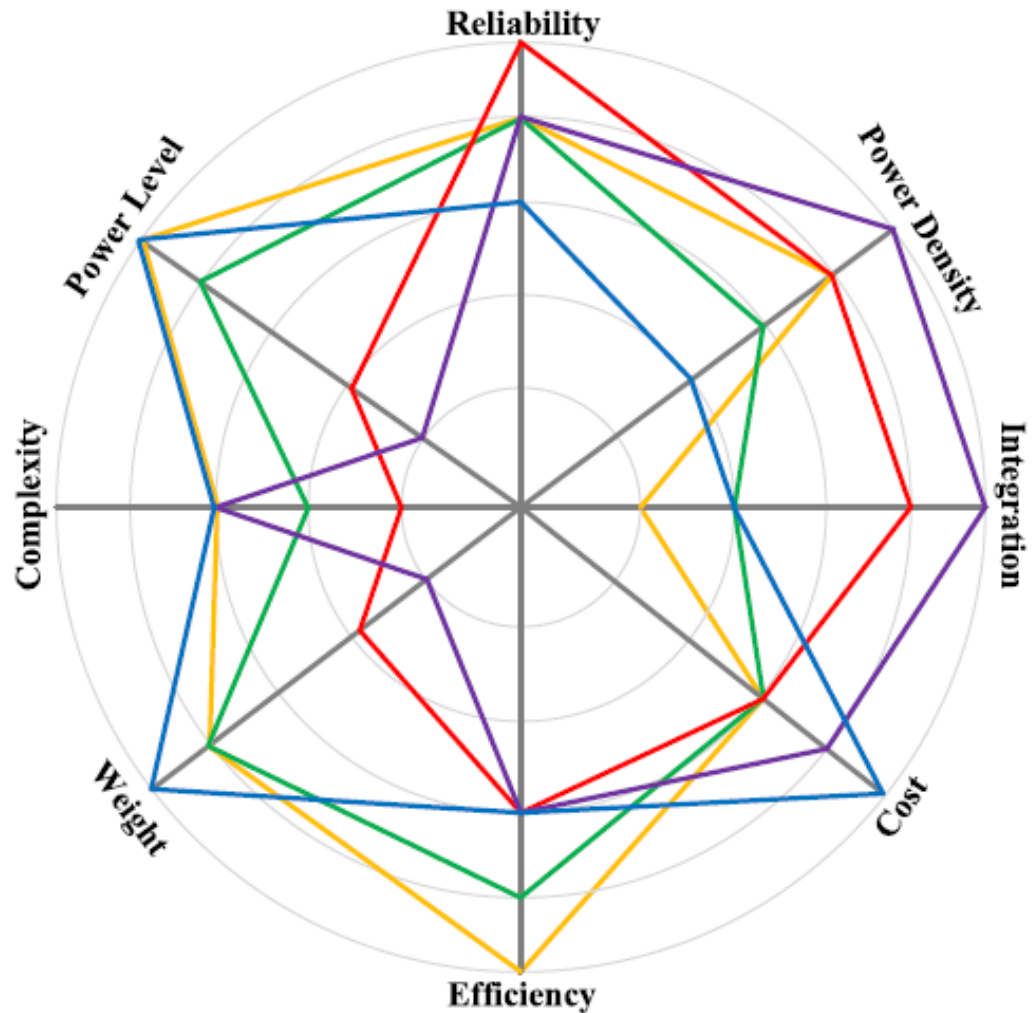
Industry

Utility

Physics

Medical/bio

Military

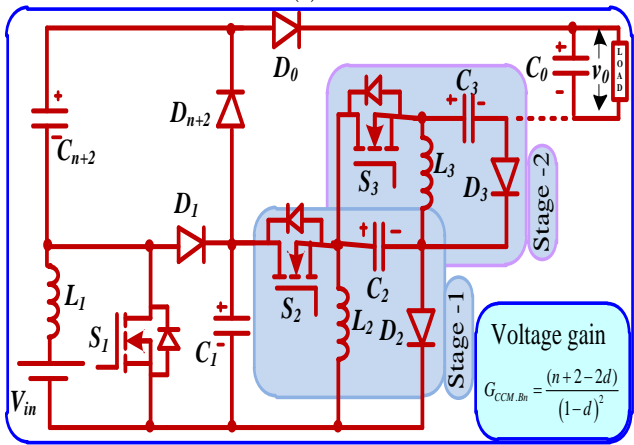
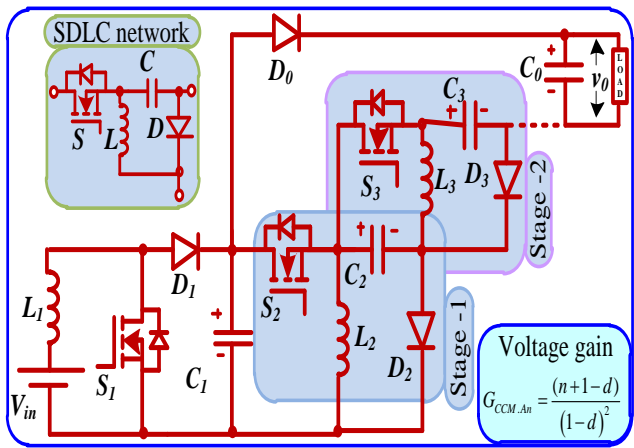


- **Switched Capacitor/Charge Pump**
- **Voltage Multiplier**
- **Switched Inductor/Voltage Lift**
- **Magnetic Coupling**
- **Multi-Stage/-Level**

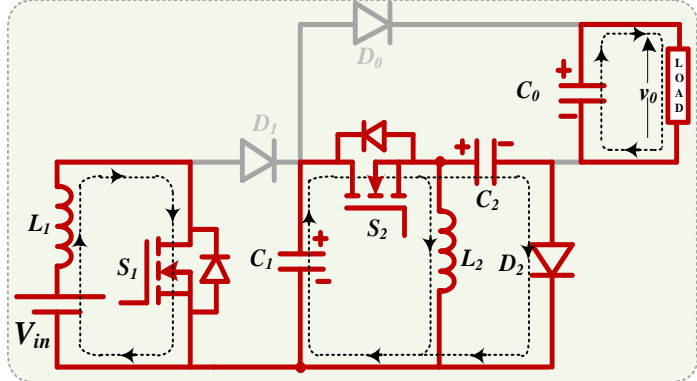
Ref: M. Forouzesh, Y. P. Siwakoti, S. A. Gorji, F. Blaabjerg and B. Lehman, "Step-Up DC-DC Converters: A Comprehensive Review of Voltage-Boosting Techniques, Topologies, and Applications," in *IEEE Transactions on Power Electronics*

Design and development of Controller for non-isolated High gain DC-DC Converter

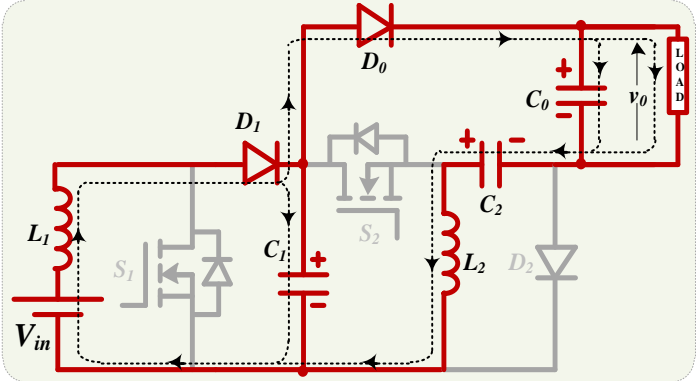
HIGH GAIN DC-DC CONVERTER TOPOLOGIES USING SDLC NETWORK



SDLCN converters (a) Converter A (b) Converter B



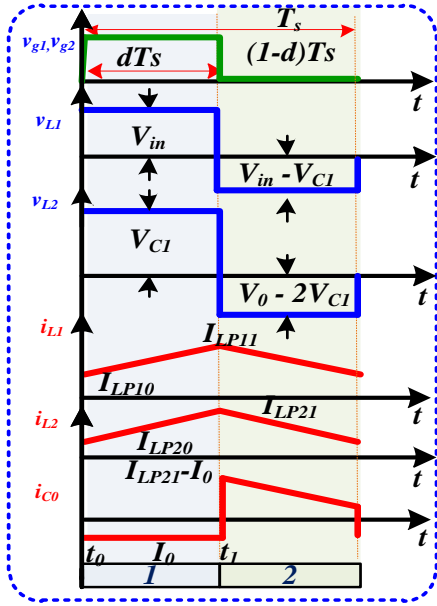
$$V_{L1} = V_{in}, V_{L2} = V_{C1}, V_{C1} = V_{C2} = V_{in} / (1-d)$$



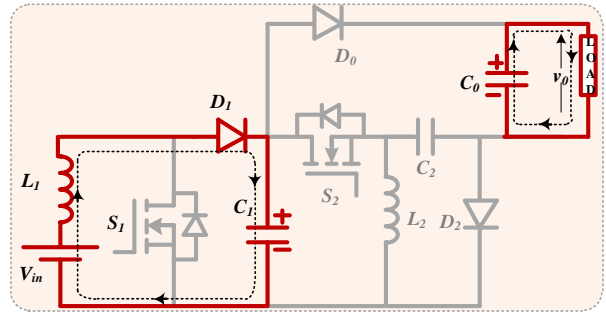
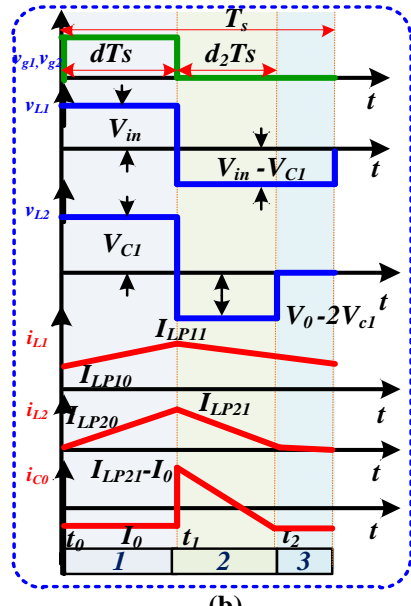
$$V_{L1} = V_{in} - V_{C1}, V_{L2} = V_{C2} + V_{C1} - V_0$$

$$G_{CCM_Conv.I} = \frac{V_0}{V_{in}} = \frac{(2-d)}{(1-d)^2}$$

Equivalent circuit of SDLCN converter A - CCM (a) mode 1 (b) mode 2



Theoretical waveforms (a) CCM (b) DCM

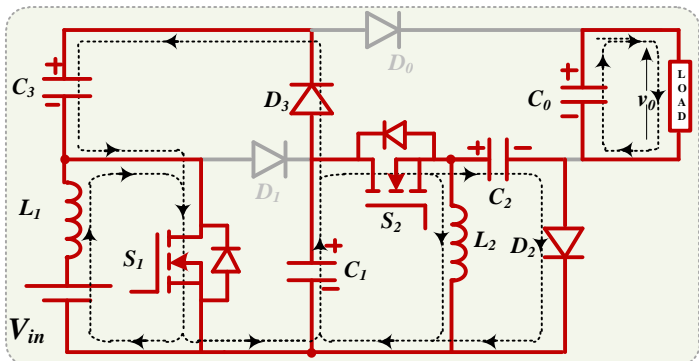


$$G_{DCM_Conv.I} = \frac{V_0}{V_{in}} = \frac{1}{1-d} \left[1 + \sqrt{1 + \frac{d^2}{2\tau_{L2}}} \right]$$

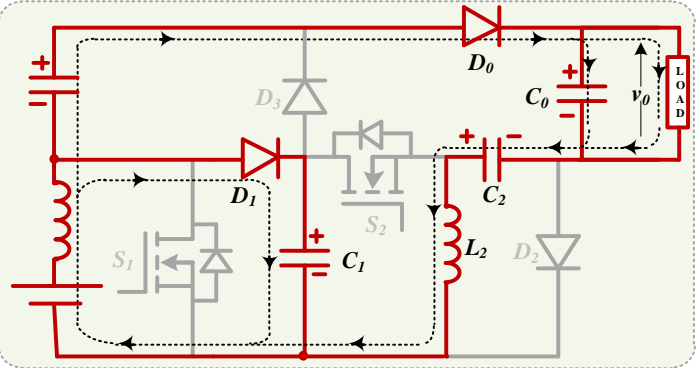
where, $\tau_{L2} = \frac{L_2 f_s}{R_0}$

Equivalent circuit of SDLCN converter A DCM mode-3

SDLCN CONVERTER B



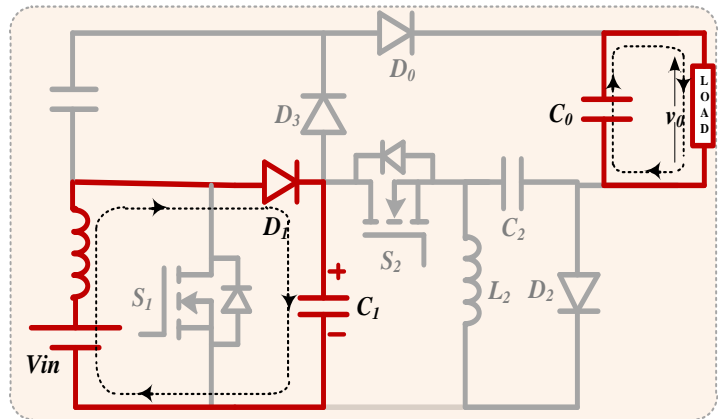
$$V_{C1} = V_{C2} = V_{C3} = \frac{V_{in}}{1-d}; V_{L1} = V_{in}, V_{L2} = V_{C1}$$



$$V_{L1} = V_{in} - V_{C1}, V_{L2} = V_{C3} + V_{C2} + V_{C1} - V_0$$

$$G_{CCM_Conv.B} = \frac{V_0}{V_{in}} = \frac{3-2d}{(1-d)^2}$$

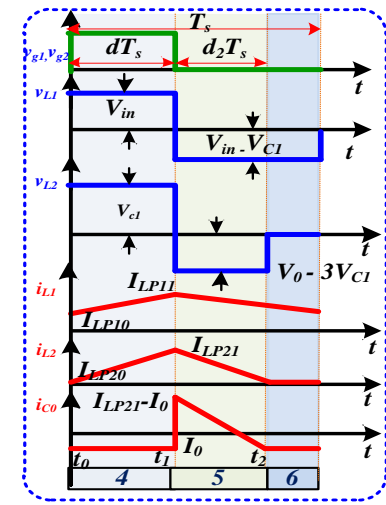
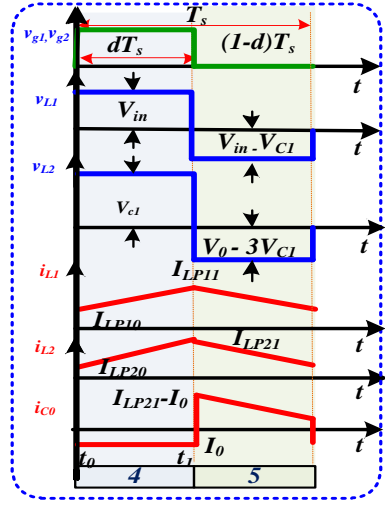
Equivalent circuit of SDLCN converter B -CCM (a) mode 1 (b) mode 2



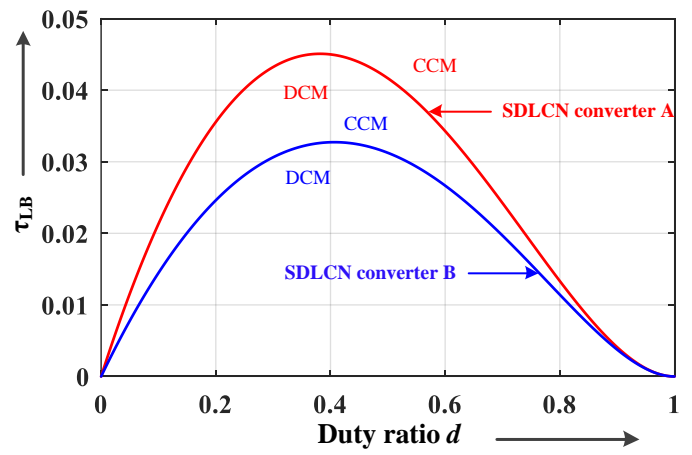
Equivalent circuit of SDLCN converter B - DCM mode 3

$$G_{DCM_Conv.B} = \frac{V_0}{V_{in}} = \frac{3}{2(1-d)} \left(1 + \sqrt{1 + \frac{2d^2}{9\tau_{L2}}} \right)$$

where, $\tau_{L2} = \frac{L_2 f_s}{R_0}$



Theoretical waveforms (a) CCM (b) DCM



$$\tau_{L_Conv.A} = \frac{d(1-d)^2}{2(2-d)}$$

$$\tau_{L_Conv.B} = \frac{d(1-d)^2}{2(3-2d)}$$

Boundary condition of SDLCN converters

DESIGN OF COMPONENTS AND HARDWARE PROTOTYPE

Selection of inductors

$$L_1 \frac{\Delta I_{L1}}{dT_s} = V_{in}; L_2 \frac{\Delta I_{L2}}{dT_s} = V_{c1} L_1 \geq \frac{V_{in} d}{\Delta I_{L1} f_s}; L_2 \geq \frac{V_{in} d}{(1-d) \Delta I_{L2} f_s} \quad (28)$$

Capacitors selection:

$$C_1 \geq \frac{I_o(2-d)}{\Delta V_{C1} f_s (1-d)}; C_2, C_3 \geq \frac{I_o}{\Delta V_{C2} f_s}; C_0 \geq \frac{I_o d}{\Delta V_{C0} f_s} \quad (29)$$

Selection of Switches and Diodes

Voltage Stress:

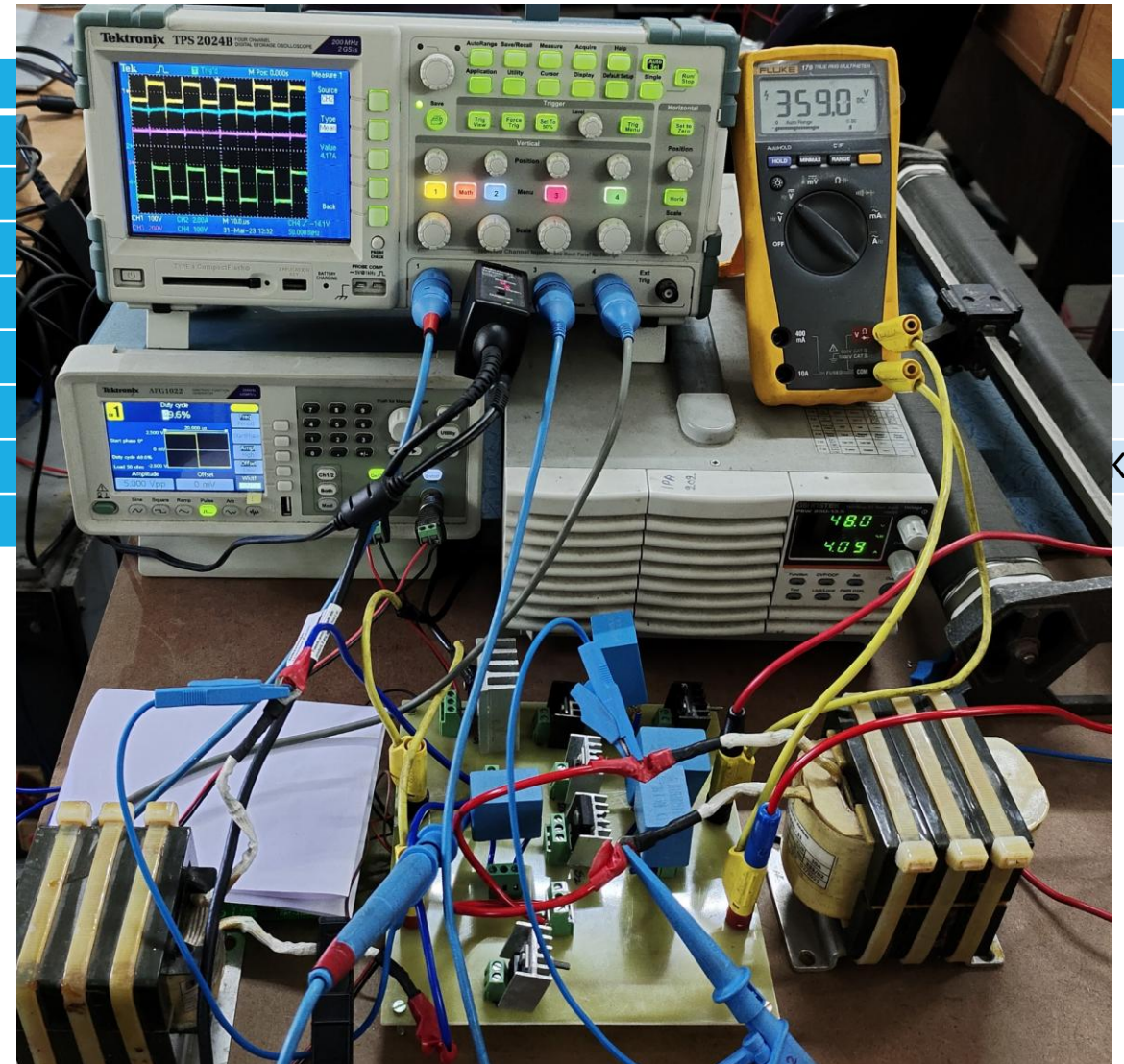
$$\text{Converter A: } \frac{V_s}{V_{in}} = \frac{1}{1-d}; \frac{1}{(1-d)^2} \quad \frac{V_d}{V_{in}} = \frac{1}{1-d}; \frac{1}{(1-d)^2} \quad (30)$$

$$\text{Converter B: } \frac{V_s}{V_{in}} = \frac{1}{1-d}; \frac{1}{(1-d)^2} \quad \frac{V_d}{V_{in}} = \frac{1}{1-d}; \frac{1}{(1-d)^2} \quad (31)$$

Current Stress:

$$\text{Converter A: } \frac{I_s}{I_o} = \frac{(2-d)\sqrt{d}}{(1-d)^2}; \frac{d^{-0.5}}{(1-d)} \quad \frac{I_d}{I_o} = (2-d)(1-d)^{-\frac{3}{2}}; (1-d)^{-0.5}; I_o d^{-0.5} \quad (32)$$

$$\text{Converter B: } \frac{I_s}{I_o} = \frac{(1+d-d^2)}{\sqrt{d}(1-d)^2}; \frac{d^{-0.5}}{(1-d)} \quad \frac{I_d}{I_o} = (2-d)(1-d)^{-\frac{3}{2}}; (1-d)^{-0.5}; I_o d^{-0.5} \quad (33)$$



Hardware prototype of converter B

PERFORMANCE ANALYSIS

Converter A

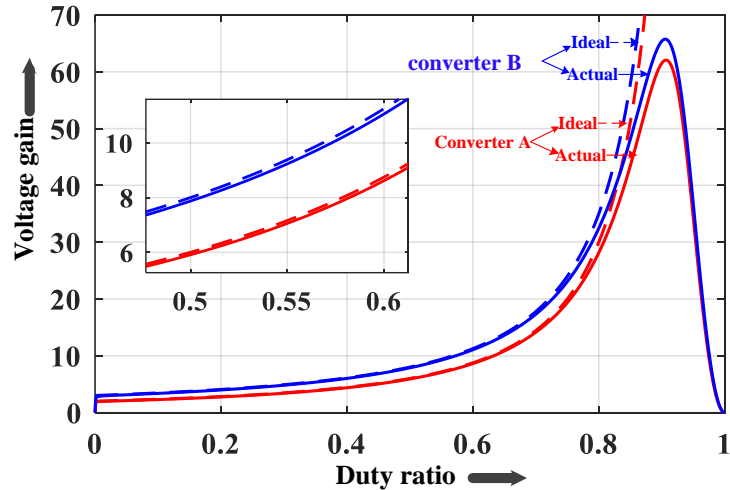
$$\frac{V_o}{V_{in}} \Big|_{Conv.I} = \frac{(2-d) - (4-7d+3d^2)(v_{fd}/V_{in})}{(1-d)^2 + A_I \frac{R_L}{R_o} + B_I \frac{R_C}{R_o} + C_I \frac{R_S}{R_o} + D_I \frac{R_d}{R_o}}$$

$$A_I = \frac{5-6d+2d^2}{(1-d)^2}; B_I = \frac{2-2d+d^2}{d(1-d)}; C_I = \frac{d^2(2-d)^2+(1-d)^2}{d(1-d)^2}; D_I = \frac{1+2d-3d^2+d^3}{d(1-d)^2}$$

Converter B

$$\frac{V_o}{V_{in}} \Big|_{Conv.II} = \frac{(3-2d) - (5-9d+4d^2) \frac{v_{fd}}{V_{in}}}{(1-d)^2 + A_{II} \frac{R_L}{R_o} + B_{II} \frac{R_C}{R_o} + C_{II} \frac{R_S}{R_o} + D_{II} \frac{R_d}{R_o}}$$

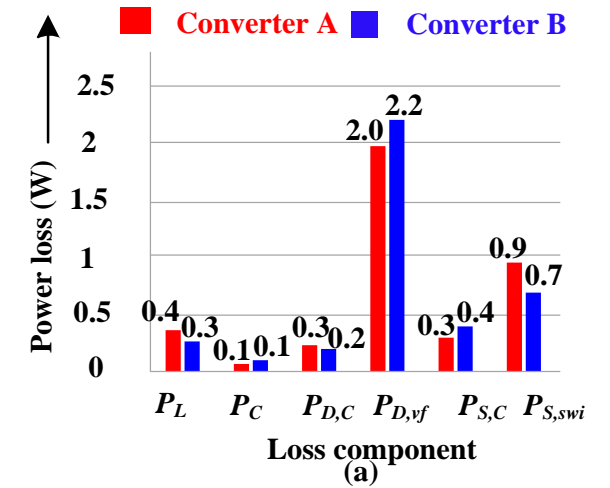
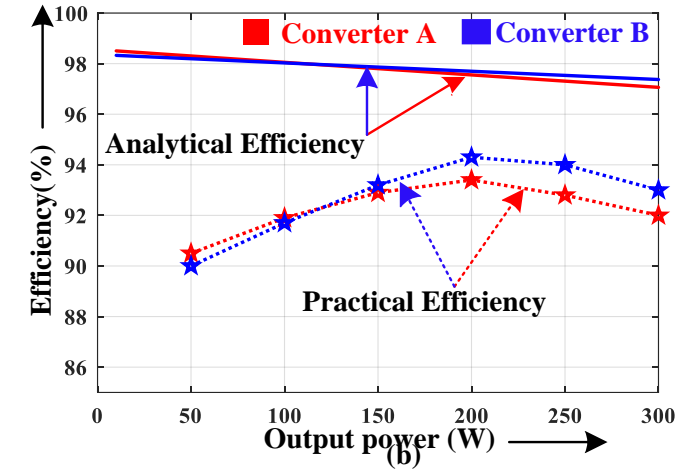
$$A_{II} = \frac{10-14d+5d^2}{(1-d)^2}; B_{II} = \frac{6-8d+3d^2}{d(1-d)}; C_{II} = \frac{(1+d-d^2)^2+(1-d)^2}{d(1-d)^2}; D_{II} = \frac{2-d}{d(1-d)}$$



Voltage gain of SDLCN converters with parasitic elements

Table 4 Loss equations

LOSSES	CONVERTER A	CONVERTER B
P_L	$\frac{5-6d+2d^2}{(1-d)^4} I_o^2 R_L$	$\frac{10-14d+6d^2}{(1-d)^4} I_o^2 R_L$
P_C	$\frac{2-2d+2d^2-2d^3+d^4}{d(1-d)^3} I_o^2 R_C$	$\frac{6-8d+4d^2-2d^3+d^4}{d(1-d)^3} I_o^2 R_C$
$P_{D,C}$	$\frac{1+2d-3d^2+d^3}{d(1-d)^3} I_o^2 R_d$	$\frac{2-d}{d(1-d)^3} I_o^2 R_d$
$P_{D,VFD}$	$\frac{4-3d}{(1-d)} v_{fd} I_o$	$\frac{5-4d}{(1-d)} v_{fd} I_o$
$P_{S,C}$	$\frac{1-2d+5d^2-4d^3+d^4}{d(1-d)^4} I_o^2 R_S$	$\frac{2-2d^3+d^4}{d(1-d)^4} I_o^2 R_S$
$P_{S,SWI}$	$\frac{2-2d^2+d^3}{2(1-d)^3} (t_{on}+t_{off}) V_{in} f_s I_o$	$\frac{1+2d-d^2}{2(1-d)^3} (t_{on}+t_{off}) V_{in} f_s I_o$



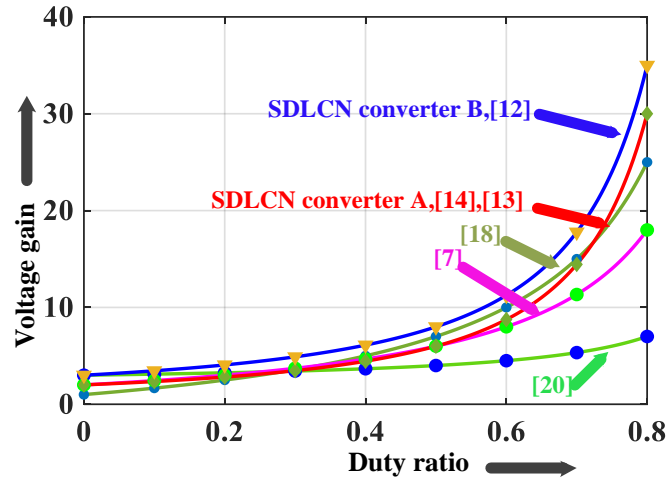
Efficiency profile (b) Loss breakdown

PERFORMANCE COMPARISON

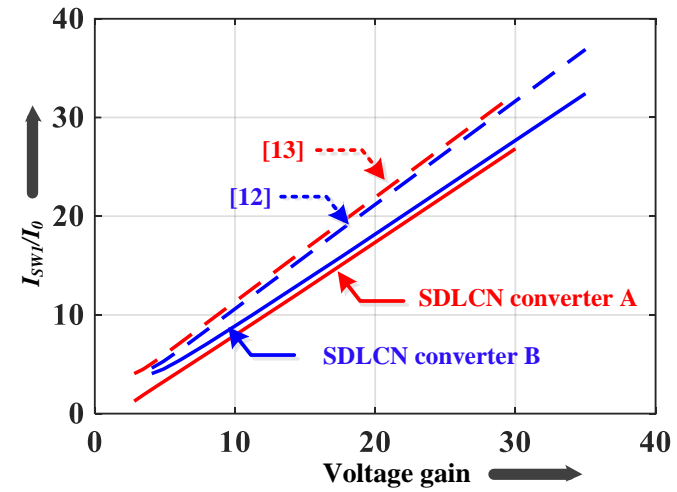
Table 5 comparison of proposed converters with conventional converters

	[18]	[20]	[13]	[19]	[9]	[7]	[14]	[12]	[15]	[31]	Conv. A	Conv. B
S/D/L/C	3/9/1/6	1/4/5/2	2/4/4/2	2/3/2/2	2/5/6/3	1/6/3/2	1/4/3/2	2/3/3/2	2/5/5/2	3/3/3/2	2/3/3/2	2/4/4/2
Total	19	12	12	9	16	12	10	10	14	11	10	12
i_{in}	Puls.	Discount	Cont.	Cont.	Puls.	Puls.	Puls.	Cont.	Cont.	Cont.	Cont.	Cont.
$G_{n=1}$	$\frac{1+5d}{(1-d)}$	$2+\frac{1}{1-d}$	$\frac{3-2d}{(1-d)^2}$	$\frac{1}{d(1-d)}$	$\frac{2+d}{(1-d)^2}$	$2\frac{1+d}{1-d}$	$\frac{2-d}{(1-d)^2}$	$\frac{2-d}{(1-d)^2}$	$\frac{3+d}{(1-d)^2}$	$\frac{1+2d}{1-d}$	$\frac{2-d}{(1-d)^2}$	$\frac{3-2d}{(1-d)^2}$
G_n	$\frac{1+(2n+3)d}{(1-d)}$	$n+1+\frac{1}{1-d}$	-	$\frac{n}{d(1-d)}$	-	$2\frac{1+nd}{1-d}$	-	-	-	$\frac{1+(n+1)d}{1-d}$	$\frac{n+1-d}{(1-d)^2}$	$\frac{n+2-2d}{(1-d)^2}$
K^{th} stage	S-1, L-2, D-5 Total-8	L-1, D-1, C-2 Total-4	S-1, L-1, D-2, C-3 Total-7	D-2, L-1, C-1 Total-4	-	D-3, L-1, C-0 Total-4	-	S-1, D-2, L-1, C-2 Total-6	-	D-2, S-1, L-1 Total-4	S-1, D-1, L-1, C-1 Total-4	S-1, D-1, L-1, C-1 Total-4
V_{sw}/V_{in}	$\frac{1+d}{1+5d}; \frac{2(2-5d)}{3(1+5d)}$	$\frac{1}{1-d}$	$\frac{1}{1-d}; \frac{1}{(1-d)^2}$	$\frac{1}{1-d}; \frac{1+d}{2(1-d)}$	$\frac{1}{1-d}; \frac{1}{(1-d)^2}$	$\frac{1+d}{(1-d)}$	$\frac{1}{(1-d)^2}$	$\frac{1}{1-d}; \frac{1}{(1-d)^2}$	$\frac{1}{1-d}; \frac{1+d}{(1-d)^2}$	$\frac{1}{1-d}; \frac{4-d}{3(1-d)}$ $\frac{2(2+d)}{3(1-d)}$	$\frac{1}{1-d}; \frac{1}{(1-d)^2}$	$\frac{1}{1-d}; \frac{1}{(1-d)^2}$
I_{sw}/I_o	$\frac{2\sqrt{d}}{1-d}$	$\frac{(3-2d)\sqrt{d}}{1-d}$	$\frac{(1+2d-2d^2)}{\sqrt{d}(1-d)^2}; \frac{1}{\sqrt{d}(1-d)}$	$\frac{2-d}{\sqrt{d}(1-d)}; \frac{1}{\sqrt{1-d}}$	$\frac{(2+d)\sqrt{d}}{(1-d)^2}; \frac{1+2d}{\sqrt{d}(1-d)}$	$\frac{1+3d}{\sqrt{d}(1-d)}$	$\frac{(1+d-d^2)}{\sqrt{d}(1-d)^2}$	$\frac{(1+d-d^2)}{\sqrt{d}(1-d)^2}; \frac{\sqrt{d}}{1-d}$	$\frac{1+3d}{\sqrt{d}(1-d)^2}; \frac{1+d}{\sqrt{d}(1-d)}$	$\frac{\sqrt{d}}{1-d}$	$\frac{(2-d)\sqrt{d}}{(1-d)^2}; \frac{d^{-0.5}}{(1-d)}$	$\frac{(1+d-d^2)}{\sqrt{d}(1-d)^2}; \frac{d^{-0.5}}{(1-d)}$
V_D/V_{in}	$\frac{1-d}{1+5d}; \frac{2(1+2d)}{1+5d}; \frac{d}{1+5d}$	$\frac{1}{1-d}$	$\frac{1}{1-d}; \frac{2-d}{(1-d)^2}$	$\frac{1}{d(1-d)}; \frac{1}{1-d}; \frac{1+d}{2(1-d)}$	$1; \frac{1}{(1-d)^2}$	$1; \frac{d}{1-d}; \frac{1+d}{(1-d)}$	$\frac{d}{(1-d)^2}; \frac{1}{1-d}; \frac{1}{(1-d)^2}$	$\frac{1}{1-d}; \frac{d}{(1-d)^2}$	$\frac{1}{1-d}; \frac{2}{(1-d)^2}$	$1; \frac{d}{1-d}$	$\frac{1}{1-d}; \frac{1}{(1-d)^2}$	$\frac{1}{1-d}; \frac{1}{(1-d)^2}; \frac{2-d}{(1-d)^2}$
I_D/I_o	$\frac{\sqrt{d}}{1-d}$	$\frac{\sqrt{d}}{1-d}; \frac{\sqrt{1-d}}{d^2}$	$\frac{(2-d)\sqrt{d}}{(1-d)^2}; \frac{1}{\sqrt{d}(1-d)}; \frac{1}{\sqrt{d}}; \frac{1}{\sqrt{1-d}}$	$\frac{2-d}{\sqrt{d}(1-d)}; \frac{\sqrt{1-d}}{d}$	$\frac{1}{\sqrt{1-d}}; \frac{1}{\sqrt{d}}; \frac{2+d}{\sqrt{1-d}}$	$\frac{2\sqrt{d}}{(1-d)}; \frac{1}{\sqrt{1-d}}; \frac{1}{\sqrt{d}}$	$\frac{(2-d)\sqrt{d}}{(1-d)^2}; \frac{1}{\sqrt{d}}; \frac{(2-d)}{(1-d)}; \frac{1}{\sqrt{1-d}}$	$\frac{1}{\sqrt{d}(1-d)}; (1-d)^{\frac{3}{2}}; \frac{1}{\sqrt{(1-d)^3}}$	$\frac{1+d}{(1-d)^2}; \frac{1}{\sqrt{d}}; \frac{2}{\sqrt{(1-d)^2}}; \frac{1}{\sqrt{1-d}}$	$\frac{\sqrt{d}}{1-d}; \frac{1}{\sqrt{1-d}}$	$(2-d)(1-d)^{-\frac{3}{2}}; (1-d)^{-0.5}; I_o d^{-0.5}$	$(2-d)(1-d)^{-\frac{3}{2}}; (1-d)^{-0.5}; I_o d^{-0.5}$

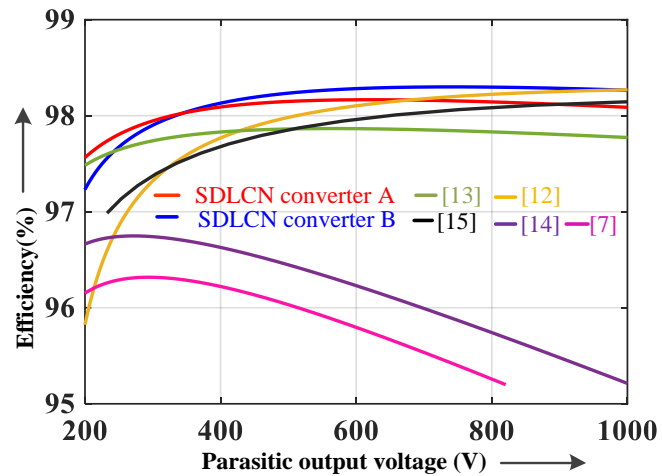
Performance comparison



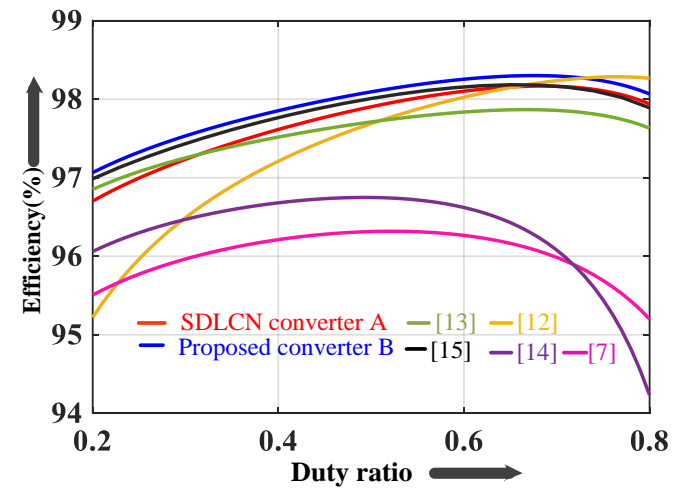
(a)



(b)



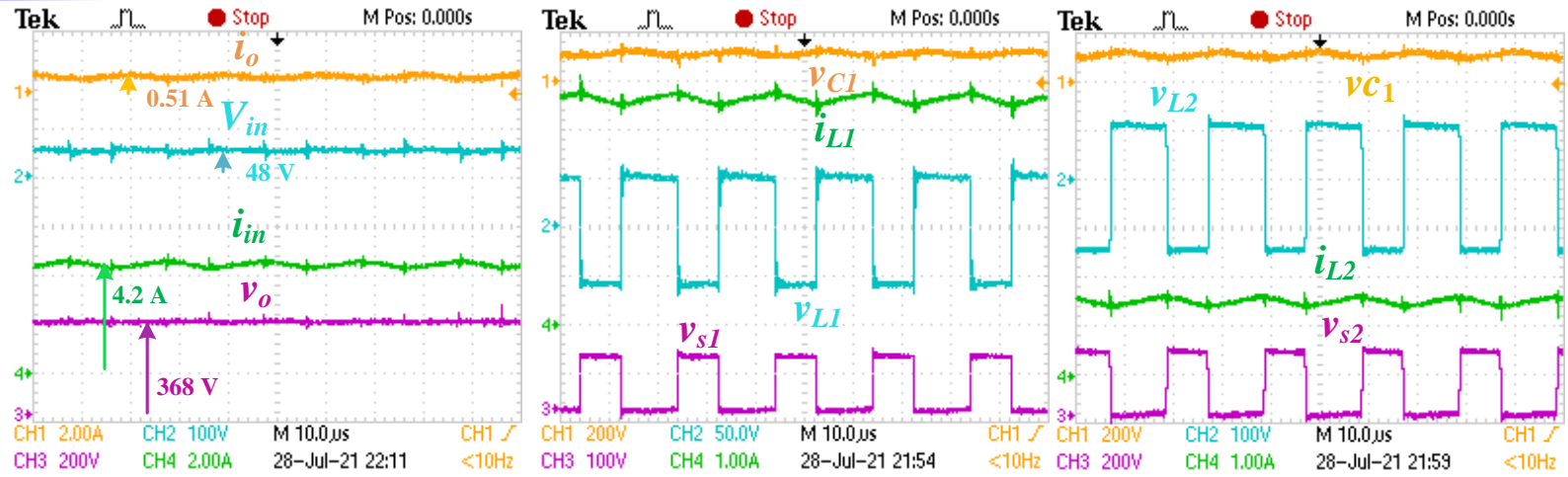
(c)



(d)

(a) Voltage gain (b) Switch current stress (c) Efficiency vs parasitic output voltage (d) Efficiency vs d

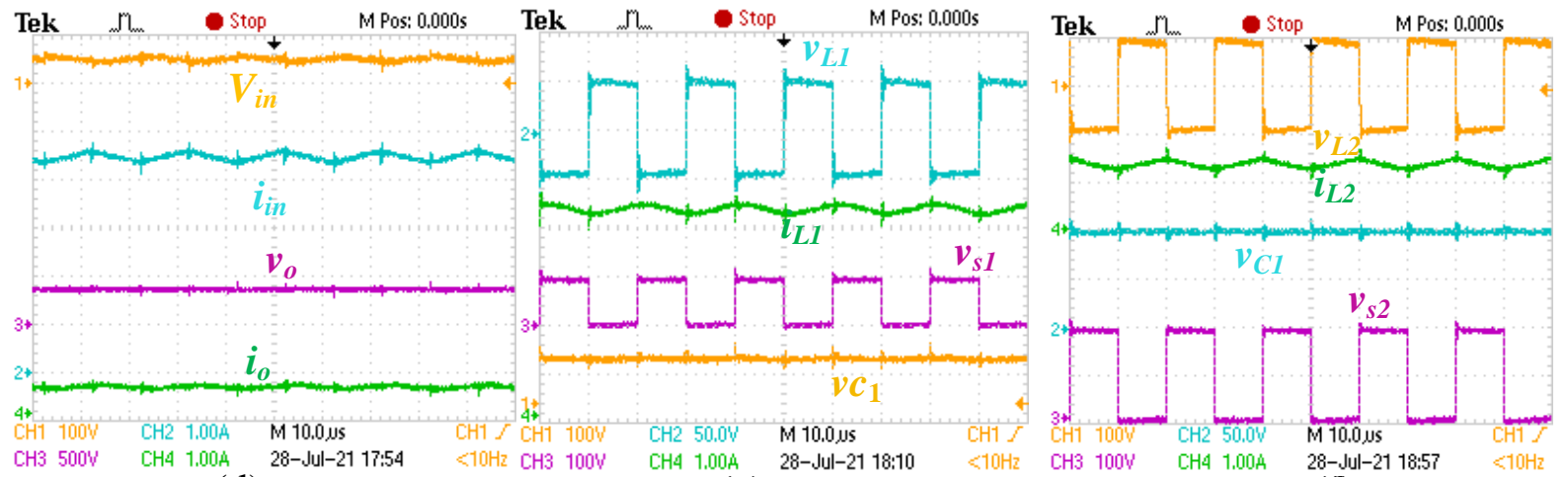
EXPERIMENTAL RESULTS-STEADY STATE



(a)

(b)

(c)



(d)

(e)

(f)

Experimental results Converter A (a) i_o , V_{in} , i_{in} , v_o (b) v_{C1} , i_{L1} , v_{L1} , v_{sw1} (c) v_{C1} , v_{L2} , i_{L2} , v_{sw2} ; Converter B (d) V_{in} , i_{in} , v_o , i_o (e) i_{L1} , v_{L1} , v_{sw1} , v_{C1} (f) v_{L2} , i_{L2} , v_{sw2} , v_{C1}

[video](#)

DYNAMIC MODEL

Mode 1

$$\begin{aligned} v_{in} - R_{L1}i_{L1} - v_{L1} - R_{S1}i_{L1} &= 0; i_{C1} = -(i_{C2} + i_{L2}) \\ v_{C1} + R_{C1}i_{C1} - R_{S2}(i_{C2} + i_{L2}) - R_{L2}i_{L2} - v_{L2} &= 0; \\ v_{C1} + R_{C1}i_{C1} - R_{S2}(i_{C2} + i_{L2}) - v_{C2} - (R_{C2} + R_{d2})i_{C2} - v_{fd2} &= 0 \end{aligned}$$

$$\dot{x} = A_1 x + B_1 u$$

$$y = C_1 x + D_1 u$$

Mode 2

$$\begin{aligned} v_{in} - R_{L1}i_{L1} - v_{L1} - v_{fd1} - R_{d1}i_{L1} - R_{C1}(i_{L1} - i_{L2}) - v_{C1} &= 0; \\ v_{C1} + R_{C1}i_{C1} - v_{fd0} - (R_{d0} + R_{C2} + R_{L2})i_{L2} - v_{C0} - R_{C0}i_{C0} + v_{C2} - v_{L2} &= 0; \\ i_{C1} = (i_{L1} - i_{L2}); i_{C2} = -i_{L2}; i_{C3} = -i_{L2} \end{aligned}$$

$$\dot{x} = A_2 x + B_2 u$$

$$y = C_2 x + D_2 u$$

$$A_1 = \begin{bmatrix} \frac{-(R_{L1} + R_{S1})}{L_1} & 0 & 0 & 0 & 0 \\ 0 & \frac{a}{L_2 R_1} & \frac{(R_{C1} + R_{D2})}{L_2 R_1} & \frac{(R_{C1} + R_{S2})}{L_2 R_1} & 0 \\ 0 & -\frac{R_{C2} + R_{D2}}{C_1 R_1} & \frac{-1}{R_1 C_1} & \frac{1}{R_1 C_1} & 0 \\ 0 & -\frac{R_{C1} + R_{S2}}{C_2 R_1} & \frac{1}{R_1 C_2} & \frac{-1}{R_1 C_2} & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{C_0(R_0 + R_{C0})} \end{bmatrix}$$

$$A_2 = \begin{bmatrix} \frac{-(R_{L1} + R_{C1} + R_{D1})}{L_1} & \frac{R_{C1}}{L_1} & \frac{-1}{L_1} & 0 & 0 \\ \frac{R_{C1}}{L_2} & \frac{b}{L_2} & \frac{1}{L_2} & \frac{1}{L_2} & \frac{-R_0}{L_2(R_0 + R_{C0})} \\ \frac{1}{C_1} & -\frac{1}{C_1} & 0 & 0 & 0 \\ 0 & -\frac{1}{C_2} & 0 & 0 & 0 \\ 0 & \frac{R_0}{C_0(R_0 + R_{C0})} & 0 & 0 & \frac{-1}{C_0(R_0 + R_{C0})} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \frac{1}{L_1} & 0 & 0 & 0 \\ 0 & 0 & \frac{-(R_{C1} + R_{S2})}{L_2 R_1} & 0 \\ 0 & 0 & \frac{1}{R_1 C_1} & 0 \\ 0 & 0 & \frac{-1}{R_1 C_2} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}; B_2 = \begin{bmatrix} \frac{1}{L_1} & -\frac{1}{L_1} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{L_2} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{R_0}{(R_0 + R_{C0})} \end{bmatrix};$$

$$C_2 = \begin{bmatrix} 0 & \frac{R_0 R_{C0}}{R_0 + R_{C0}} & 0 & 0 & \frac{R_0}{(R_0 + R_{C0})} \end{bmatrix}$$

$$a = (R_{C1} + R_{S2})^2 - (R_{C1} + R_{S2} + R_{L2}) R_1; b = R_2 + R_0 R_{C0} / (R_0 + R_{C0}).$$

DYNAMIC MODEL

Converter-A

$$\begin{bmatrix} \dot{\hat{i}}_{L1} \\ \dot{\hat{i}}_{L2} \\ \dot{\hat{v}}_{C1} \\ \dot{\hat{v}}_{C2} \\ \dot{\hat{v}}_{C0} \end{bmatrix} = \begin{bmatrix} \frac{-R_B}{L_1} & \frac{R_{C1}(1-D)}{L_1} & \frac{-(1-D)}{L_1} & 0 & 0 \\ \frac{R_{C1}(1-D)}{L_1} & \frac{R_A + R_1 R_C}{L_1} & \frac{R_D}{L_1} & \frac{R_E}{L_1} & \frac{-R_0(1-D)}{L_1} \\ \frac{L_2}{R_{C1}(1-D)} & \frac{L_2}{R_A + R_1 R_C} & \frac{L_2 R_1}{L_1} & \frac{L_2 R_1}{L_1} & \frac{L_2(R_0 + R_{C0})}{L_1} \\ \frac{\hat{v}_0(s)}{\hat{d}(s)} \Big|_{Conv.A} & = & \frac{0.5784s^5 - 7.225 \times 10^4 s^4 + 1.07 \times 10^9 s^3 + 6.489 \times 10^{13} s^2 - 3.01 \times 10^{16} s + 2.576 \times 10^{20}}{s^5 + 5.691 \times 10^4 s^4 + 5.183 \times 10^7 s^3 + 8.896 \times 10^{11} s^2 + 2.908 \times 10^{14} s + 2.473 \times 10^{17}} \\ \frac{\hat{v}_0(s)}{\hat{v}_{in}(s)} \Big|_{Conv.A} & = & \frac{-0.4794s^4 - 3.295 \times 10^4 s^3 + 9.568 \times 10^8 s^2 - 6.118 \times 10^{11} s + 5.332 \times 10^{15}}{s^4 + 847.3s^3 + 2.027 \times 10^7 s^2 + 8.042 \times 10^9 s + 5.924 \times 10^{12}} \\ \frac{\hat{v}_{in}(s)}{\hat{v}_{in}(s)} \Big|_{Conv.A} & = & \frac{5614s^3 + 1.166 \times 10^9 s^2 + 8.008 \times 10^{13} s + 1.86 \times 10^{18}}{s^5 + 5.691 \times 10^4 s^4 + 5.183 \times 10^7 s^3 + 8.896 \times 10^{11} s^2 + 2.908 \times 10^{14} s + 2.473 \times 10^{17}} \end{bmatrix} \begin{bmatrix} \hat{i}_{L1} \\ \hat{i}_{L2} \\ \hat{v}_{C1} \\ \hat{v}_{C2} \\ \hat{v}_{C0} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} & u \\ 0 & v_{in} \\ 0 & y \\ 0 & z \\ -1 & 0 \end{bmatrix}$$

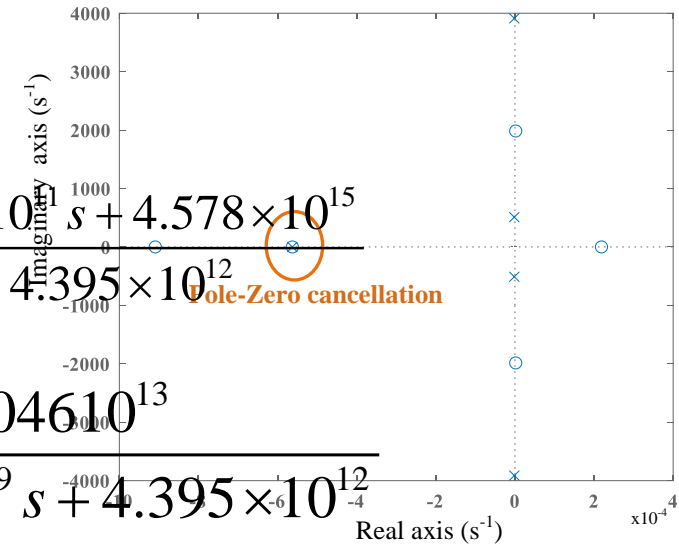
Converter-B

$$y = \frac{R_1 I_{L1} - (R_{C1} + R_{S2} - R_1) I_{L2} + V_{C1} - V_{C2} + v_{fd2}}{R_0 + R_{C0}} ; z = \frac{-R_0 I_{L2}}{R_0 + R_{C0}}$$

$$u = \frac{\hat{v}_0(s)}{\hat{d}(s)} \Big|_{Conv.A} = \frac{0.5784s^5 - 7.225 \times 10^4 s^4 + 1.07 \times 10^9 s^3 + 6.489 \times 10^{13} s^2 - 3.01 \times 10^{16} s + 2.576 \times 10^{20}}{s^5 + 5.691 \times 10^4 s^4 + 5.183 \times 10^7 s^3 + 8.896 \times 10^{11} s^2 + 2.908 \times 10^{14} s + 2.473 \times 10^{17}}$$

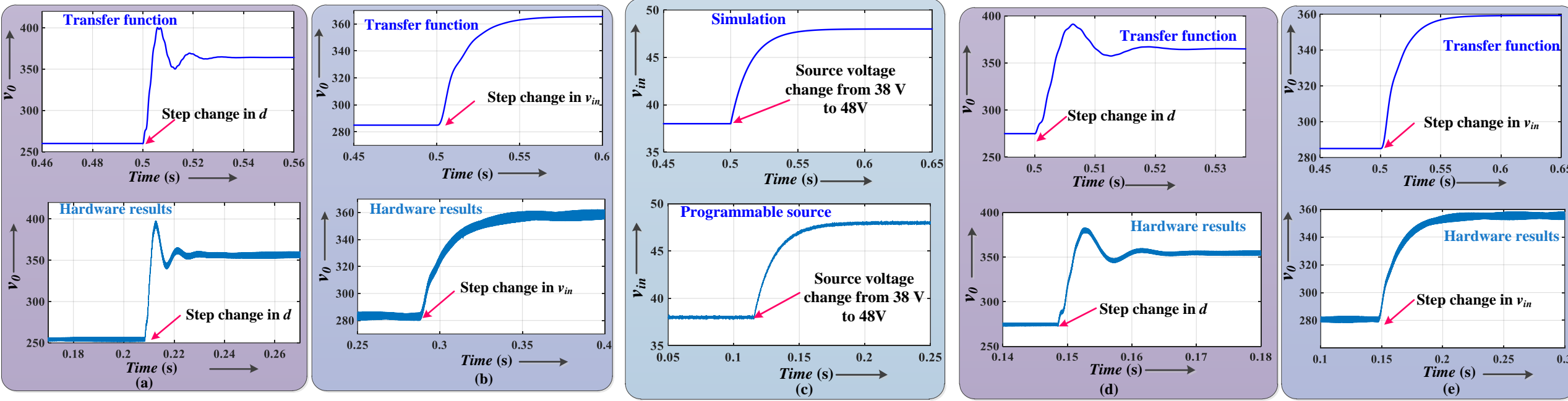
$$v = \frac{-R_{C1} I_{L1} + (R_3 - R_1) R_2 - \frac{R_1 R_{C0}}{R_0 + R_{C0}} I_{L2} + (R_{C2} + R_{D2} - R_1) V_{C1} + (R_{C1} + R_{S2} - R_1) V_{C2} + \frac{R_1 R_{C0}}{R_0 + R_{C0}} V_{C0} - (R_{C1} + R_{S3}) v_{fd2} + R_1 v_{fd0}}{L_2 R_1} = \frac{-0.4794s^4 - 3.295 \times 10^4 s^3 + 9.568 \times 10^8 s^2 - 6.118 \times 10^{11} s + 5.332 \times 10^{15}}{s^4 + 847.3s^3 + 2.027 \times 10^7 s^2 + 8.042 \times 10^9 s + 5.924 \times 10^{12}}$$

$$\hat{v}_0 = \begin{bmatrix} \hat{v}_0(s) \\ \hat{v}_{in}(s) \\ 0 \\ \hat{v}_{in}(s) \\ \hat{v}_{C0} \end{bmatrix} = \begin{bmatrix} \frac{\hat{v}_0(s)}{\hat{v}_{in}(s)} \Big|_{Conv.A} \\ \frac{\hat{v}_0(s)}{\hat{v}_{in}(s)} \Big|_{Conv.B} \\ 0 \\ \frac{\hat{v}_0(s)}{\hat{v}_{in}(s)} \Big|_{Conv.A} \\ \frac{\hat{v}_0(s)}{\hat{v}_{in}(s)} \Big|_{Conv.B} \end{bmatrix} = \begin{bmatrix} \frac{0.5784s^5 - 7.225 \times 10^4 s^4 + 1.07 \times 10^9 s^3 + 6.489 \times 10^{13} s^2 - 3.01 \times 10^{16} s + 2.576 \times 10^{20}}{s^5 + 5.691 \times 10^4 s^4 + 5.183 \times 10^7 s^3 + 8.896 \times 10^{11} s^2 + 2.908 \times 10^{14} s + 2.473 \times 10^{17}} \\ \frac{-0.4794s^4 - 3.295 \times 10^4 s^3 + 9.568 \times 10^8 s^2 - 6.118 \times 10^{11} s + 5.332 \times 10^{15}}{s^4 + 847.3s^3 + 2.027 \times 10^7 s^2 + 8.042 \times 10^9 s + 5.924 \times 10^{12}} \\ 0 \\ \frac{0.5784s^5 - 7.225 \times 10^4 s^4 + 1.07 \times 10^9 s^3 + 6.489 \times 10^{13} s^2 - 3.01 \times 10^{16} s + 2.576 \times 10^{20}}{s^5 + 5.691 \times 10^4 s^4 + 5.183 \times 10^7 s^3 + 8.896 \times 10^{11} s^2 + 2.908 \times 10^{14} s + 2.473 \times 10^{17}} \\ \frac{-0.4794s^4 - 3.295 \times 10^4 s^3 + 9.568 \times 10^8 s^2 - 6.118 \times 10^{11} s + 5.332 \times 10^{15}}{s^4 + 847.3s^3 + 2.027 \times 10^7 s^2 + 8.042 \times 10^9 s + 5.924 \times 10^{12}} \end{bmatrix}$$



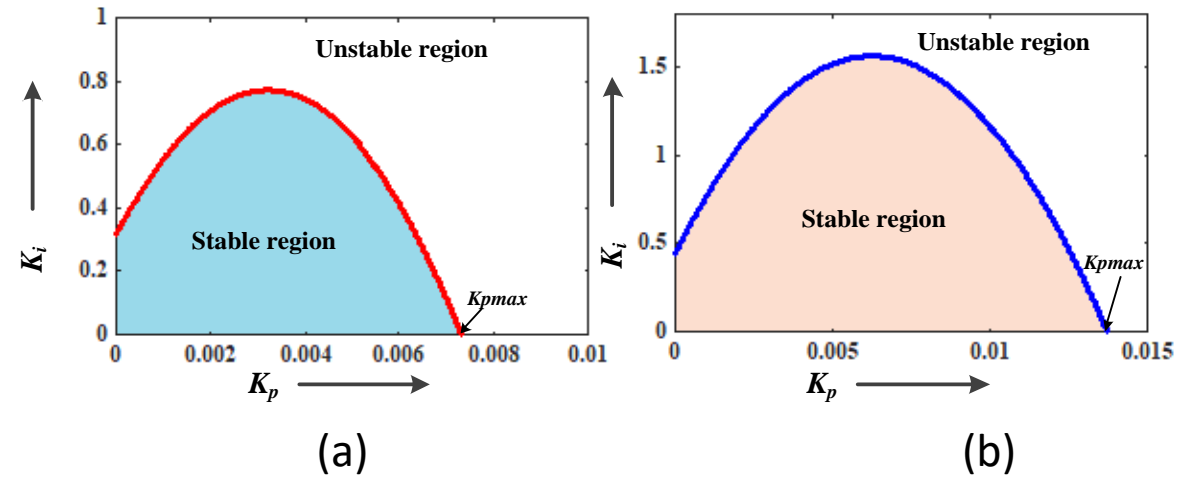
Pole-zero plot

HARDWARE VALIDATION OF SMALL-SIGNAL MODEL

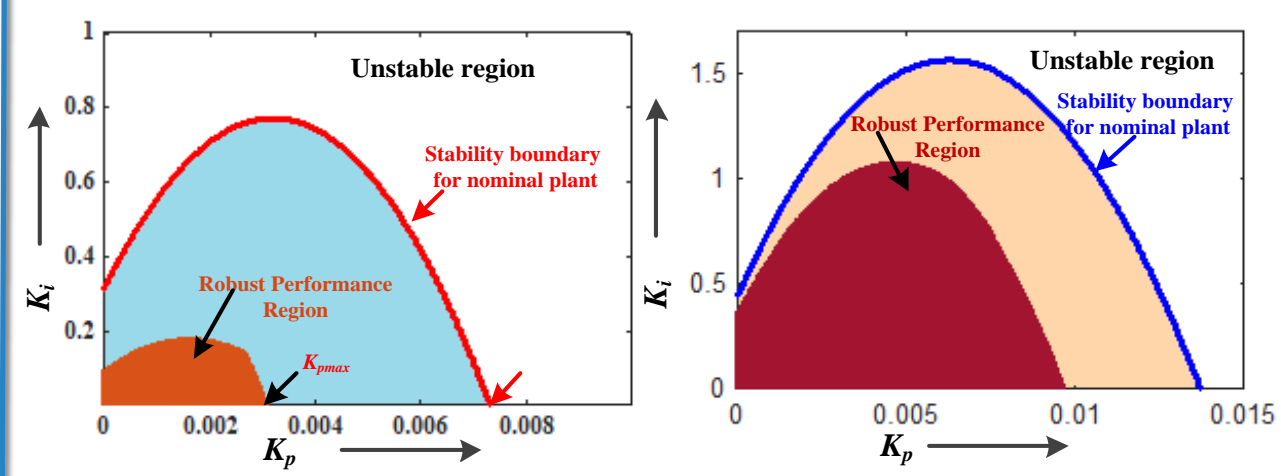


Dynamic validation (a) Step change in d for converter A (b) Step change in v_{in} for converter A (c) source voltage change (d) Step change in d for converter B (e) Step change in v_{in} for converter B

CONTROLLER DESIGN

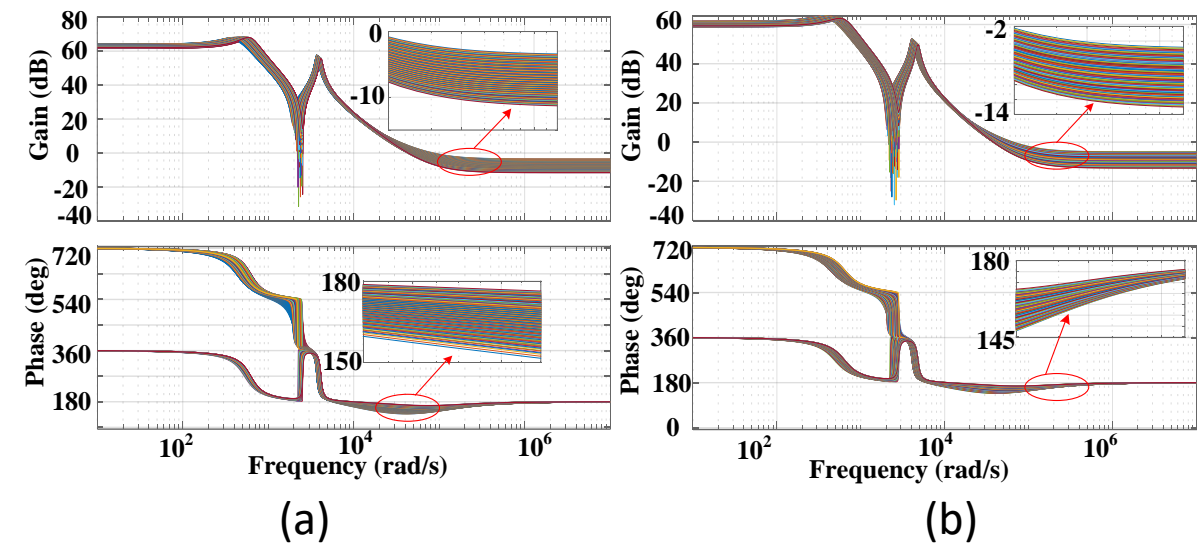


Stability boundary locus for (a) Converter A (b) Converter B

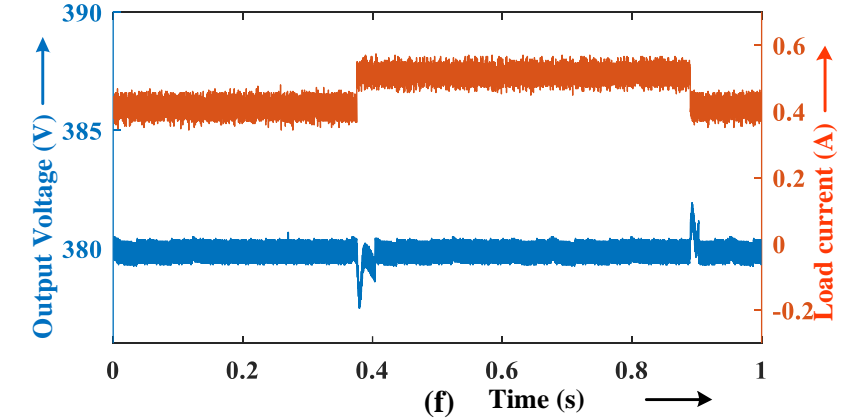
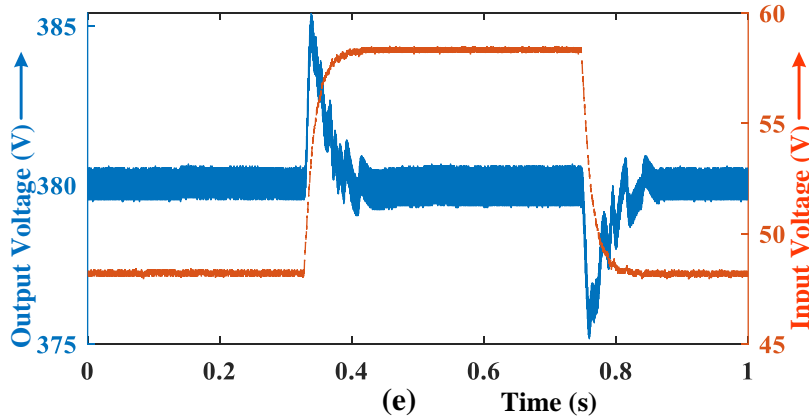
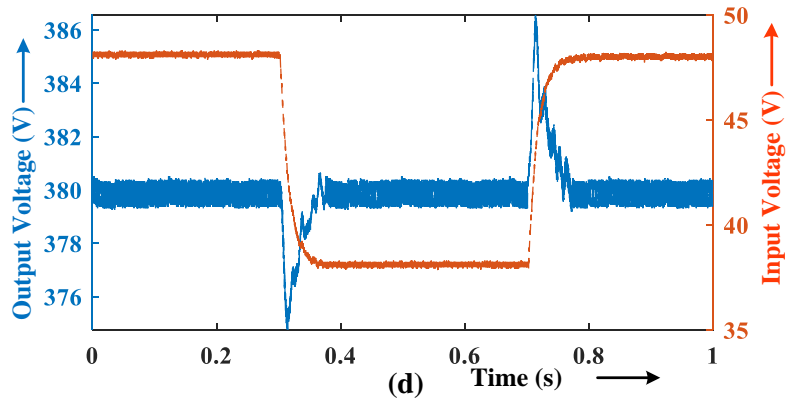
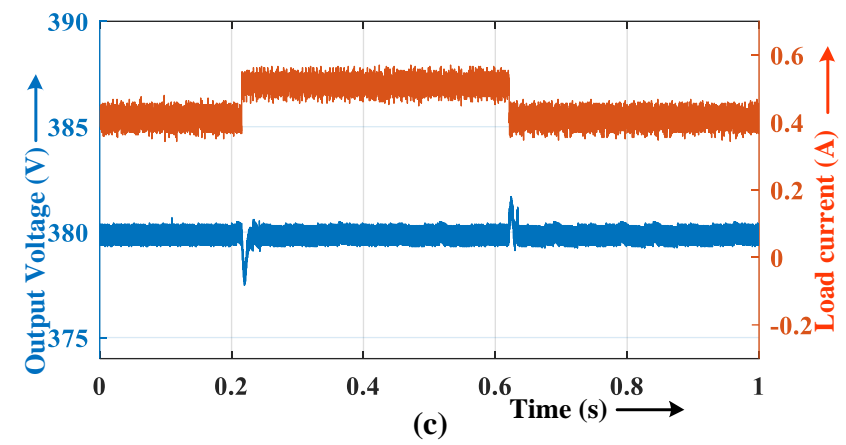
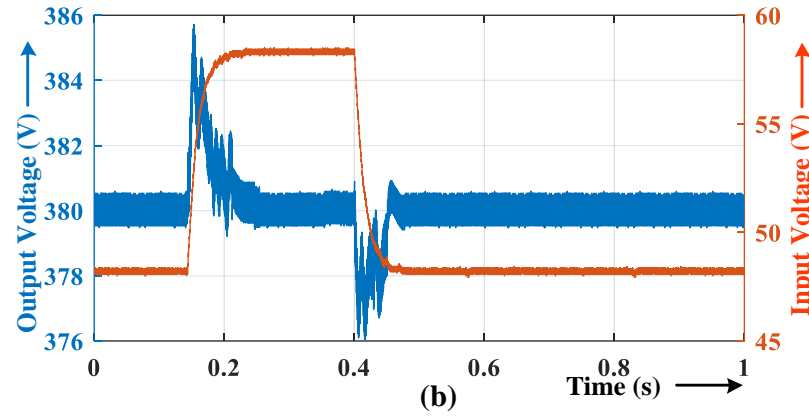
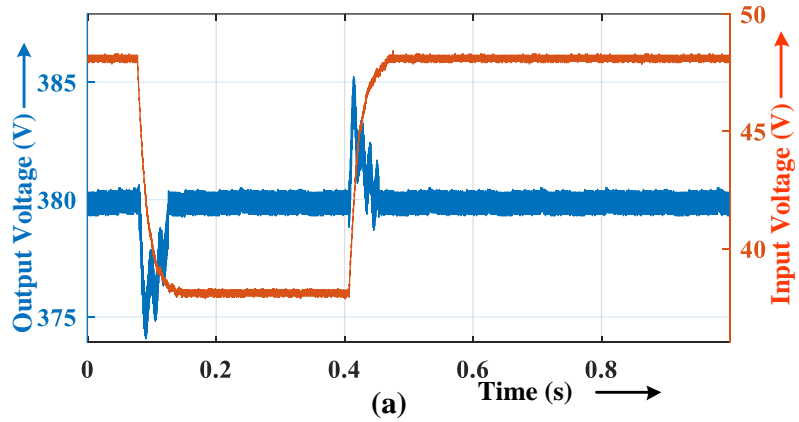


Stability boundary locus for (a) Converter A (b) Converter B

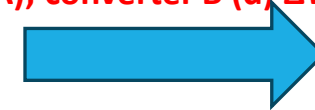
$K_p = 0.0024$ and $K_i = 0.15$ for the converter A,
 $K_p = 0.008$ and $K_i = 0.456$ for the converter B.



Frequency response (a) Converter A (b) Converter B



Closed-loop results; converter A (a) ΔV_{in} (48V-38V-48V) (b) ΔV_{in} (48V-58V-48V) (c) ΔI_o (0.395A-0.495A-0.395A); converter B (d) ΔV_{in} (48V-38V-48V) (e) ΔV_{in} (48V-58V-48V) (f) ΔI_o (0.395A-0.495A-0.395A)



SUMMARY

- Two high gain multistage non-isolated converter topologies were proposed
- Hardware prototypes of both converters were fabricated for 200 W, 380 V, 50 kHz with 48 V input.
- The experimental efficiency is 93.4% and 94.3% for the converters A and B, respectively.
- Compared to the conventional converters, the input current is continuous with low ripple content, reduced switch current stress and requires lower component count to extend the converter structure to next stage.
- The dynamic model of the converter was derived and the transfer functions \hat{v}_o / \hat{v}_{in} and \hat{v}_o / \hat{d} were obtained.
- The dynamic response of the transfer functions was validated experimentally.
- A PI controller for the closed-loop operation was designed using stability boundary locus approach and Kharitonov's theorem and is implemented in Zynq 7000 FPGA controller.

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Thank You