Non-isolated Multiport DC/DC Converters: Applications, Challenges and Solutions

Professor Dylan Lu and Dr Hamzeh Aljarajreh

School of Electrical and Data Engineering
Faculty of Engineering and IT
University of Technology Sydney, Australia

Research Team and Acknowledgement

Prof Dylan Lu
PhD (HKPU). Head of Discipline of Electrical Power and Energy Systems, School of Electrical and Data Engineering, FEIT, UTS

Dr Hamzeh Aljarajreh
PhD (University of Technology Sydney)
Casual academic at the School of Electrical and Data Engineering, FEIT, UTS

Dr John Long Soon
PhD (The University of Sydney). Lead Power Electronics Engineer at ION Mobility Pty. Ltd., Singapore.

Miss Tian Cheng
PhD candidate at UTS on the reliability of power electronics devices and circuits

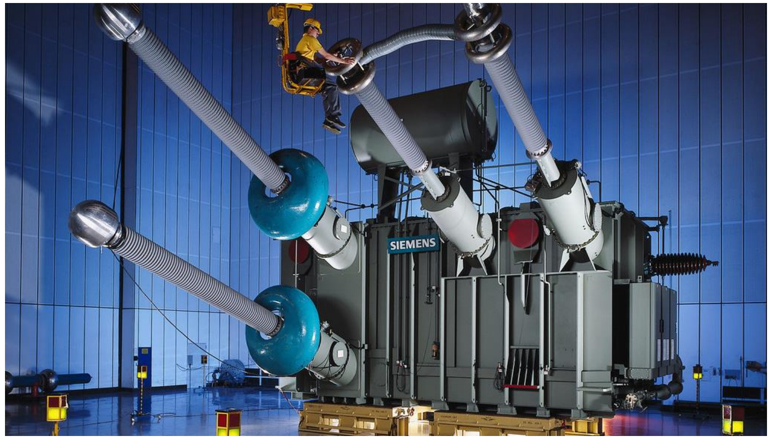
Mr Muhammad Mubashir Alam
PhD candidate at UTS on control and reliability of three-port dc/dc converters

Content

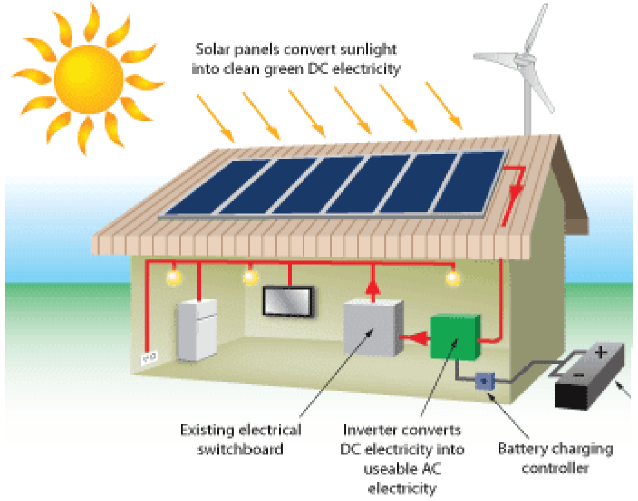
- Background
- Existing and Future Applications of Multiport Converters (MPCs)
- Major Challenges with MPCs and Some Solutions
- Tool to Derive and Develop MPC Topologies
- Reliability and Fault-tolerant Operations of MPCs
- Conclusion

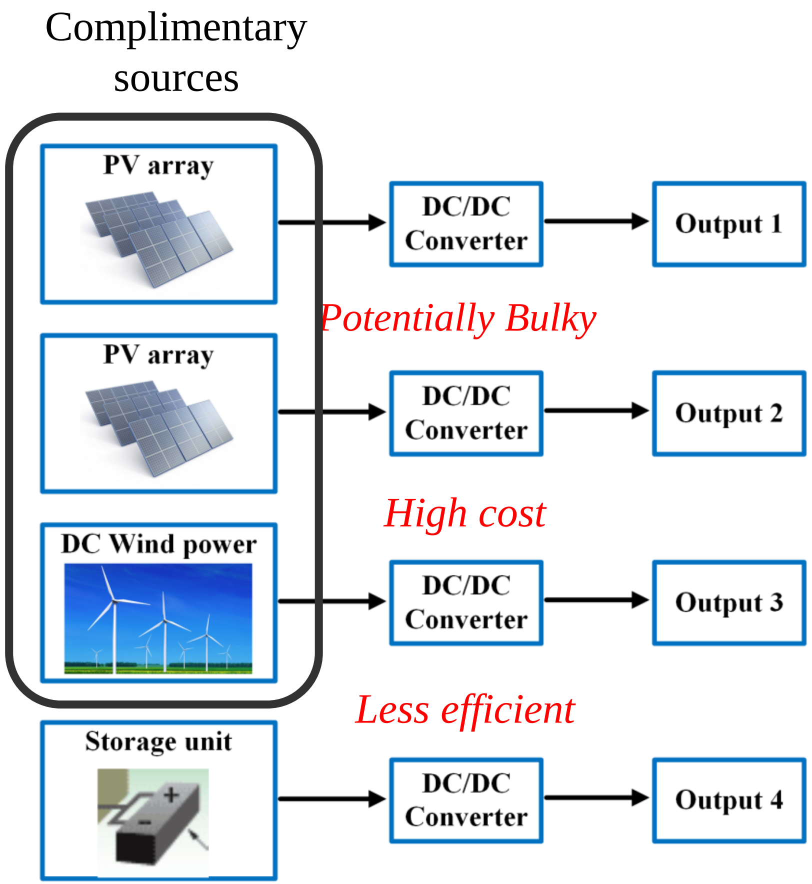
- Existing and Future Applications of Multiport Converters (MPCs)
- Major Challenges with MPCs and Some Solutions
- Tool to Derive and Develop MPC Topologies
- Reliability and Fault-tolerant Operations of MPCs

Power Electronics is Everywhere!

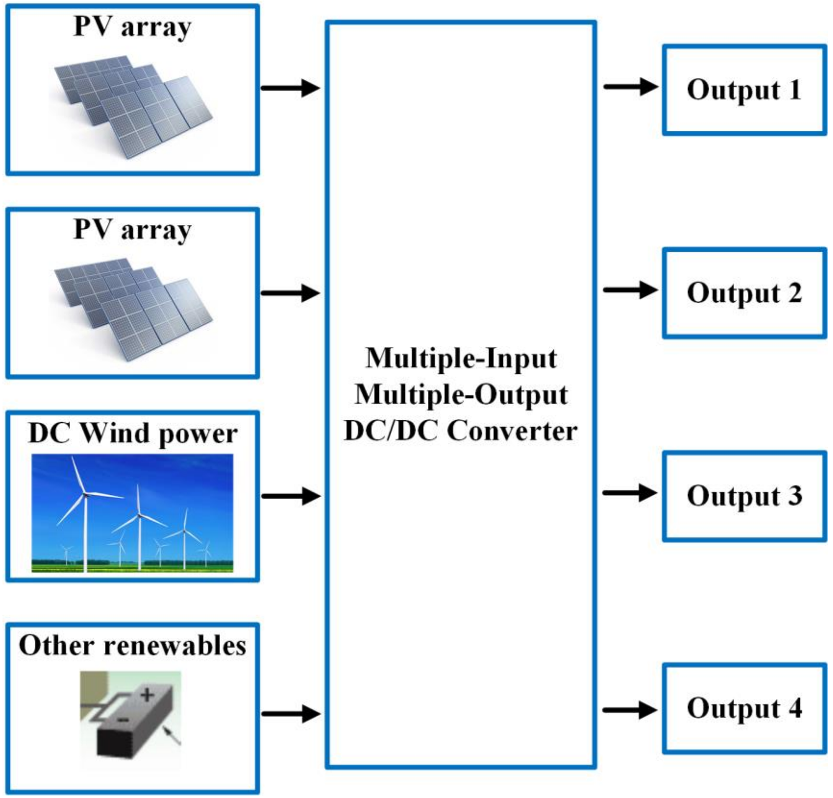


Existing Application of Multiport Converters





- ✓ *Size reduced up to 30%*
- ✓ *Cost reduced by 20-40%*
- ✓ *Better controllability*



Existing and Future Applications of Multiport Converters (MPCs)

Major Challenges with MPCs and Some Solutions

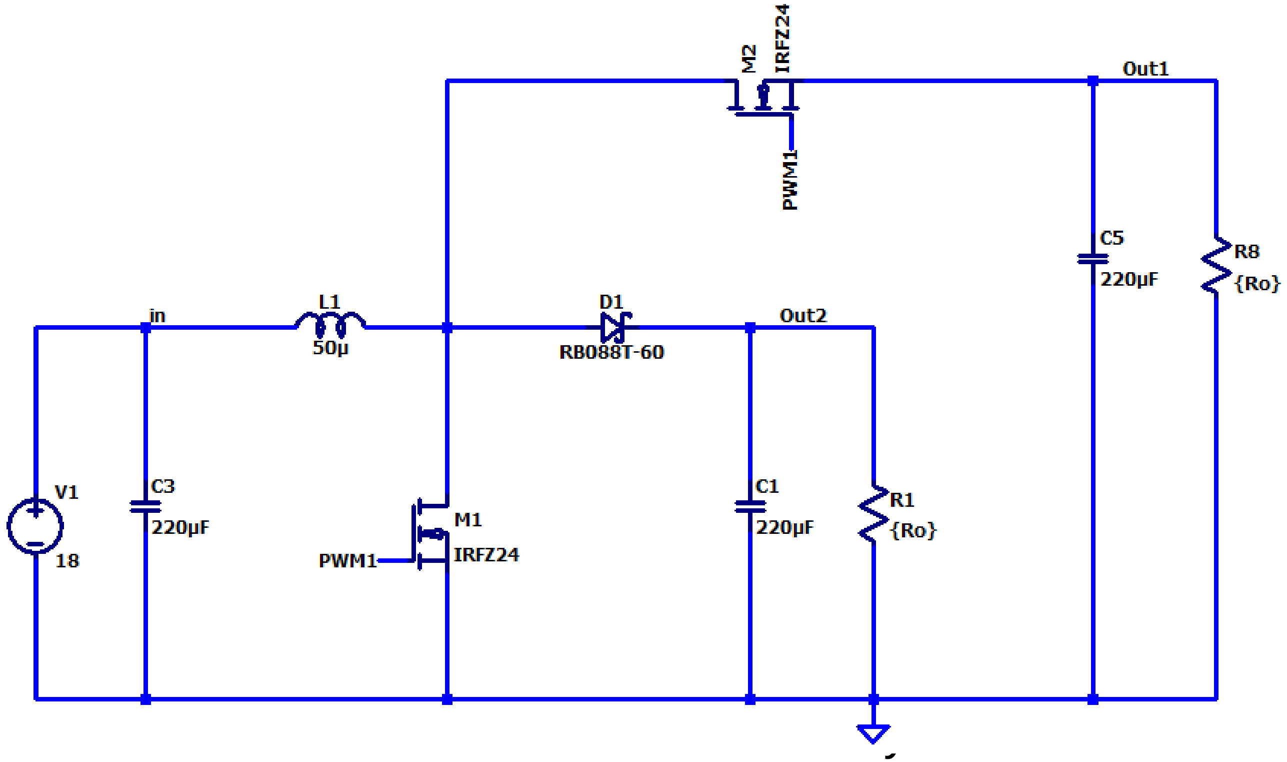
Tool to Derive and Develop MPC Topologies

Reliability and Fault-tolerant Operations of MPCs

MPC Challenge #1

Power-sharing and Cross-regulation Issues and Some Solutions

Problem Definition



A single-input dual-output boost converter
Single-input dual-output flyback converter

- What are cross-regulation and power-sharing issues?
- Issue does not exist in SISO converter-based MPCs
- Different perspectives of cross-regulation in non-isolated and isolated converters

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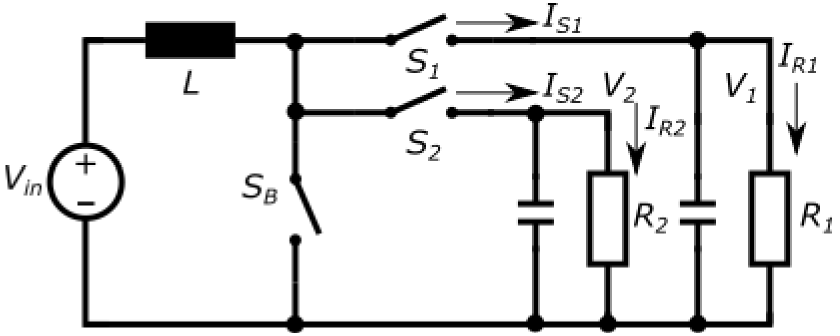
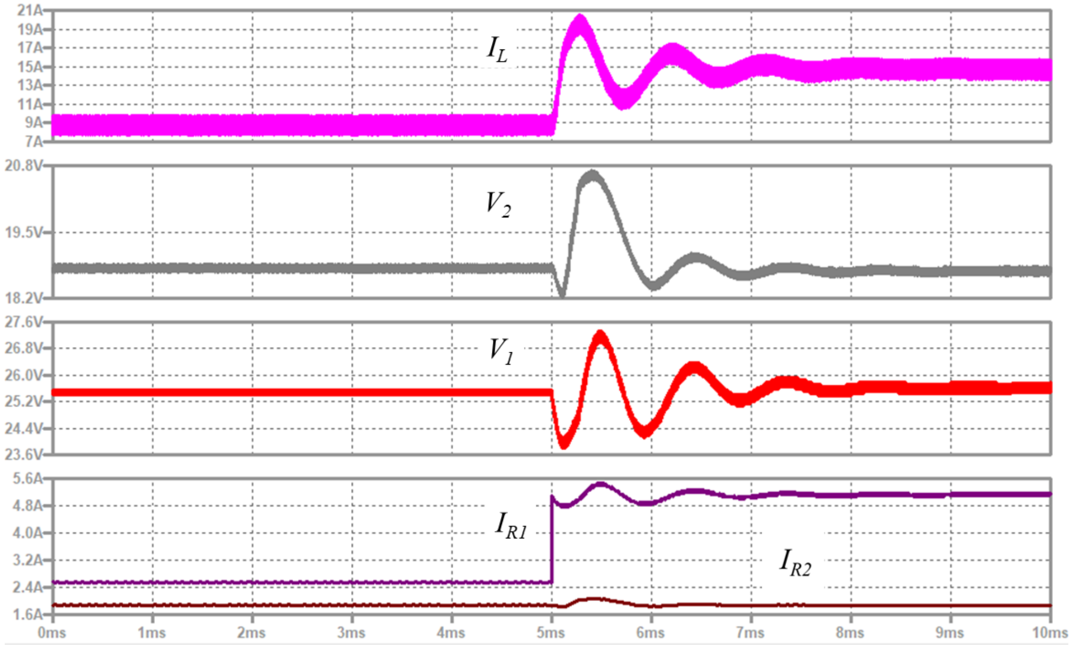
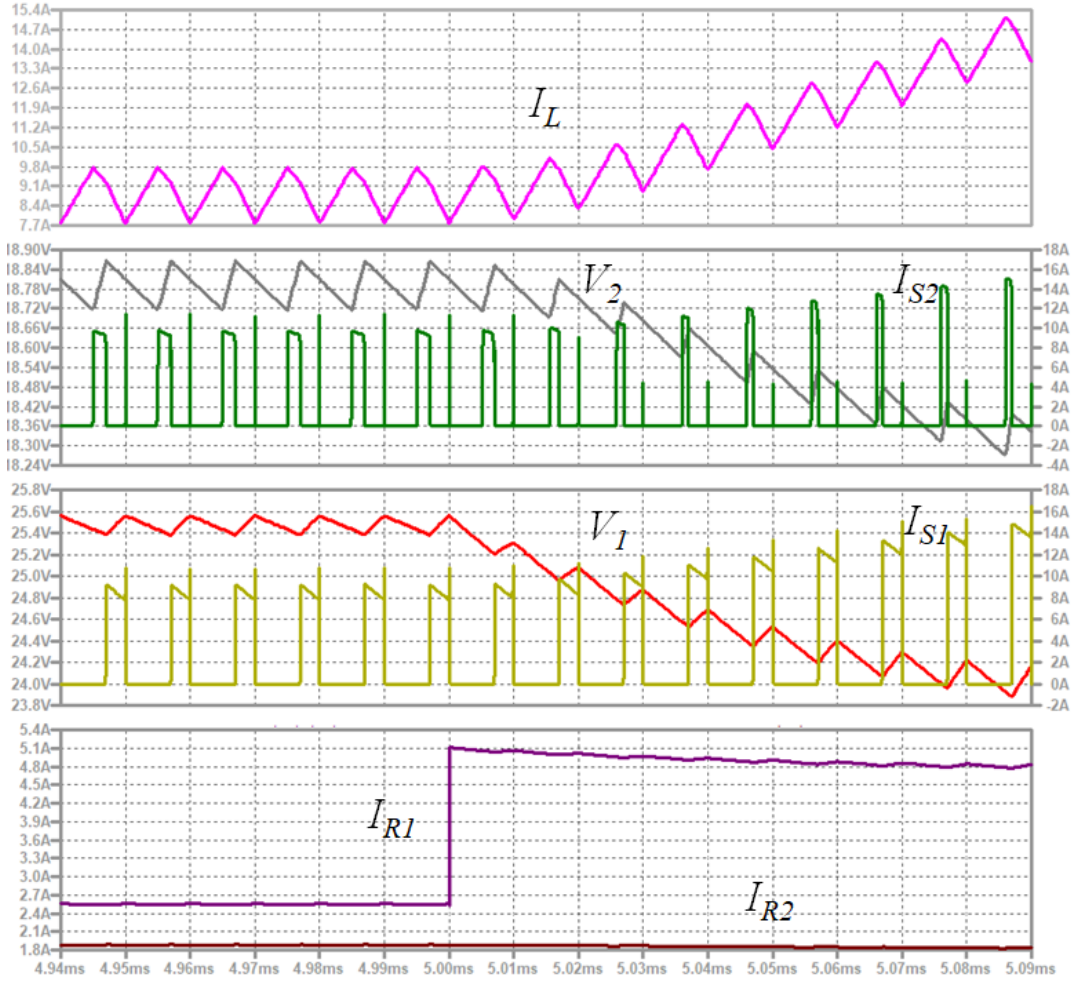
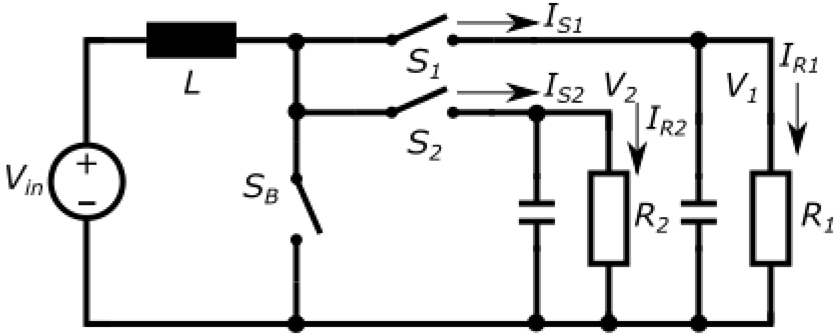
Cross Regulation in Non-isolated SIDO Converter

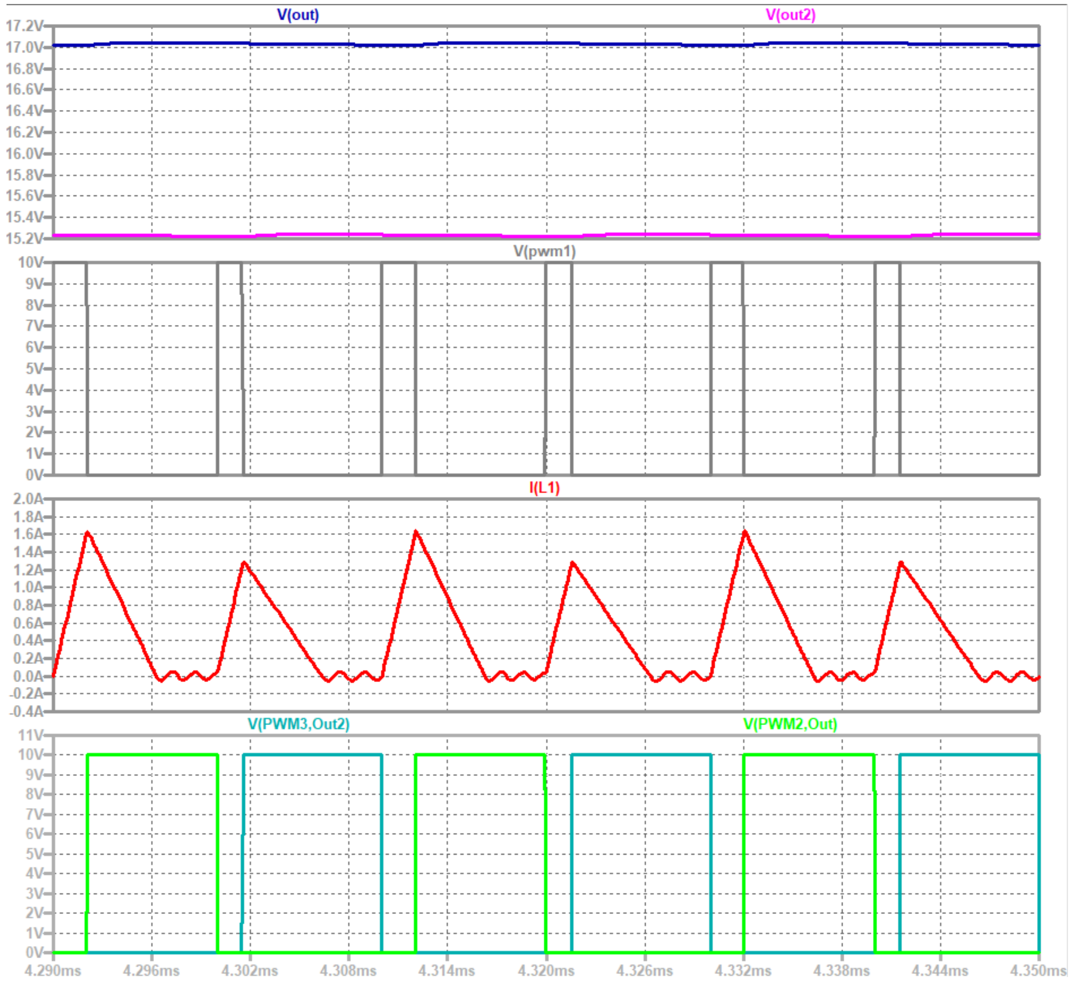






Solution #1: Discontinuous Conduction Mode (DCM) Operation

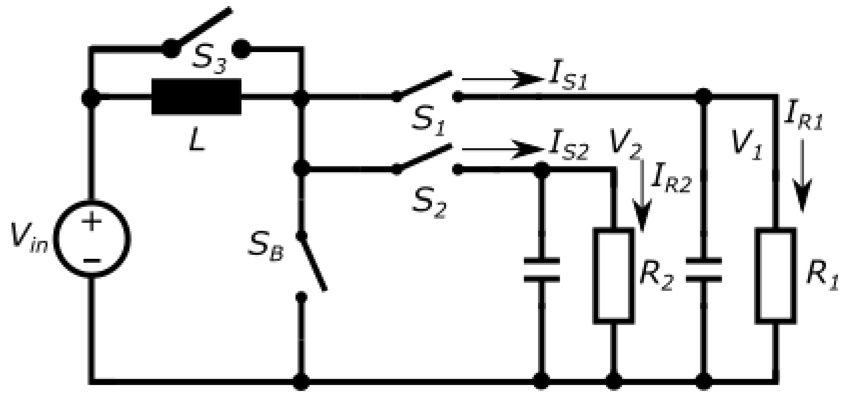


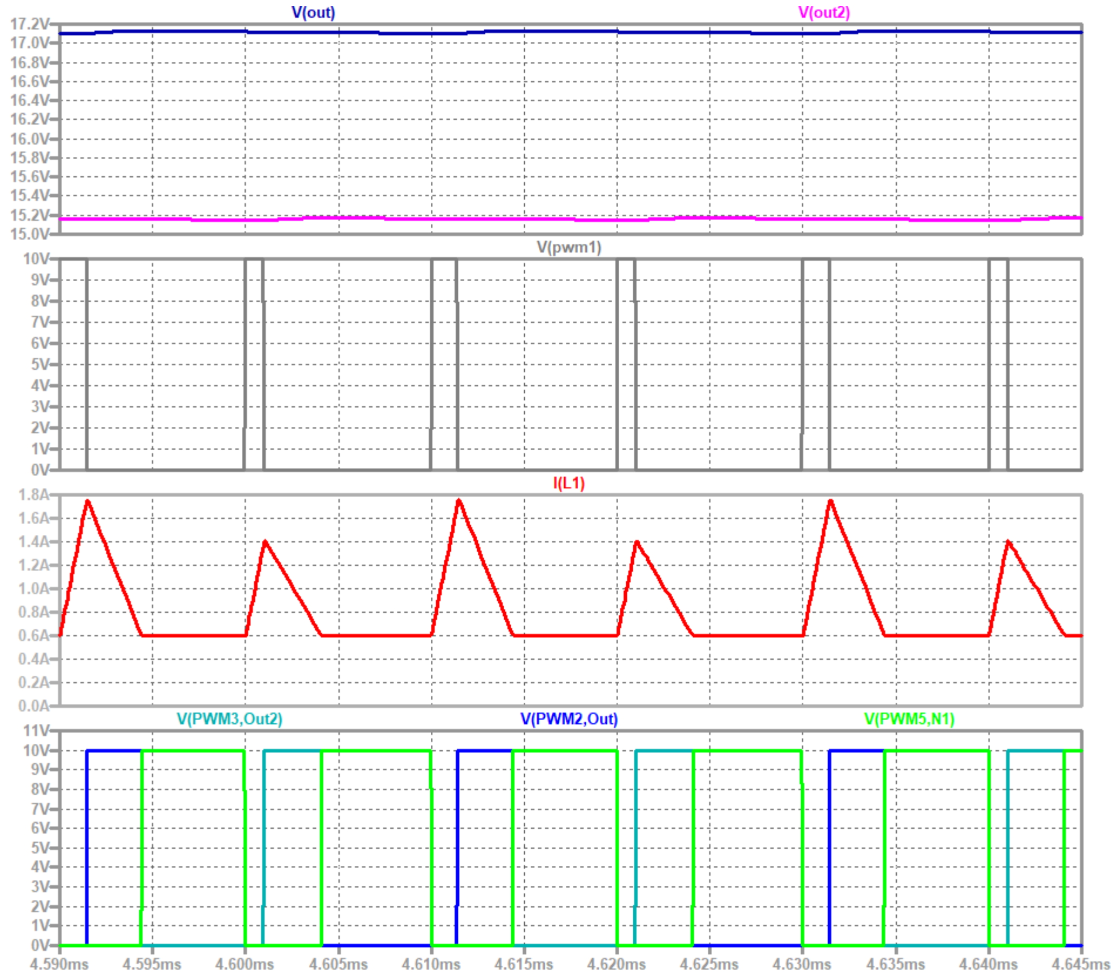


- Each switching cycle corresponds to one output regulation
- Current reset to decouple
- High RMS current in heavy loading condition
- Increasing filtering requirement with more outputs

D. Ma, W.-H. Ki, C.-Y. Tsui, and P. Mok, “Single-inductor multiple-output switching converters with time-multiplexing control in discontinuous conduction mode,” *IEEE Journal of Solid-State Circuits*, vol. 38, no. 1, pp. 89–100, Jan 2003

Solution #2: Pseudo DCM/CCM Operation

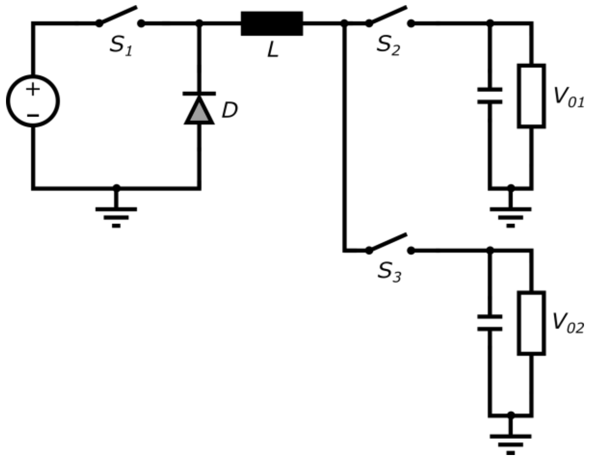


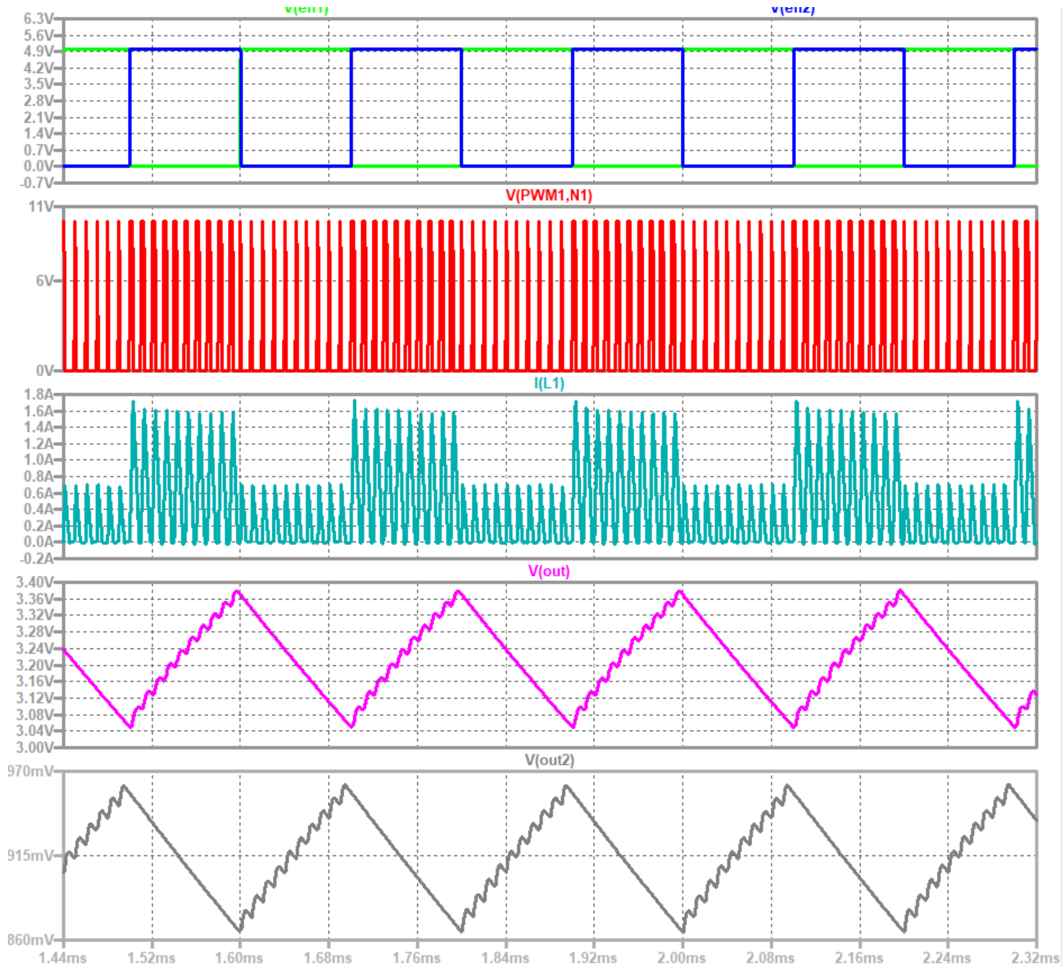


- Each switching cycle corresponds to one output regulation
- Current reset at a constant value
- Lower RMS current?
- Increasing filtering requirement with more outputs

D. Ma, W.-H. Ki, and C.-Y. Tsui, "A pseudo-CCM/DCM SIMO switching converter with freewheel switching," *IEEE Journal of Solid-State Circuits*, vol. 38, no. 6, pp. 1007–1014, June 2003.

Solution #3: Slower Time-Multiplexing Method



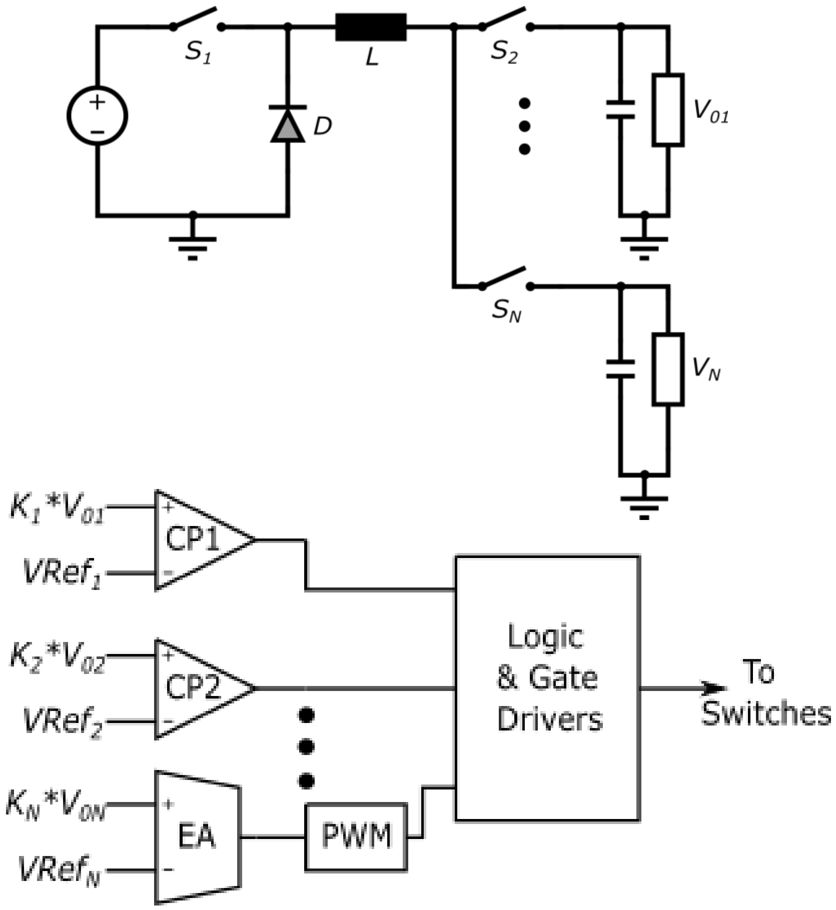


- Each switching cycle corresponds to one output regulation (hysteretic)
- Current reset at zero inductor current
- Increasing filtering requirement with more outputs

W. Huang, J. A. A. Qahouq, and Z. Dang, "CCM–DCM Power-Multiplexed Control Scheme for Single-Inductor Multiple-Output DC–DC Power Converter With No Cross Regulation," *IEEE Transactions on Industry Applications*, vol. 53, no. 2, pp. 1219–1231, March 2017

Solution #4: Orderly Power Distribution Control (OPDC)

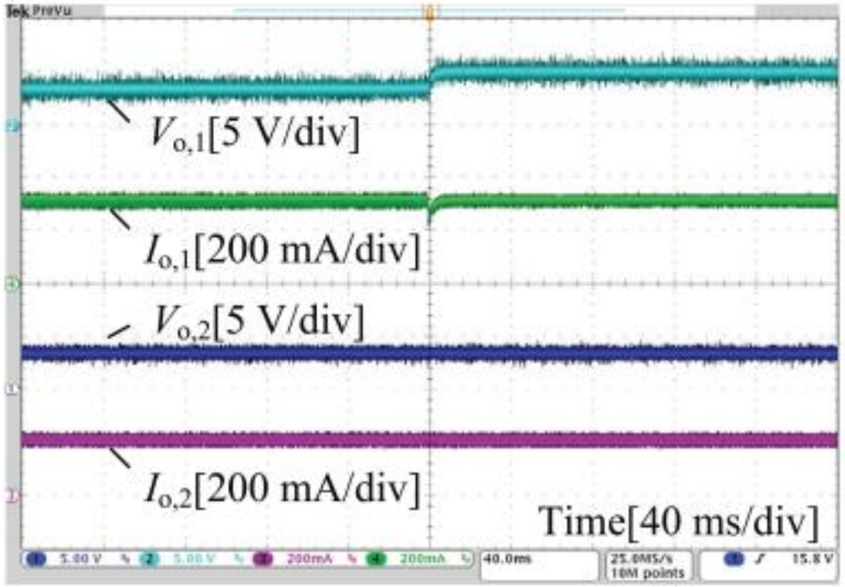
- All outputs are engaged for each switching period
- All outputs are regulated through a comparator except for the last output, which is regulated through a compensated PI controller
- Variations of control methods to improve conversion efficiency and dynamic responses

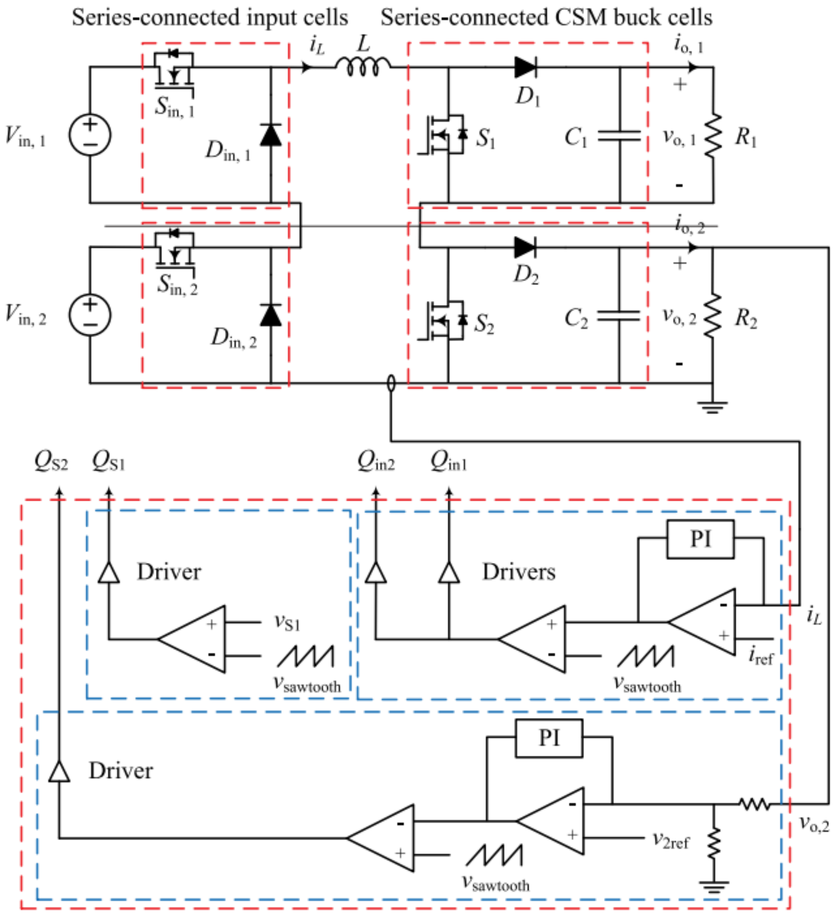


H.-P. Le, C.-S. Chae, K.-C. Lee, S.-W. Wang, G.-H. Cho, and G.-H. Cho, “A single-inductor switching dc–dc converter with five outputs and ordered power-distributive control,” *IEEE Journal of Solid-State Circuits*, vol. 42, no. 12, pp. 2706–2714, 2007

Solution #5: Current Converter Mode Operation

- Duality principle of voltage converter mode
- Constant inductor current for output regulation

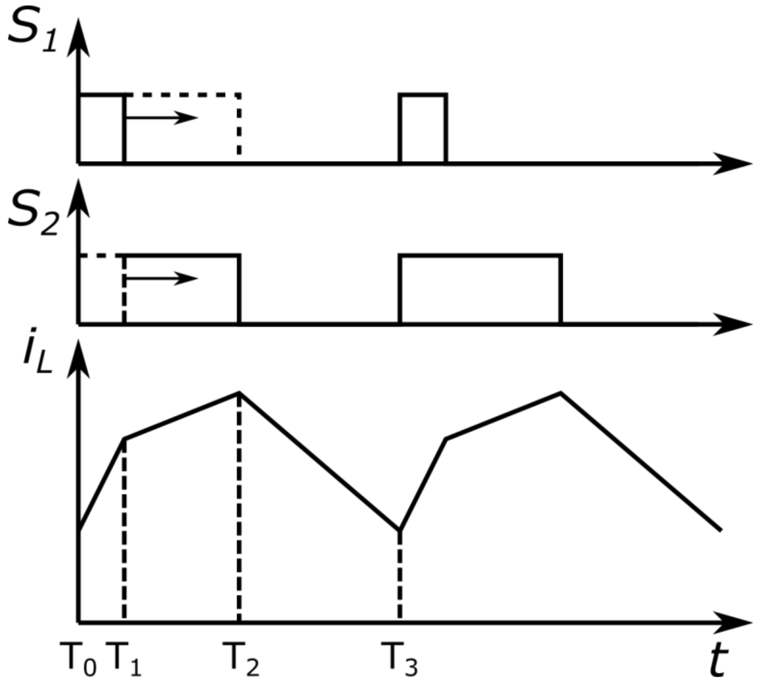


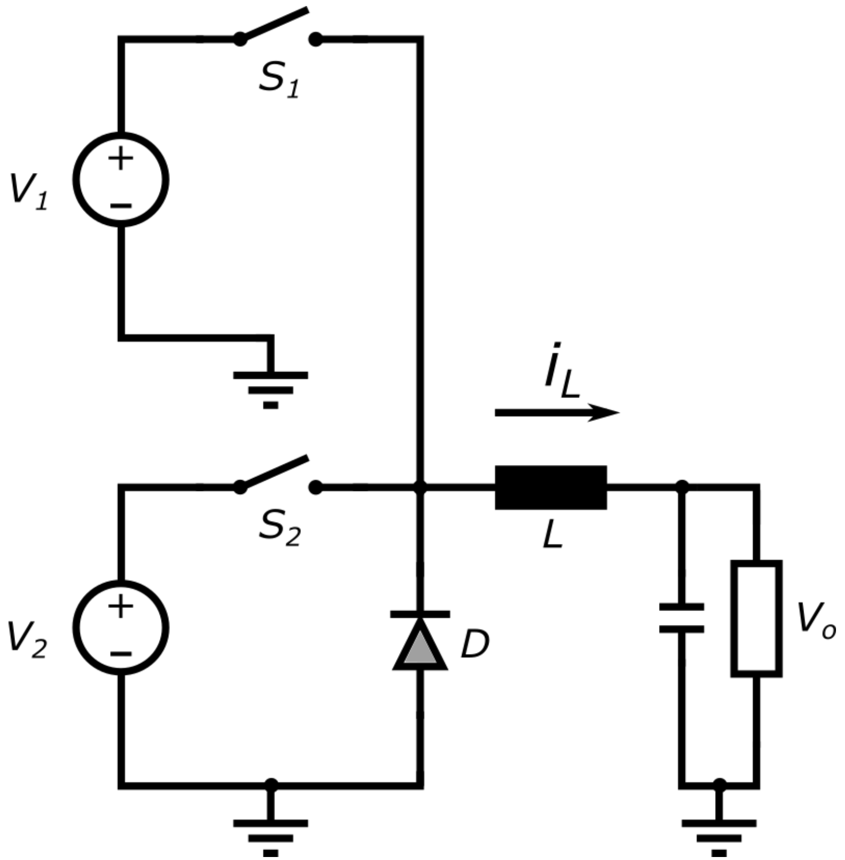


X. L. Li, Z. Dong, C. K. Tse and D. D. -C. Lu, "Single-Inductor Multi-Input Multi-Output DC–DC Converter With High Flexibility and Simple Control," *in IEEE Transactions on Power Electronics*, vol. 35, no. 12, pp. 13104-13114, Dec. 2020, doi: 10.1109/TPEL.2020.2991353.

Power Sharing Problem in MISO Converter

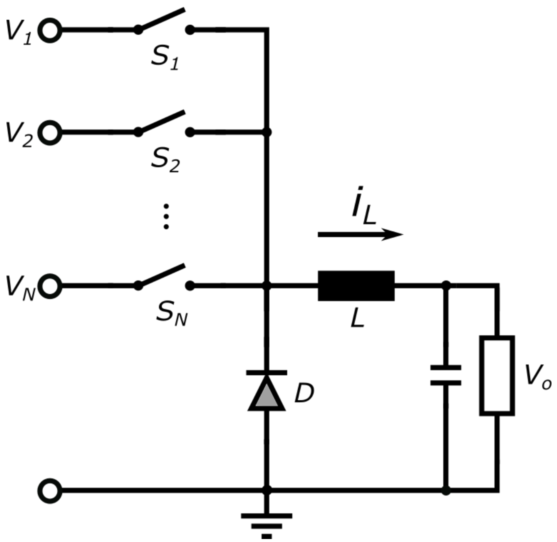
- Highly coupled, influencing both inputs and output
- State undetermined if the two input voltages are equal

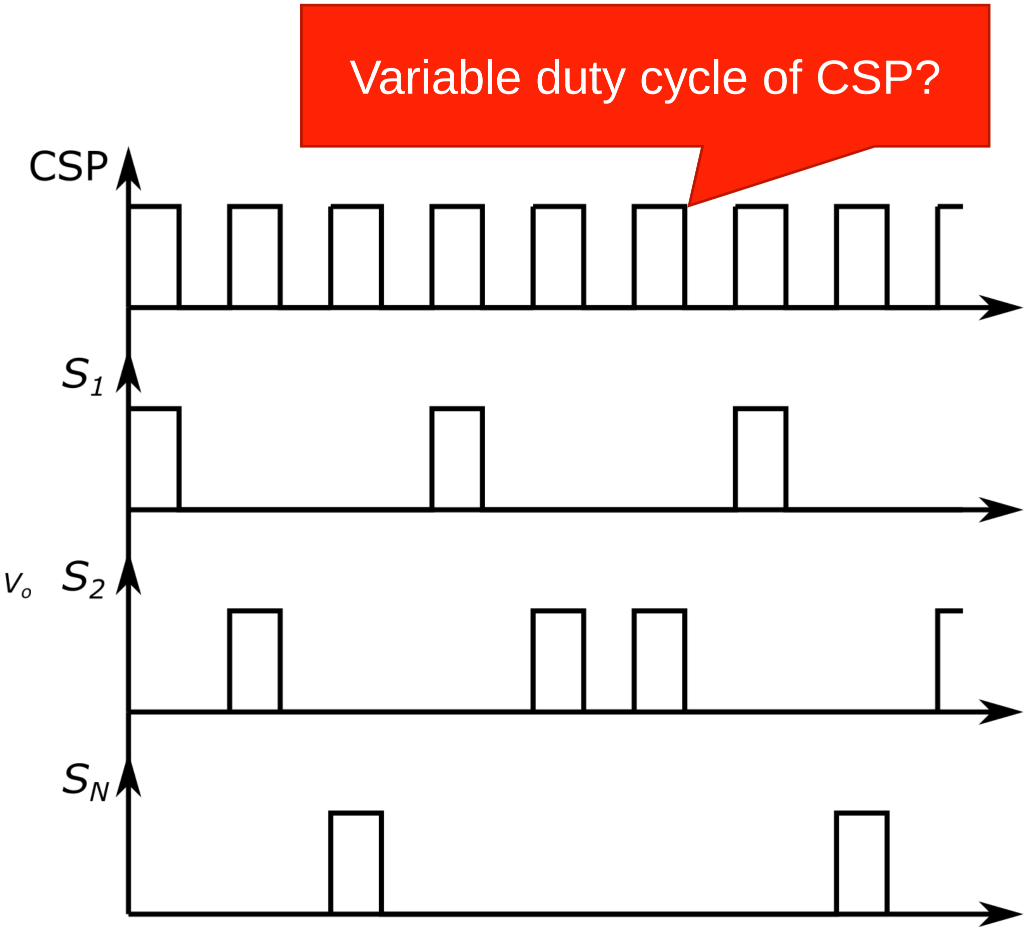




Solution #1: Common Switching Strategy

- Set up a common switching pattern (CSP)
- Use PI controller and frequency division
- Each input takes turns arbitrary in a decoupled manner
- Essentially an adaptive time-multiplexing control strategy

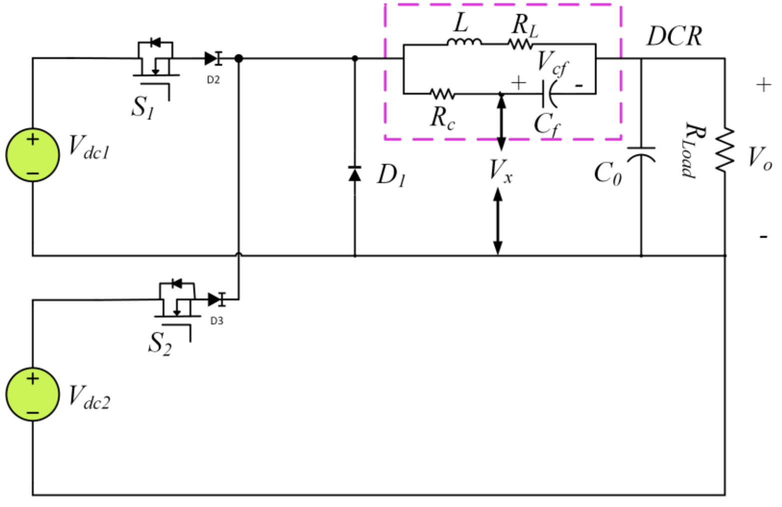


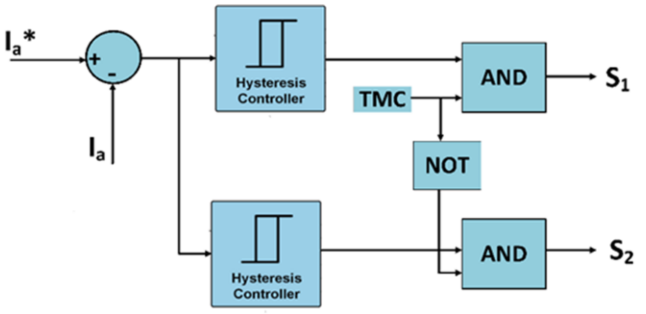


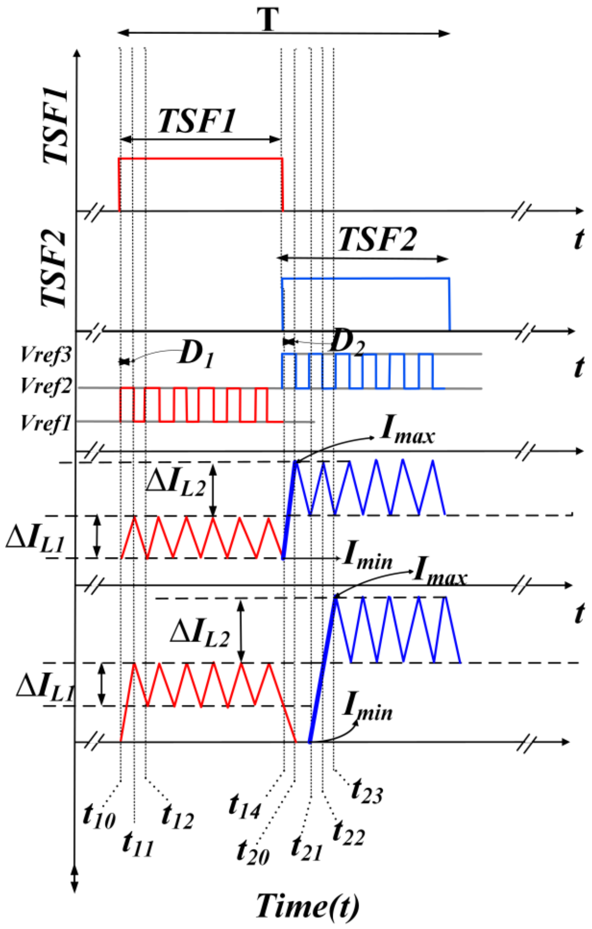
C. N. Onwuchekwa and A. Kwasinski, "A switching strategy for multiple-input DC-DC converters," 2011 IEEE Energy Conversion Congress and Exposition, 2011, pp. 3657-3664, doi: 10.1109/ECCE.2011.6064265.

Solution #2: Time-multiplexed Hysteretic Control

- Slower time-multiplexing concept
- Inductor current does not reach zero but goes to the next current reference point
- Faster dynamics and less filtering requirement



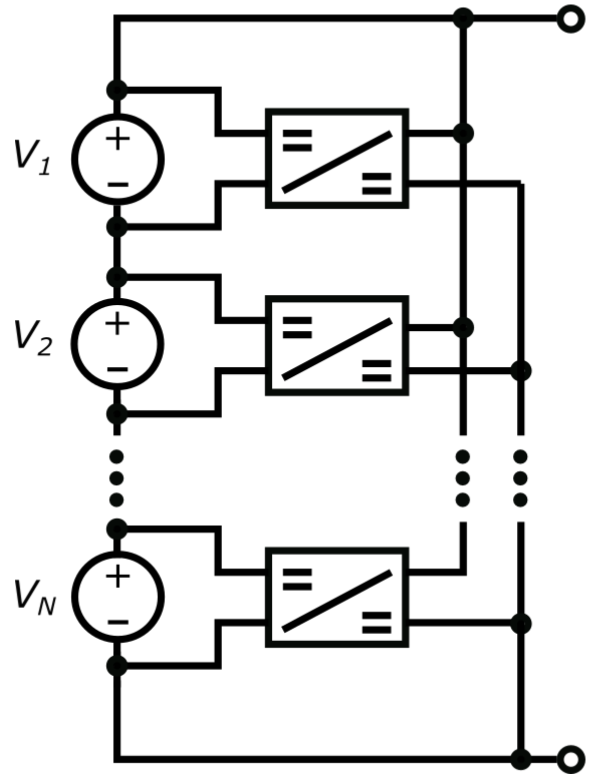




M.M. Alam, D.D.-C. Lu, and Y. Siwakoti, “Time Multiplexed Hysteretic Control (TMHC) for Single-Inductor Dual-Input Single-Output (SI-DISO) DC-DC Power Converter,” in *International Journal of Circuit Theory and Applications*, Vol. 50, No. 4, pp. 1235-1249, April 2022.

Solution #3: Differential Power Processing

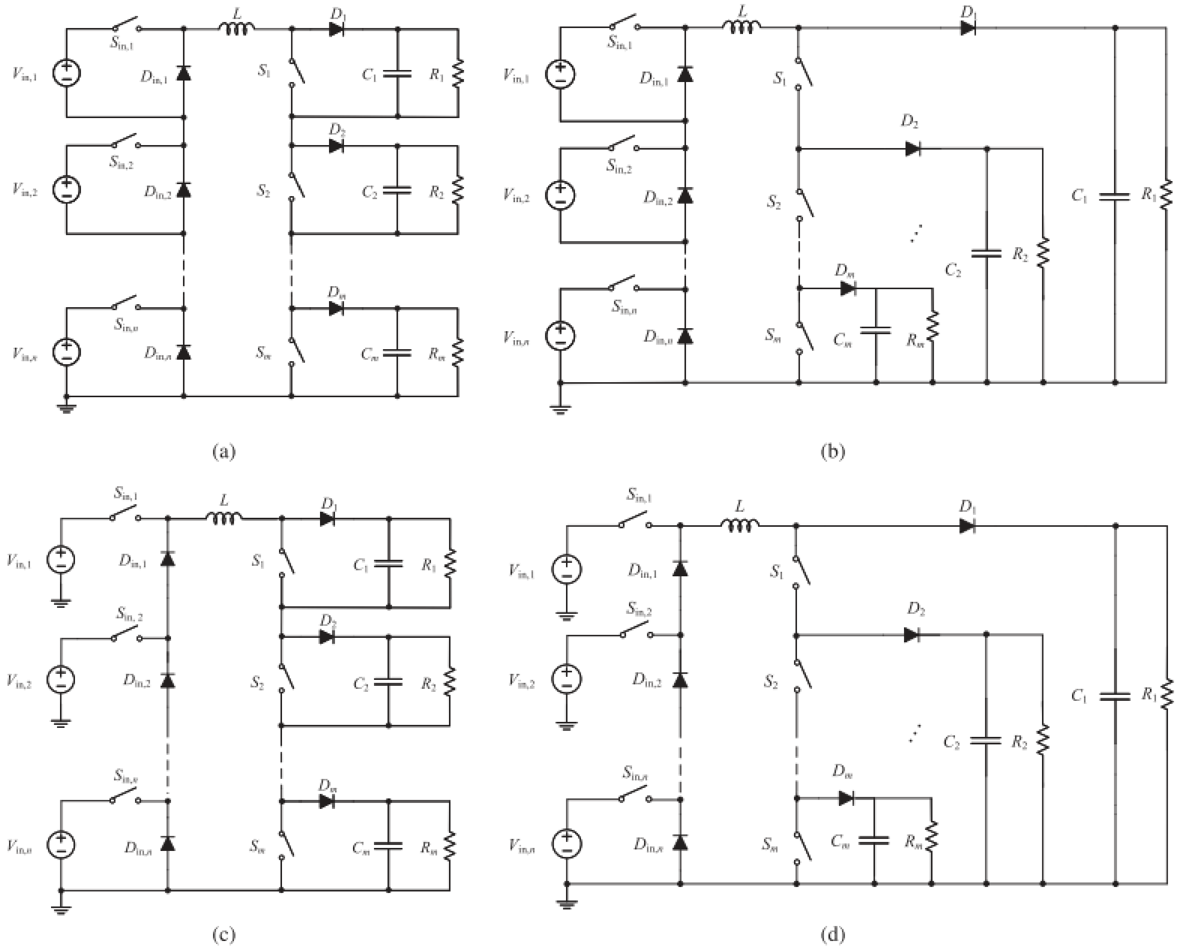
- Input-series and output-parallel/series structure
- DC/DC converters only process the current/power difference
- Good potential for MPC design



H. Jeong, H. Lee, Y. -C. Liu and K. A. Kim, "Review of Differential Power Processing Converter Techniques for Photovoltaic Applications," in IEEE Transactions on Energy Conversion, vol. 34, no. 1, pp. 351-360, March 2019, doi: 10.1109/TEC.2018.2876176.

Solution #4: Current Converter Mode Operation

- Four combinations with input-series, input-parallel, output-series (floating) and output-parallel
- Both inputs and outputs can be independently controlled
- More switches for true output-series configuration



X. L. Li, C. K. Tse and D. D. -C. Lu, "Synthesis of Reconfigurable and Scalable Single-Inductor Multiport Converters With No Cross Regulation," in IEEE Transactions on Power Electronics, vol. 37, no. 9, pp. 10889-10902, Sept. 2022, doi: 10.1109/TPEL.2022.3167119.

Short Summary

- Integrated circuit approach to MPC design saves some components but complicates and compromises controllability, particularly output regulation and input power conditioning
- Time-multiplexing and time-sharing are two distinctive solutions but both have pros and cons in terms of filtering requirements, responses and controllability
- Differential power processing and current converter mode operations are alternative design options that may provide additional advantages of simple control, higher efficiency and smaller footprint

MPC Challenge #2

Limited or Range-reduced Operation Modes

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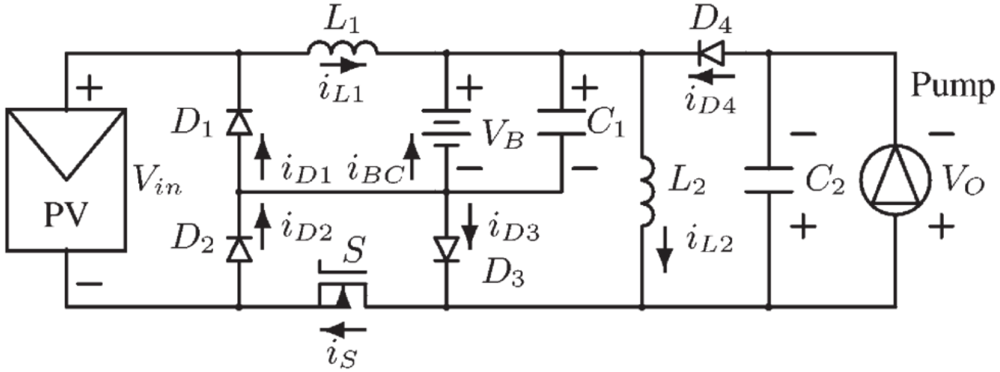
Single-switch Three-port DC/DC Converter

- Two cascading stages shared a single power switch
- Cost-saving design
- Impossible to implement all operation modes unless some working conditions are met or additional switches are inserted



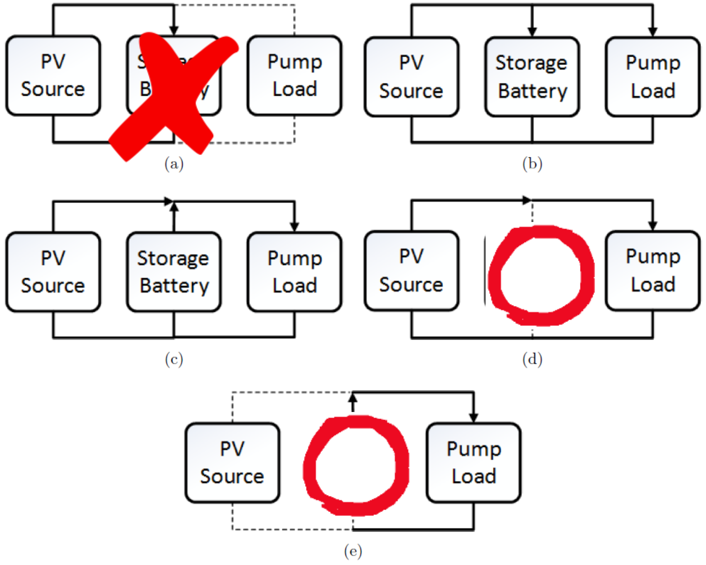


TABLE III
ESTIMATED COST OF THE SWITCHING COMPONENTS

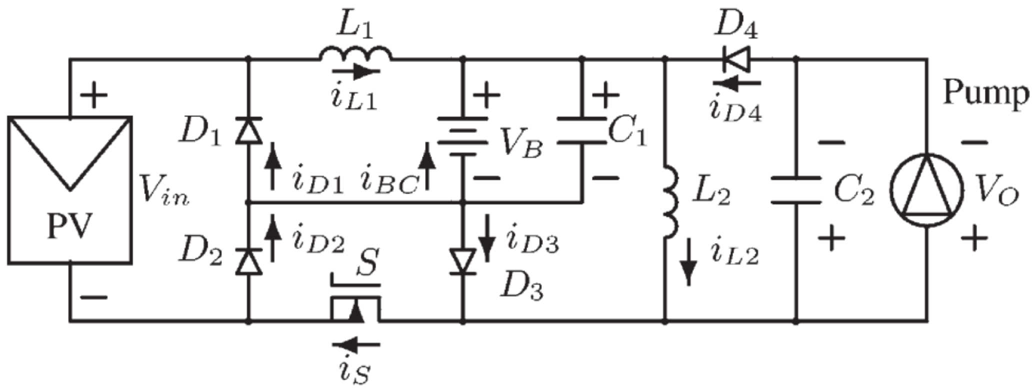
	Proposed SSC			Two-stage converter		
Components	**VA Rating**	**Model**	**Cost**	**VA Rating**	**Model**	**Cost**
MOSFET S	53W	IRLML2-6-TRPBF 1.2A 60V	\$0.26	20W	NDS311n 1.3A 20V	\$0.11
MOSFET S_2	NA			24W	NDS311n 1.3A 20V	\$0.11
Gate Driver	1(number)	TC1427 (two channels parallelled)	\$0.663	2(number)	TC1427 (two channels parallelled)	\$1.326
Diode D_1	20W	NXP PMEG3015EJ 1.5A 30V	\$0.067	20W	NXP PMEG3015EJ 1.5A 30V	\$0.067
Diode D_2	14W	NXP PMEG3010EJ 1A 30V	\$0.026	NA		
Diode D_3	24W	NXP PMEG3015EJ 1.5A 30V	\$0.067	NA		
Diode D_4	24W	NXP PMEG3010EJ 1A 30V	\$0.026	24W	NXP PMEG3010EJ 1A 30V	\$0.026
Total cost		\$1.109			\$1.639	

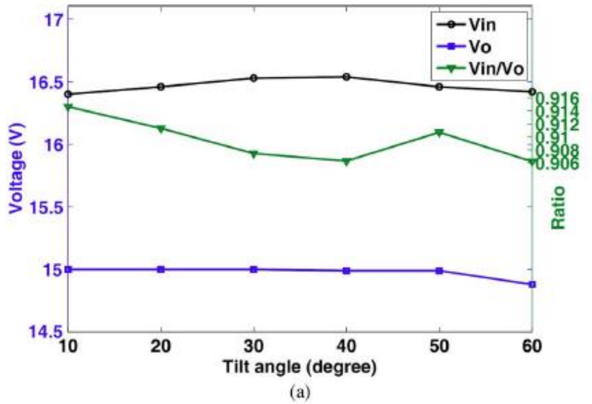
The costing is based on Element14 Pty Ltd. (au.element14.com) and in AUD.

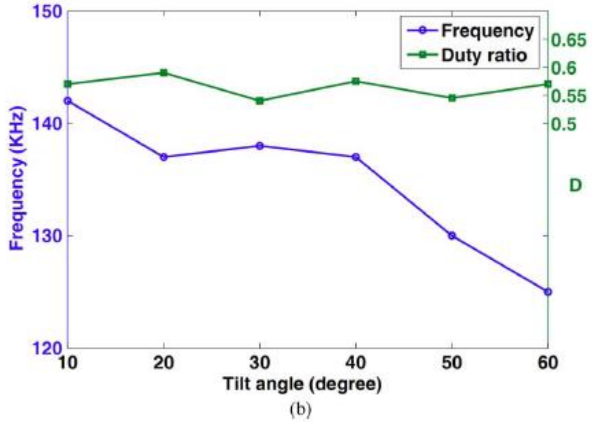
L. An and D. D. -C. Lu, "Design of a Single-Switch DC/DC Converter for a PV-Battery-Powered Pump System With PFM+PWM Control," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 2, pp. 910-921, Feb. 2015, doi: 10.1109/TIE.2014.2359414.

Single-switch Three-port DC/DC Converter

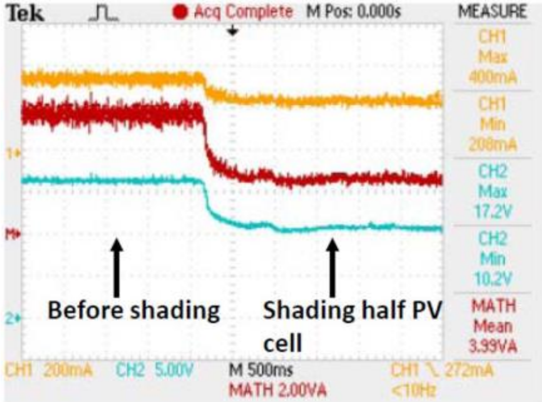
- Either output regulation or input power conditioning (MPPT) based on duty cycle control only → Solution: PWM + PFM
- Operating range extended but more restricted than two separate SISO converters



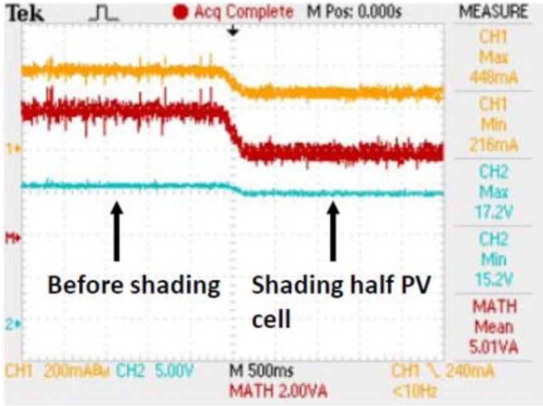




$$f_s = \frac{D^2}{2L_1 I_{in,\max}}(V_{in,\max} - V_B)$$



Vo regulation only

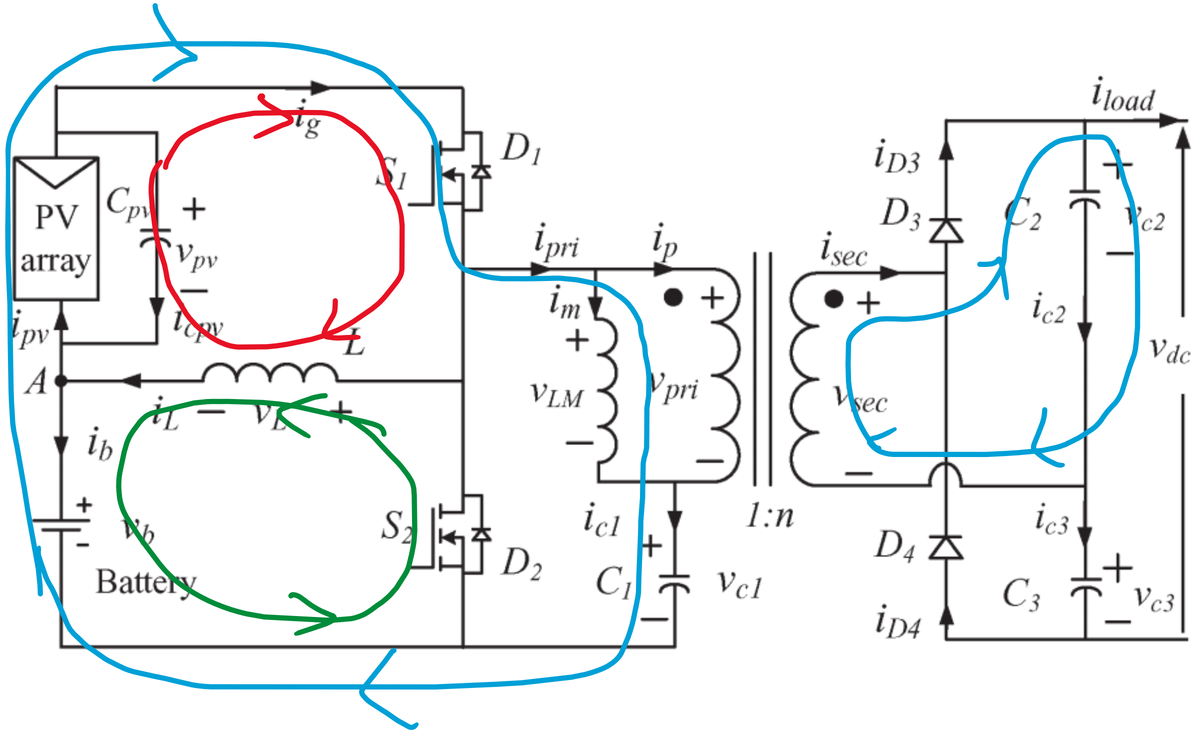


MPPT + Vo Regulation

L. An and D. D. -C. Lu, "Design of a Single-Switch DC/DC Converter for a PV-Battery-Powered Pump System With PFM+PWM Control," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 2, pp. 910-921, Feb. 2015, doi: 10.1109/TIE.2014.2359414.

Other Integrated Converter Designs

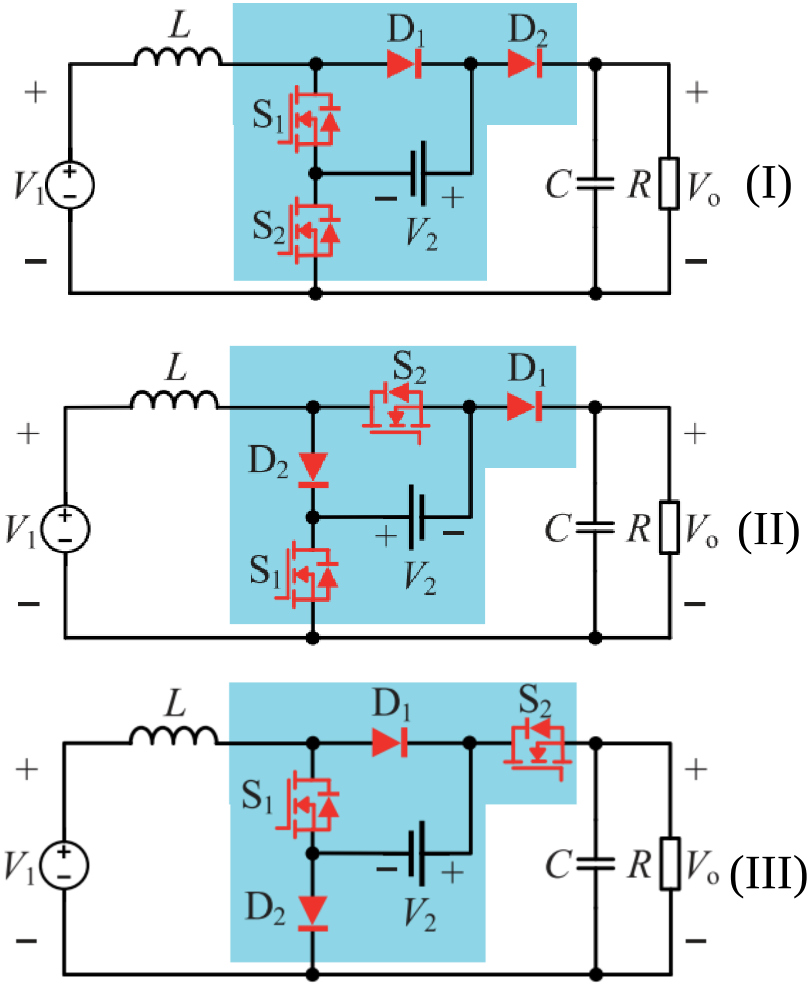
- PV delivers to battery and output simultaneously
- Output voltage depends on the sum of battery and PV voltages → loose output regulation or less accurate MPPT
- Cannot achieve PV-to-load or PV-to-battery only operation mode



D. Debnath and K. Chatterjee, "Two-Stage Solar Photovoltaic-Based Stand-Alone Scheme Having Battery as Energy Storage Element for Rural Deployment," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 7, pp. 4148-4157, July 2015.

Other Integrated Converter Designs

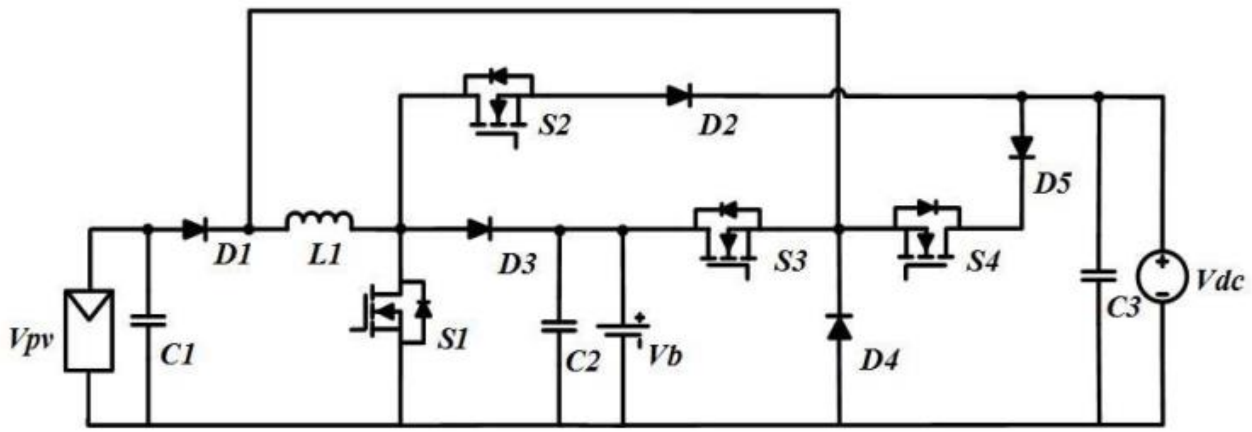
- Single-inductor approach
- Input (V_1) and battery (V_2) share the same semiconductors
- Two separate control loops
- Cannot achieve battery-to-load only mode in general
- Battery in converters (I) and (III) cannot operate when V_1 = 0V
- Difficult to achieve MPP and Output regulation simultaneously



Q. Tian, G. Zhou, R. Liu, X. Zhang and M. Leng, "Topology Synthesis of a Family of Integrated Three-Port Converters for Renewable Energy System Applications," in IEEE Transactions on Industrial Electronics, vol. 68, no. 7, pp. 5833-5846, July 2021, doi: 10.1109/TIE.2020.2994864.

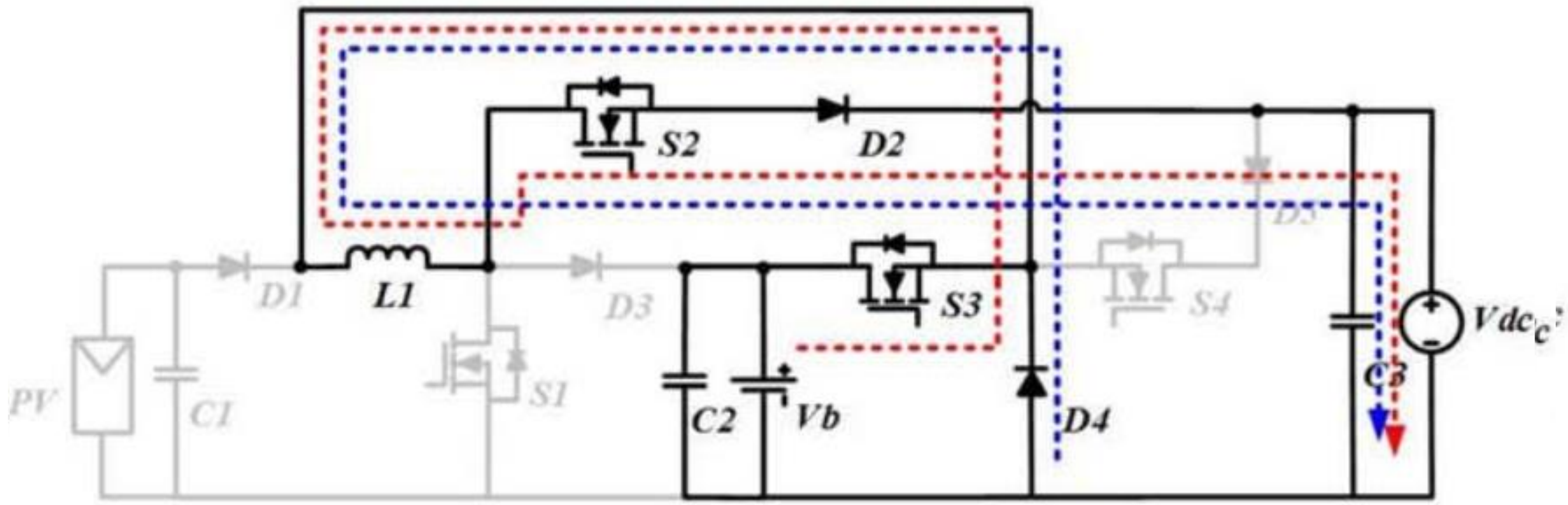
Reconfigurable Structure for All Possible Modes

- Single-inductor multiple-switch approach
- All 7 operation modes possible including bi-directional output port for DC grid and DC motor applications
- Efficiency range 88% – 92% (hard-switched) for all modes



T. Cheng, D.D.C. Lu, and L. Qin, “Non-Isolated Single-Inductor DC/DC Converter with Fully Reconfigurable Structure for Renewable Energy Applications,” *IEEE Transactions on Circuits and Systems II: Express Briefs*, Vol. 65, No. 3, pp. 351-355, March 2018

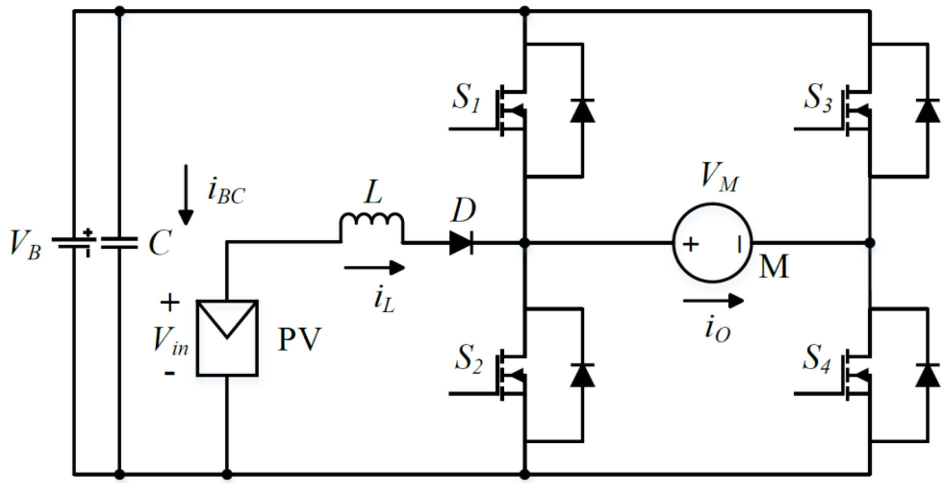
Reconfigurable Structure for All Possible Modes

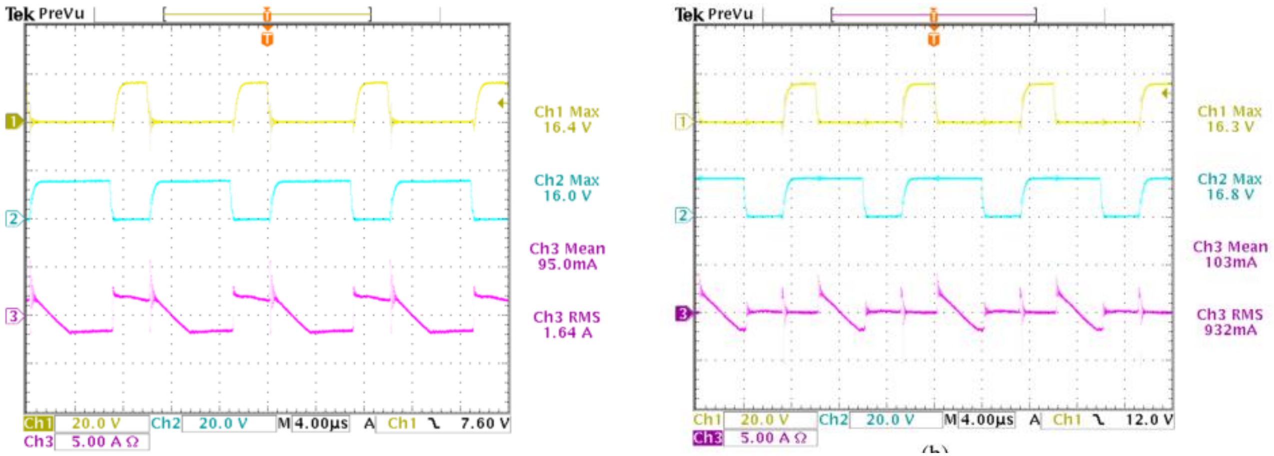


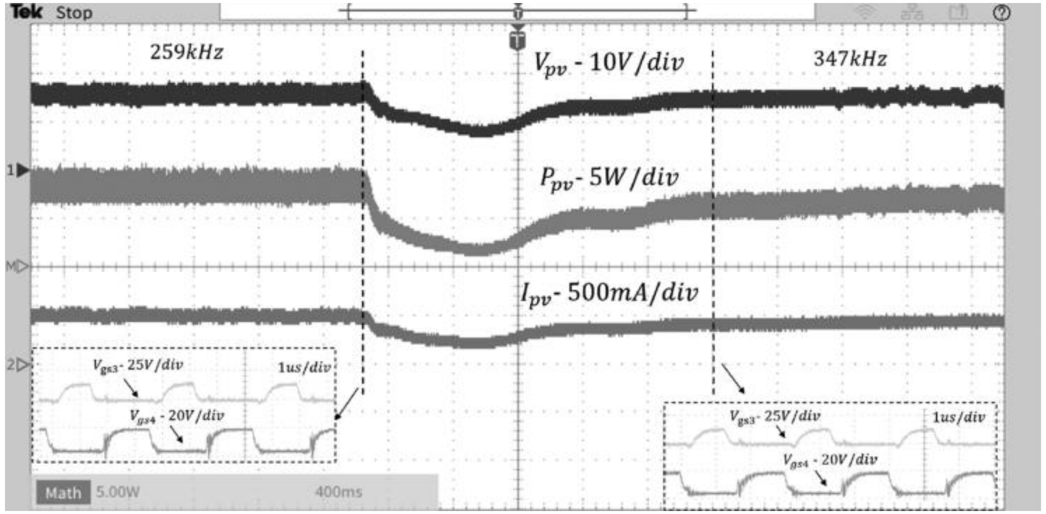
T. Cheng, D.D.C. Lu, and L. Qin, "Non-Isolated Single-Inductor DC/DC Converter with Fully Reconfigurable Structure for Renewable Energy Applications," *IEEE Transactions on Circuits and Systems II: Express Briefs*, Vol. 65, No. 3, pp. 351-355, March 2018

Range-extension Method

- Single-inductor approach
- Average V_M = 0V when d = 0.5 instead of d = 0
- Combine PWM, PFM and Phase Angle Shift (PAS) to achieve output regulation (speed), MPPT and RMS current reduction (2-4% efficiency gain)







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L. An, T. Cheng, and D.D.C. Lu, “Single-Stage Boost-Integrated Full-Bridge Converter with Simultaneous MPPT, Wide DC Motor Speed Range and Current Ripple Reduction,” IEEE Transactions on Industrial Electronics, Vol. 66, No. 9, pp. 6968-6978, September 2019.

Short Summary

- Integrated converter structure, by sharing some common components, can reduce converter cost
- Integrated converters usually suffer from limited or ranged-reduced operation modes
- Operation modes can be fully achieved by alternative converter designs
- Operation range, depending on the circuitry, can be extended by combining different modulation schemes

L. An and D. D. -C. Lu, "Design of a Single-Switch DC/DC Converter for a PV-Battery-Powered Pump System With PFM+PWM Control," in IEEE Transactions on Industrial Electronics, vol. 62, no. 2, pp. 910-921, Feb. 2015, doi: 10.1109/TIE.2014.2359414.

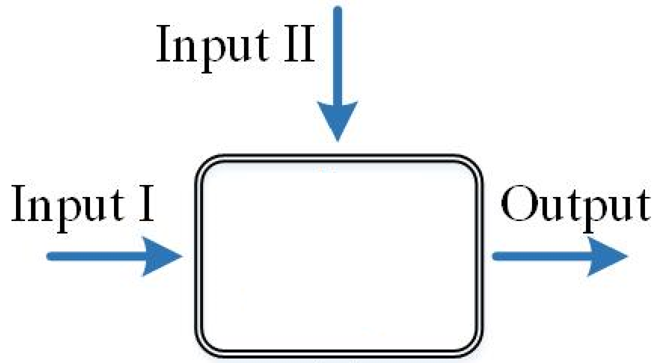
MPC Challenge #3

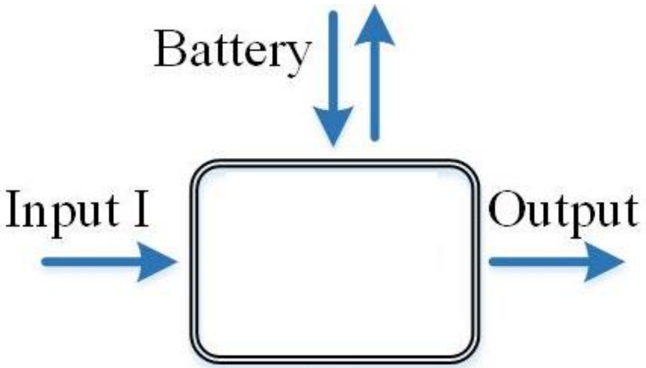
Heavy Computational Burden and Sensor Requirement

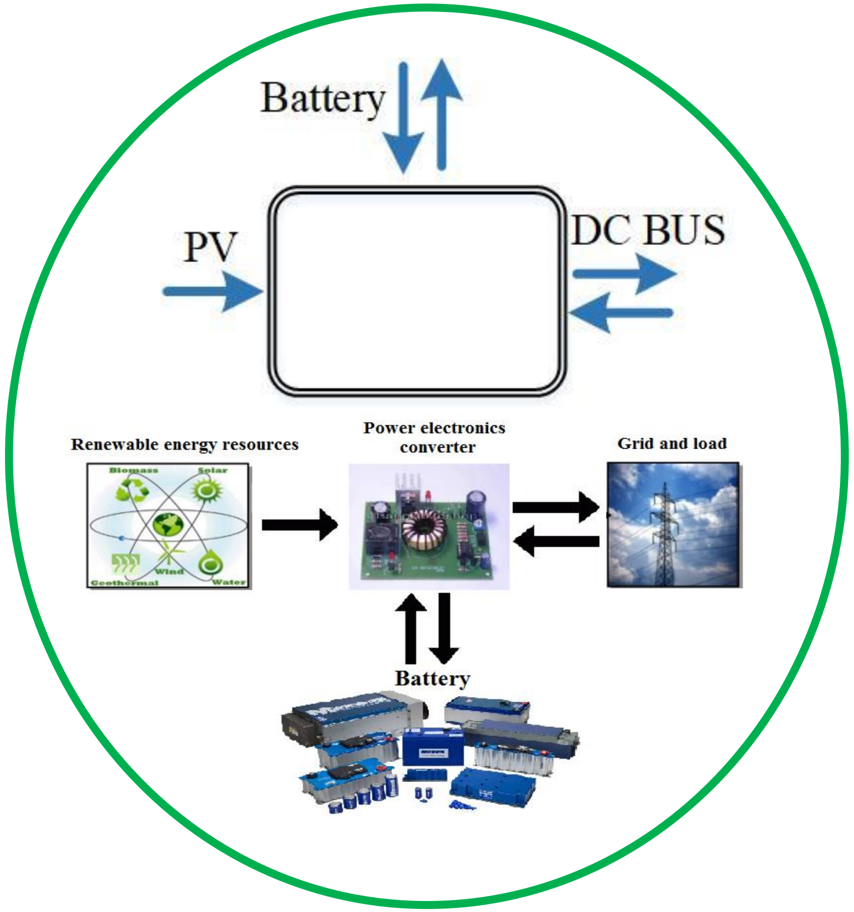
Three-Port Converters

Why bidirectional ports?

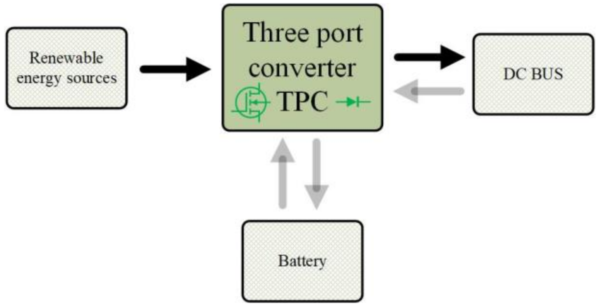
- ✓ **Regenerative braking**
- ✓ **DC grid**



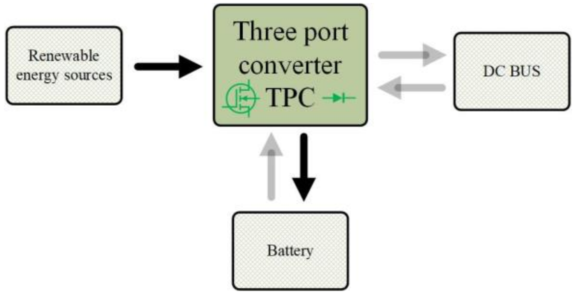




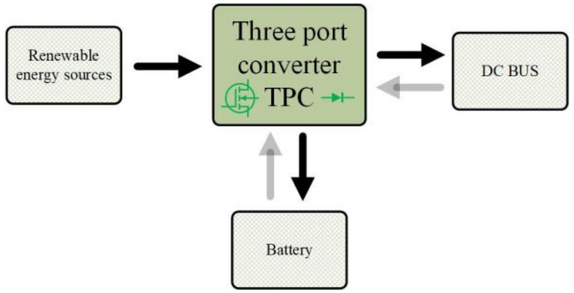
C. K. Tse, M. H. L. Chow and M. K. H. Cheung, "A family of PFC voltage regulator configurations with reduced redundant power processing," in IEEE Transactions on Power Electronics, vol. 16, no. 6, pp. 794-802, Nov 2001.



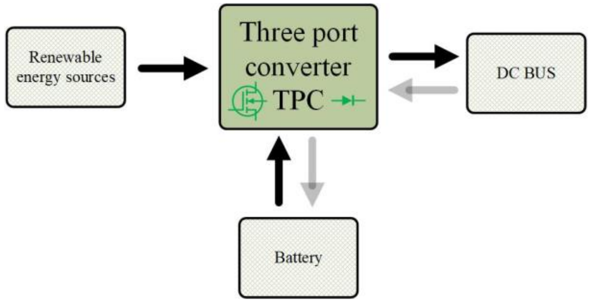
Mode 1 (PV to DC bus)



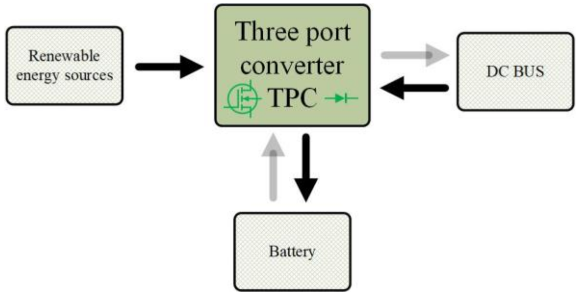
Mode 2 (PV to battery)



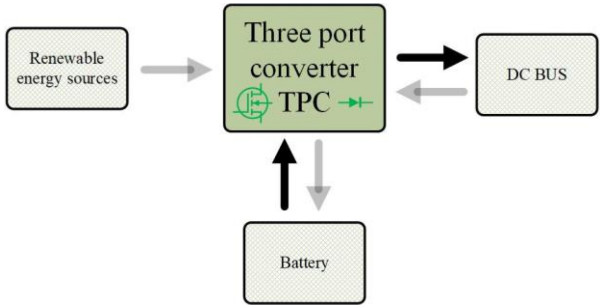
Mode 3 (PV to Battery and DC bus)



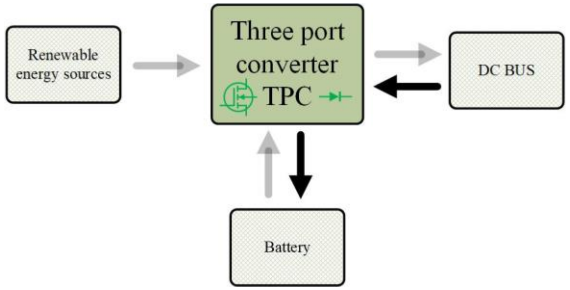
Mode 4 (PV and Battery to DC BUS)



Mode 5 (DC BUS and PV to Battery)



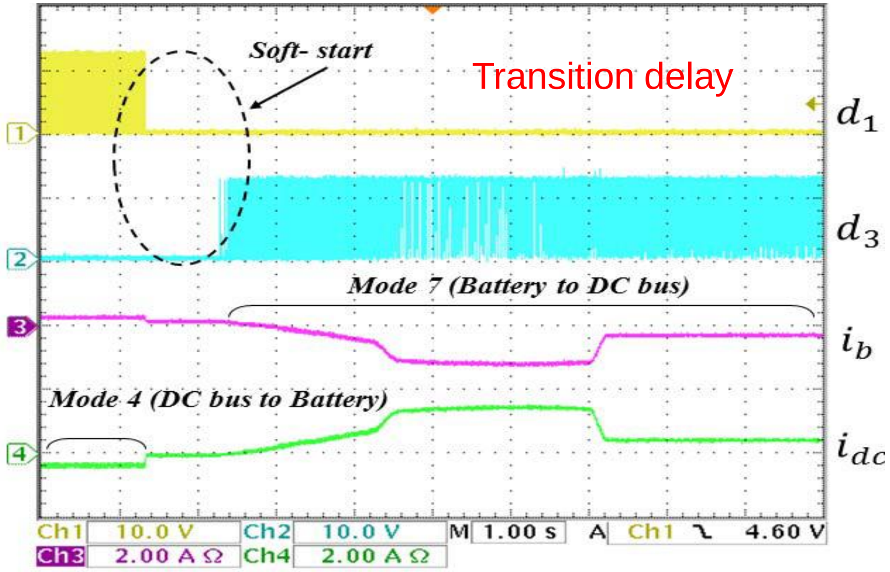
Mode 6 (Battery to DC BUS)

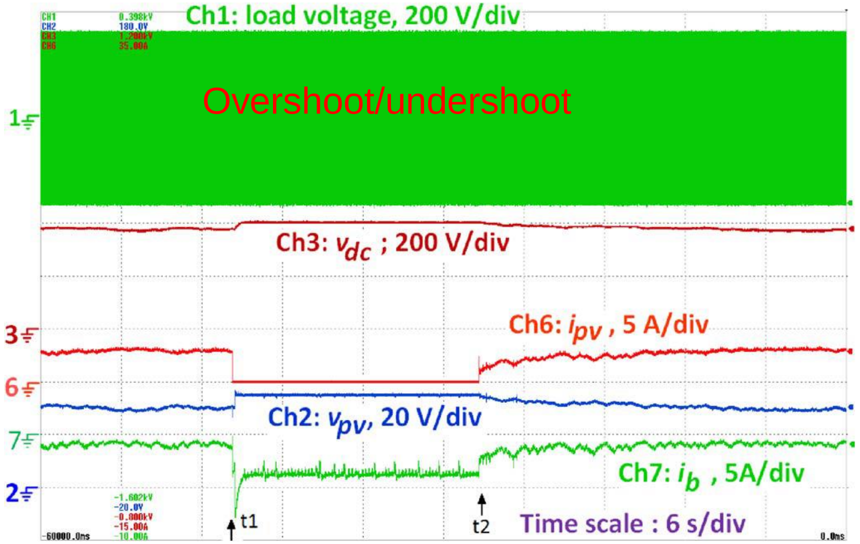


Mode 7 (DC BUS to Battery)

Fully controlled and maintain the battery lifespan

Previous work:





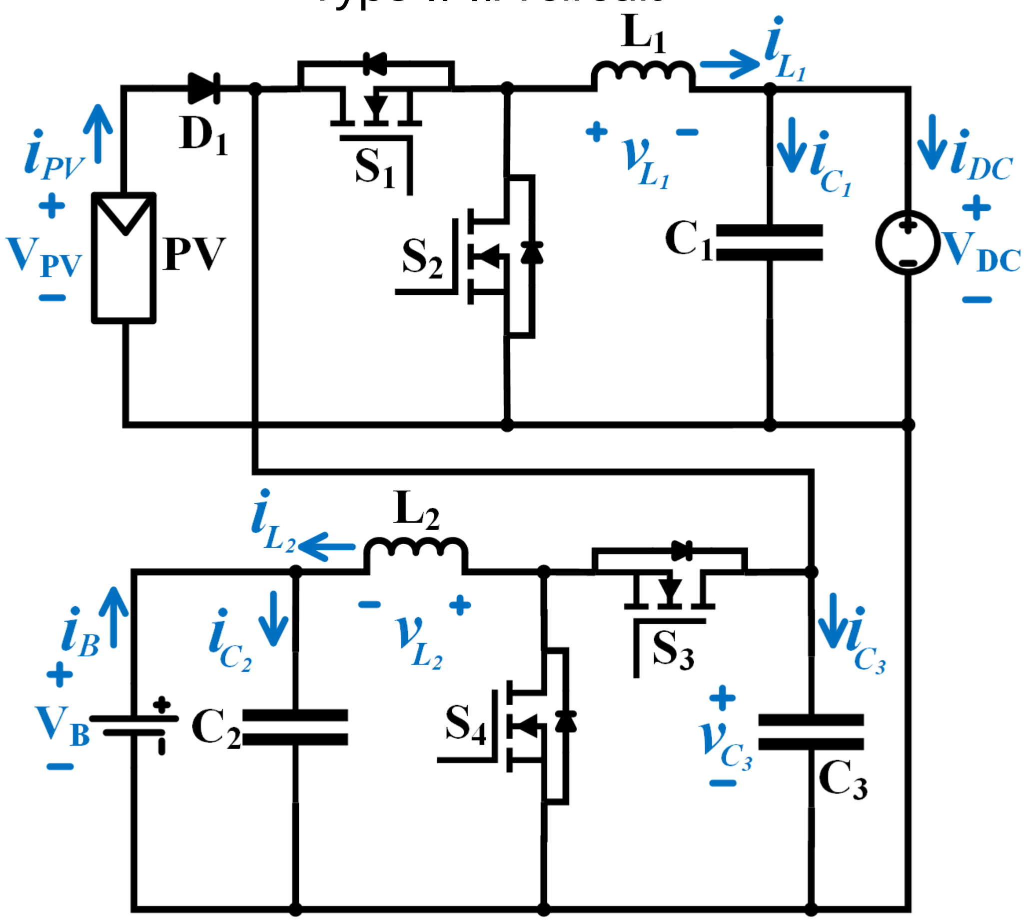
Settling time

UTS

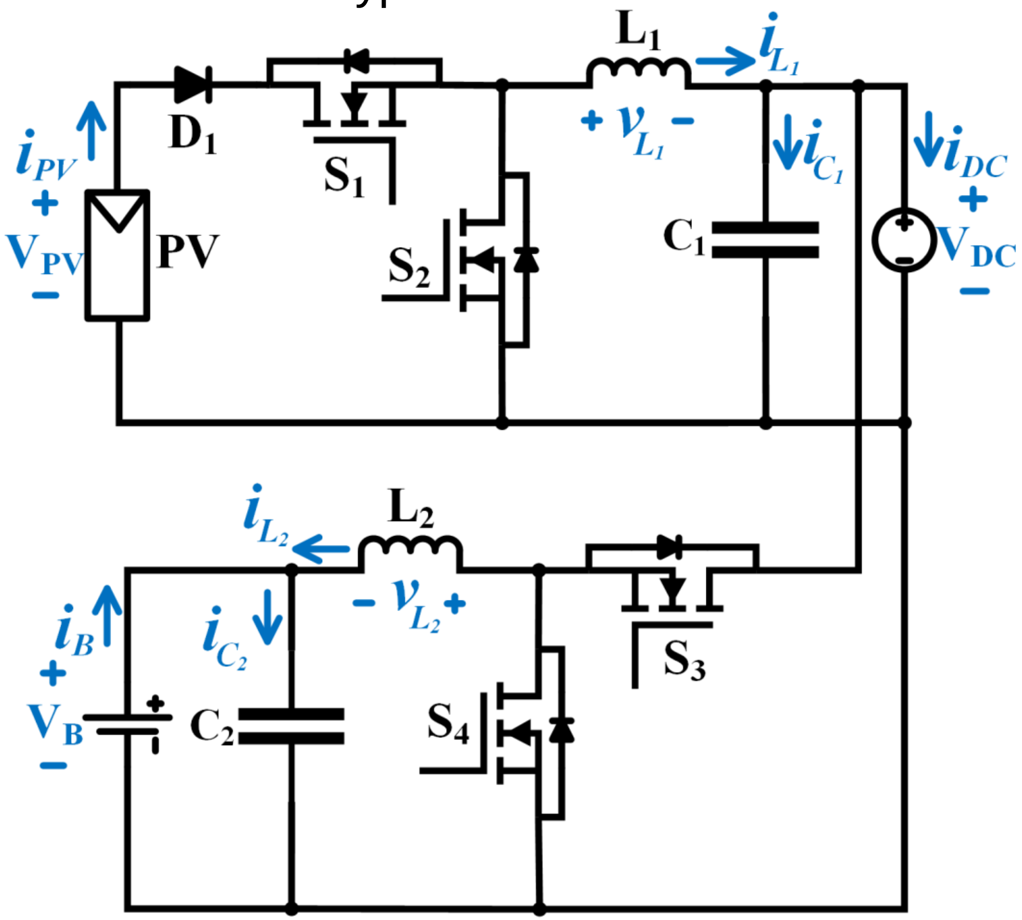
[1] T. Cheng, D. D. Lu, and L. Qin. Non-isolated single-inductor dc/dc converter with fully reconfigurable structure for renewable energy applications. IEEE Transactions on Circuits and Systems II: Express Briefs, 65(3):351-355, 2018. [2] D. Debnath and K. Chatterjee. Two-stage solar photovoltaic-based stand-alone scheme having battery as energy storage element for rural deployment. IEEE Transactions on Industrial Electronics, 62(7):4148{4157, Jul. 2015.

TPC circuits

Type II-IIA circuit



Type II-IIB circuit



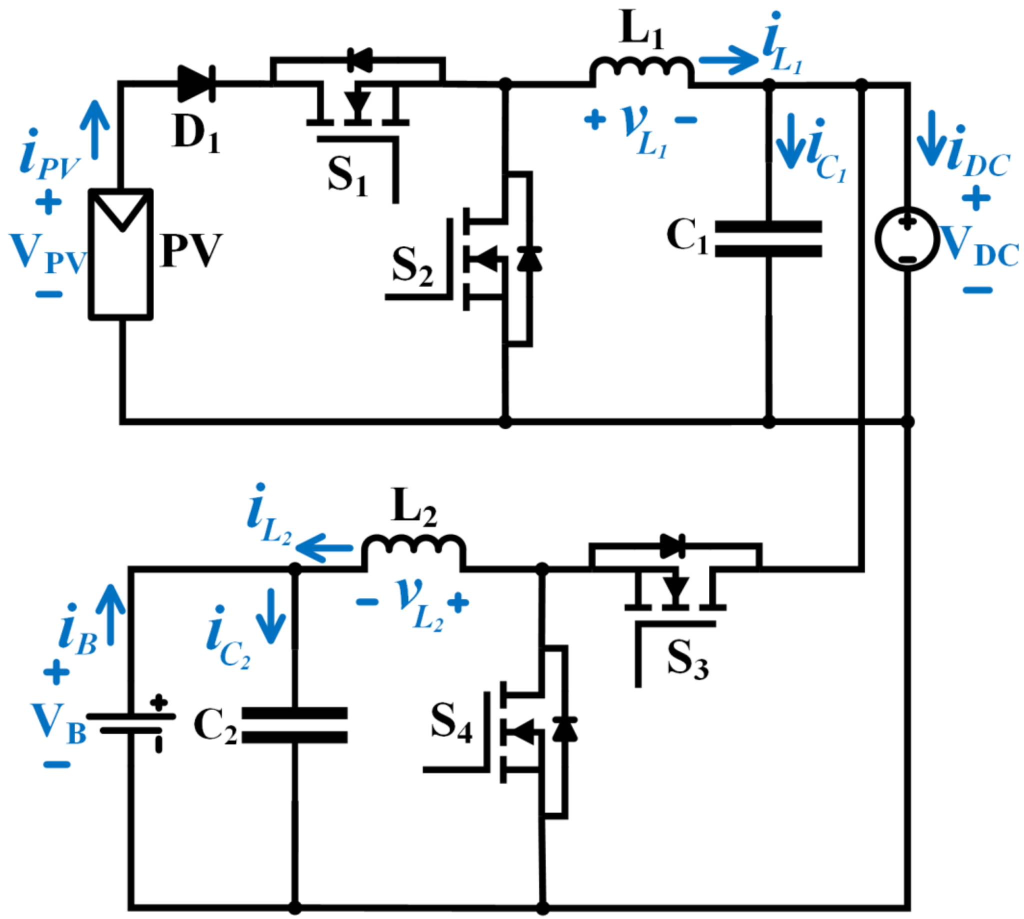
Switching Look-up Table for Different Modes

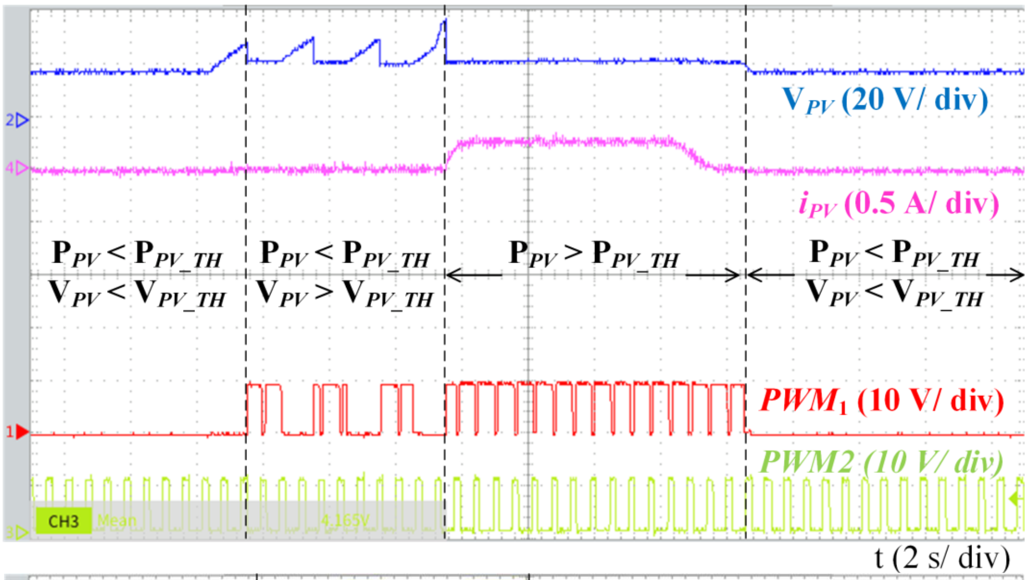
Modes	Power	Active Components	State	Switch state ON	Switch state OFF	Duty condition	Fig
PV to DC bus	$P_{pv} = P_{DC}$	D_1, S_1, S_2, L_1 & C_1	I	$S_1{}^*$	$S_2{}^*$	–	–
			II	$S_2{}^*$	$S_1{}^*$		–
PV to battery	$P_{pv} = P_B$	All active except S_4	I	$S_1{}^*$, $S_3{}^\circ$	$S_2{}^*$	–	–
			II	$S_2{}^*$, $S_3{}^\circ$	$S_1{}^*$		–
PV to DC bus and battery	$P_{pv} = P_{DC} + P_B$	All active	I	$S_1{}^*$, $S_4{}^*$	$S_2{}^*$, $S_3{}^*$	$\frac{1}{D_3} \approx \frac{V_{DC}}{V_B}$	Fig. 5(a)
			II	$S_1{}^*$, $S_3{}^*$	$S_2{}^*$, $S_4{}^*$		Fig. 5(b)
			III	$S_2{}^*$, $S_3{}^*$	$S_1{}^*$, $S_4{}^*$		Fig. 5(c)
			IV	$S_2{}^*$, $S_4{}^*$	$S_1{}^*$, $S_3{}^*$		Fig. 5(d)
PV and battery to DC bus	$P_{pv} + P_B = P_{DC}$	All active	I	$S_1{}^*$, $S_4{}^*$	$S_2{}^*$, $S_3{}^*$	$\frac{1}{D_3} \geqslant \frac{V_{DC}}{V_B}$	Fig. 6(a)
			II	$S_1{}^*$, $S_3{}^*$	$S_2{}^*$, $S_4{}^*$		Fig. 6(b)
			III	$S_2{}^*$, $S_3{}^*$	$S_1{}^*$, $S_4{}^*$		Fig. 6(c)
			IV	$S_2{}^*$, $S_4{}^*$	$S_1{}^*$, $S_3{}^*$		Fig. 6(d)
PV and DC bus to battery	$P_{pv} + P_{DC} = P_B$	All active	I	$S_1{}^*$, $S_4{}^*$	$S_2{}^*$, $S_3{}^*$	$\frac{1}{D_3} \leqslant \frac{V_{DC}}{V_B}$	Fig. 7(a)
			II	$S_1{}^*$, $S_3{}^*$	$S_2{}^*$, $S_4{}^*$		Fig. 7(b)
			III	$S_2{}^*$, $S_3{}^*$	$S_1{}^*$, $S_4{}^*$		Fig. 7(c)
			IV	$S_2{}^*$, $S_4{}^*$	$S_1{}^*$, $S_3{}^*$		Fig. 7(d)
battery to DC bus	$P_B = P_{DC}$	S_3, S_4, L_2, C_1 & C_2	I	$S_3{}^*$	$S_4{}^*$	–	–
			II	$S_4{}^*$	$S_3{}^*$		–
DC bus to battery	$P_{DC} = P_B$	S_3, S_4, L_2, C_1 & C_2	I	$S_3{}^*$	$S_4{}^*$	–	–
			II	$S_4{}^*$	$S_3{}^*$		–

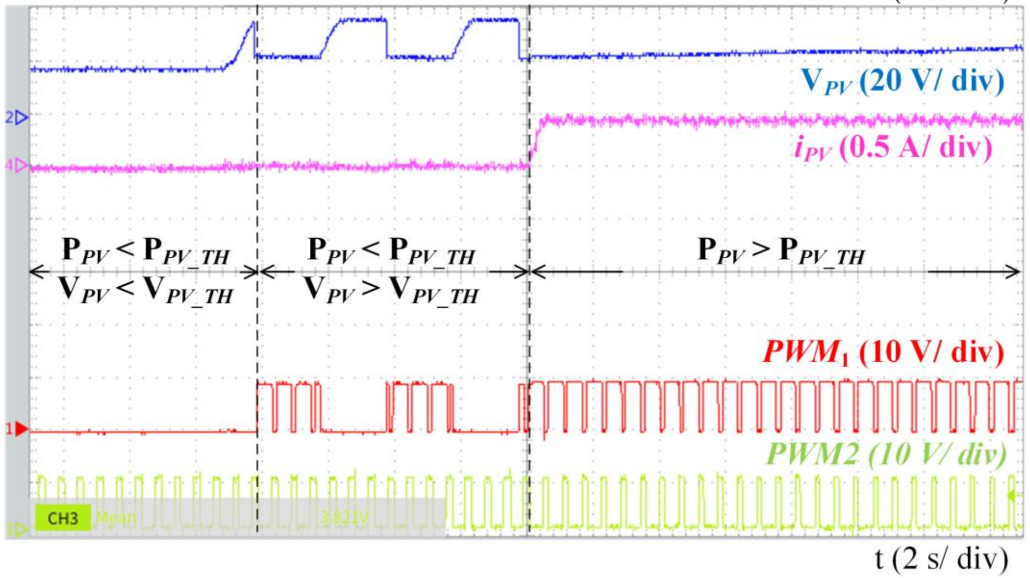
* Switch operates in PWM $\quad$ $^\circ$ Switch is fully ON

No PV power condition

Type II-IIB circuit





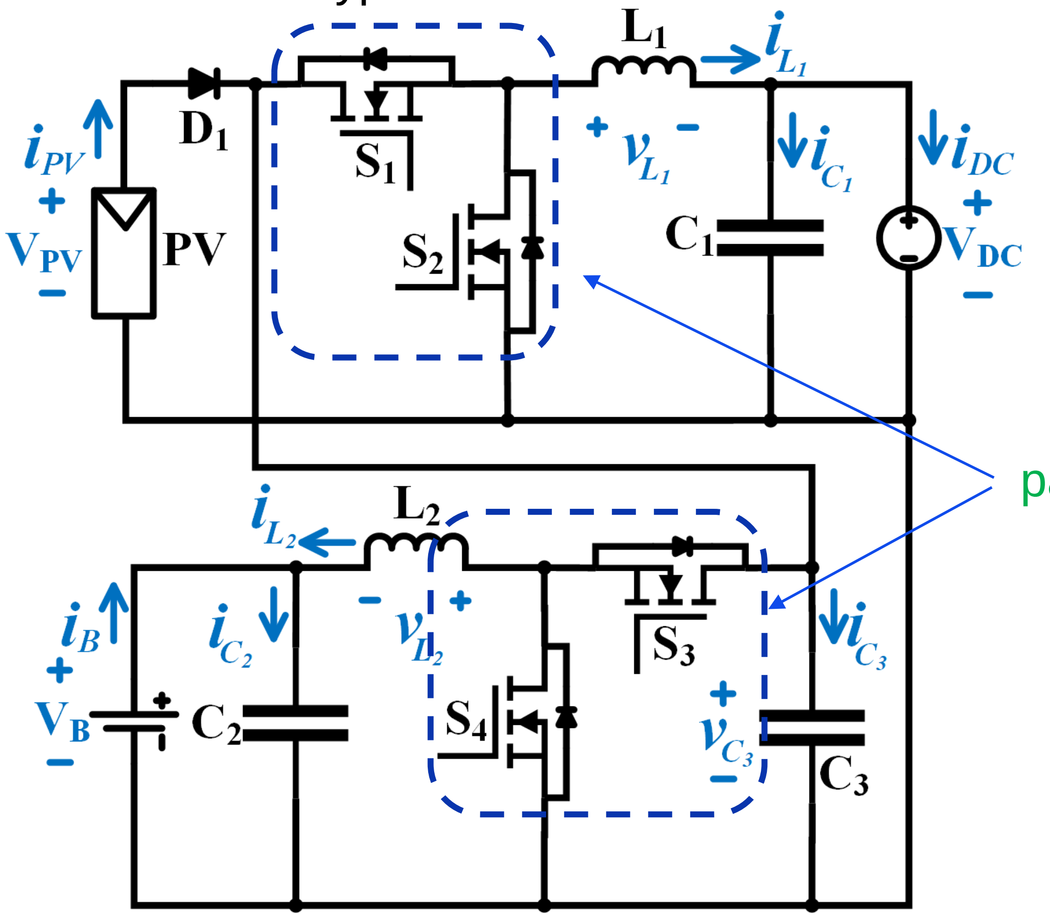


H. Aljarajreh, D. D. -C. Lu, Y. P. Siwakoti, R. P. Aguilera and C. K. Tse, "A Method of Seamless Transitions Between Different Operating Modes for Three-Port DC-DC Converters," in *IEEE Access*, vol. 9, pp. 59184-59195, 2021, doi: 10.1109/ACCESS.2021.3073948.

Proposed Method:

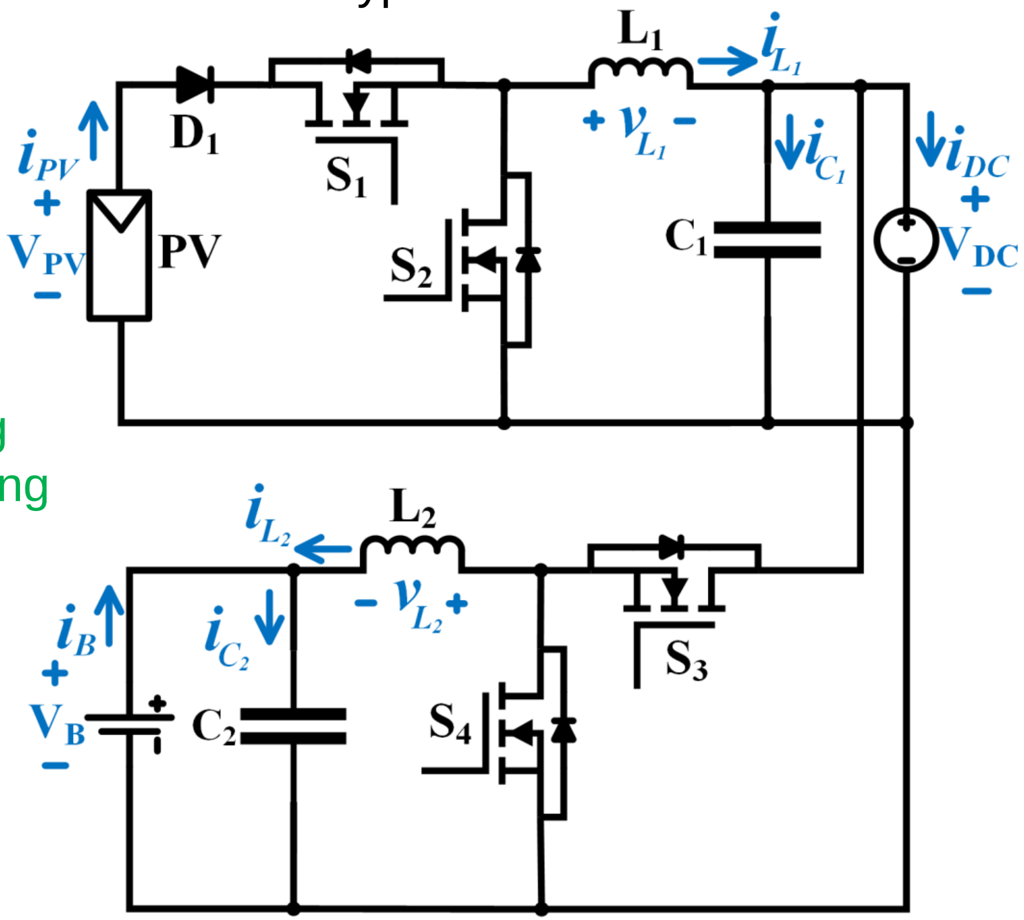
- Smooth transition
- No obvious Overshoot/undershoot
- Fast response
- 4 sensors

Type II-IIA circuit

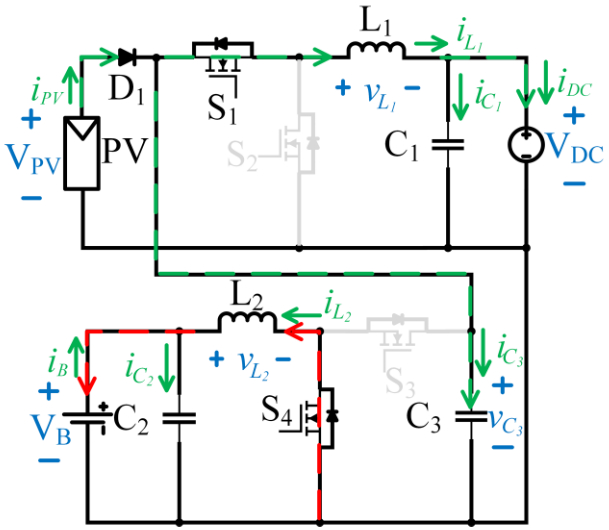


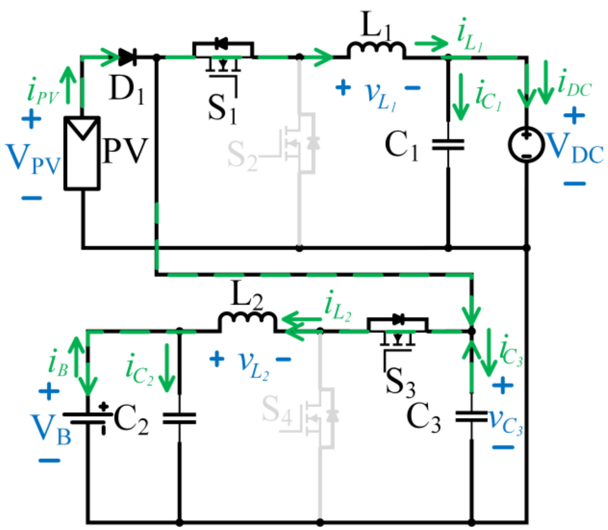
Both switching pairs are receiving PWM signals

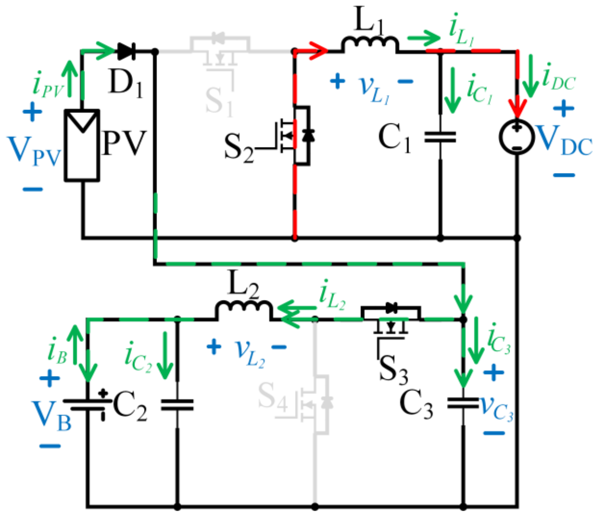
Type II-IIB circuit

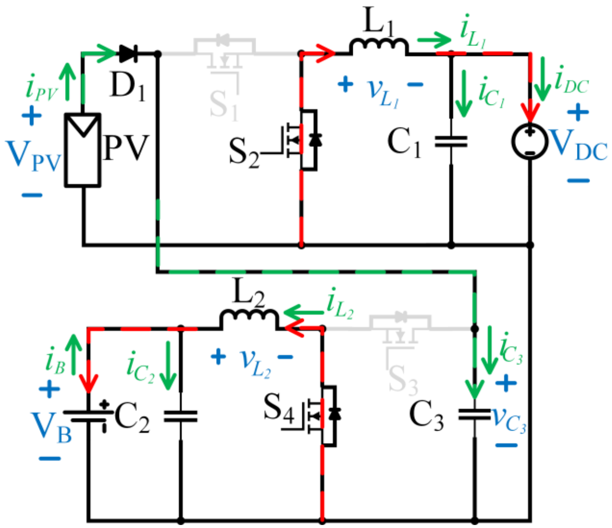


Mode 3 (PV to Battery and DC bus)

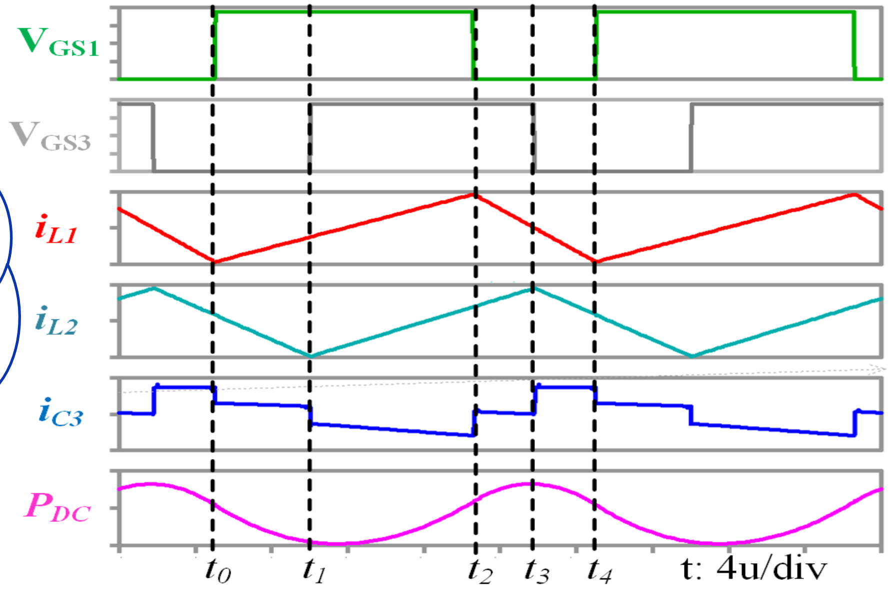




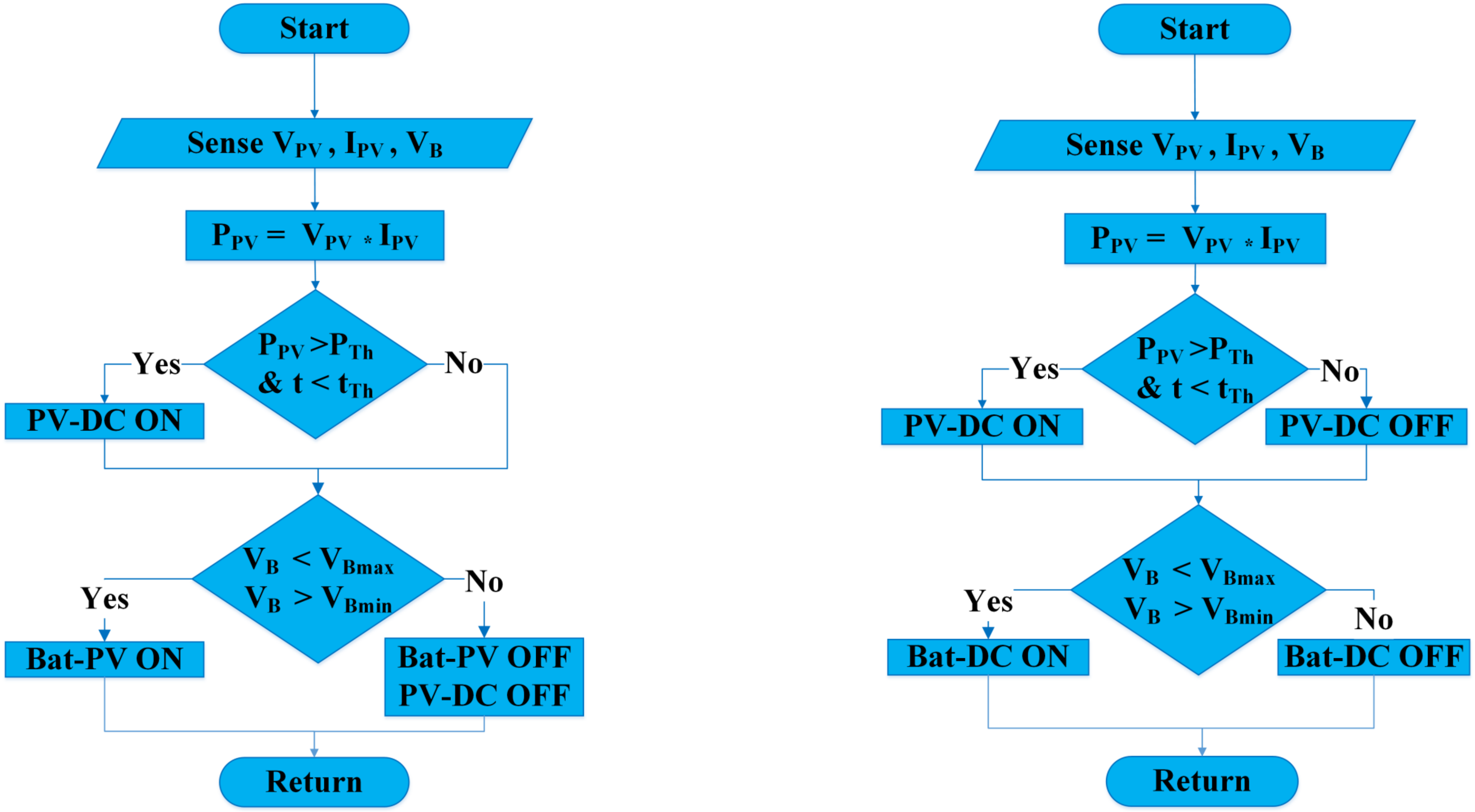




Delay between two PWM

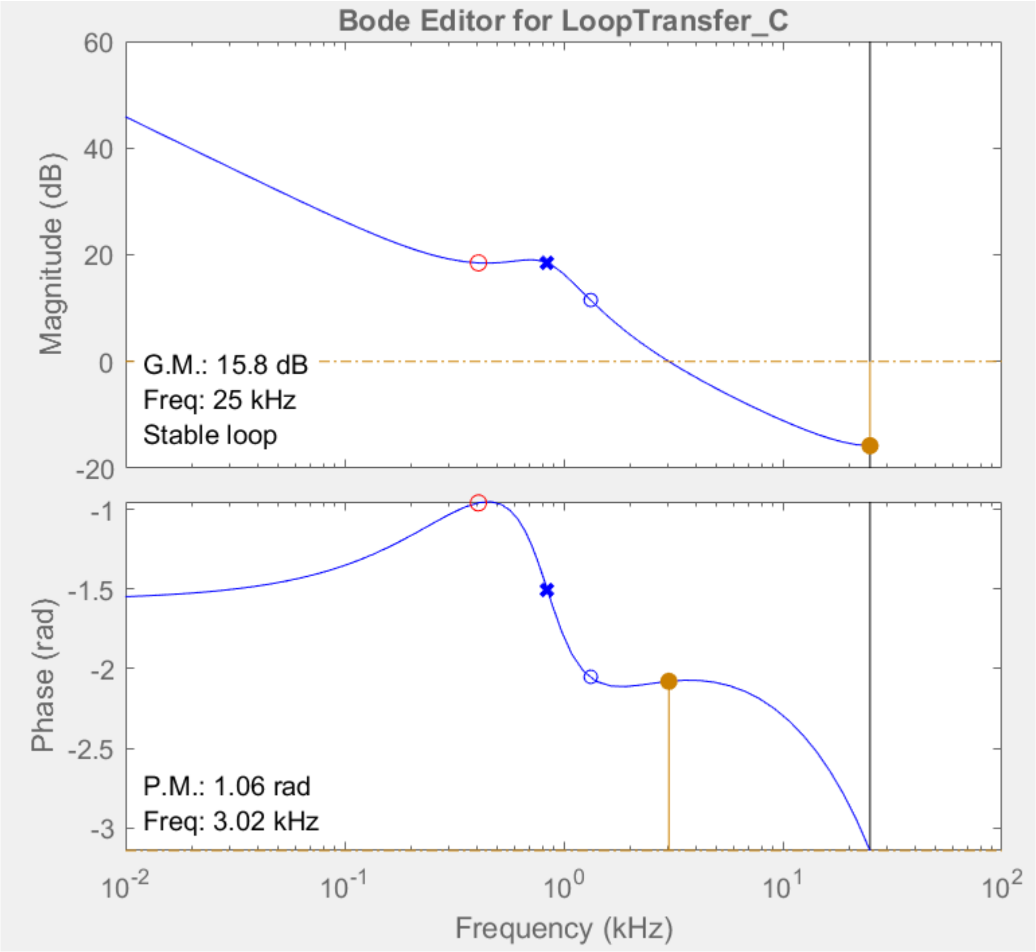


Flowchart of all possible modes and conditions

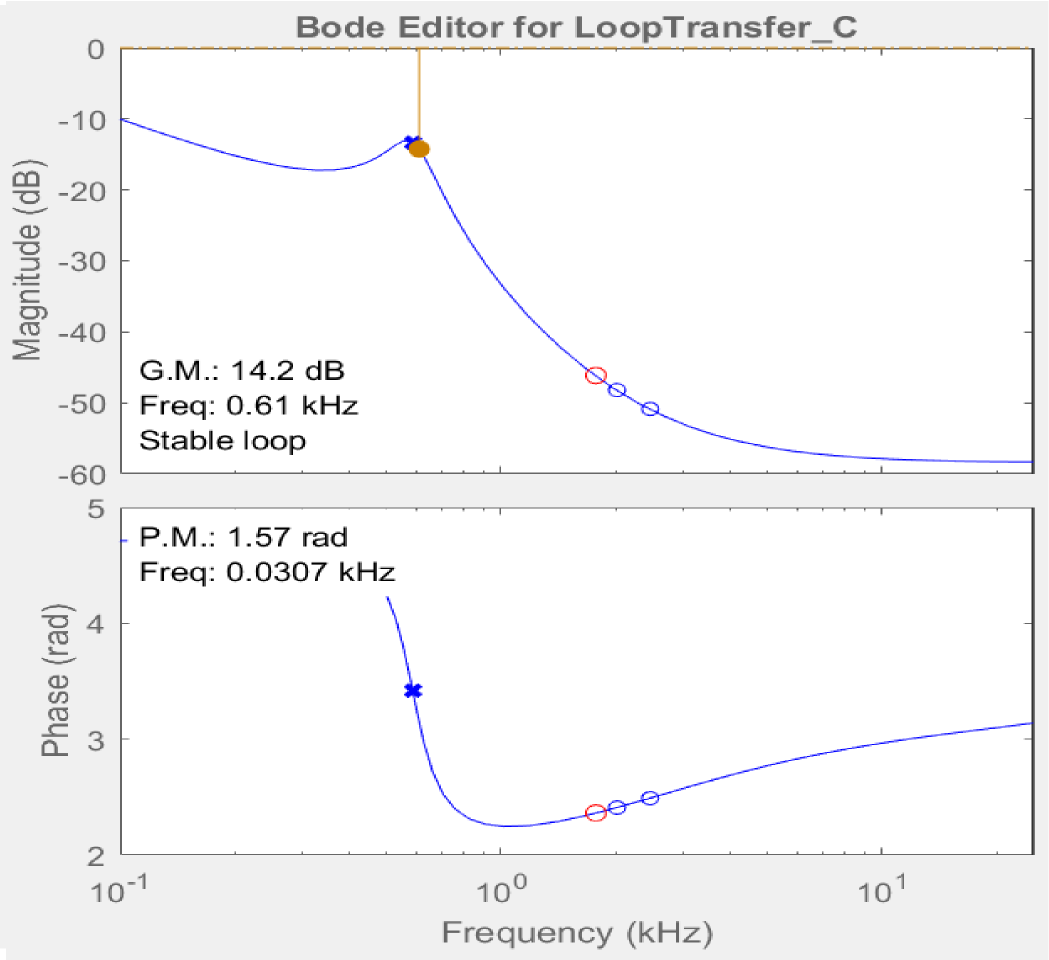


Control Structure

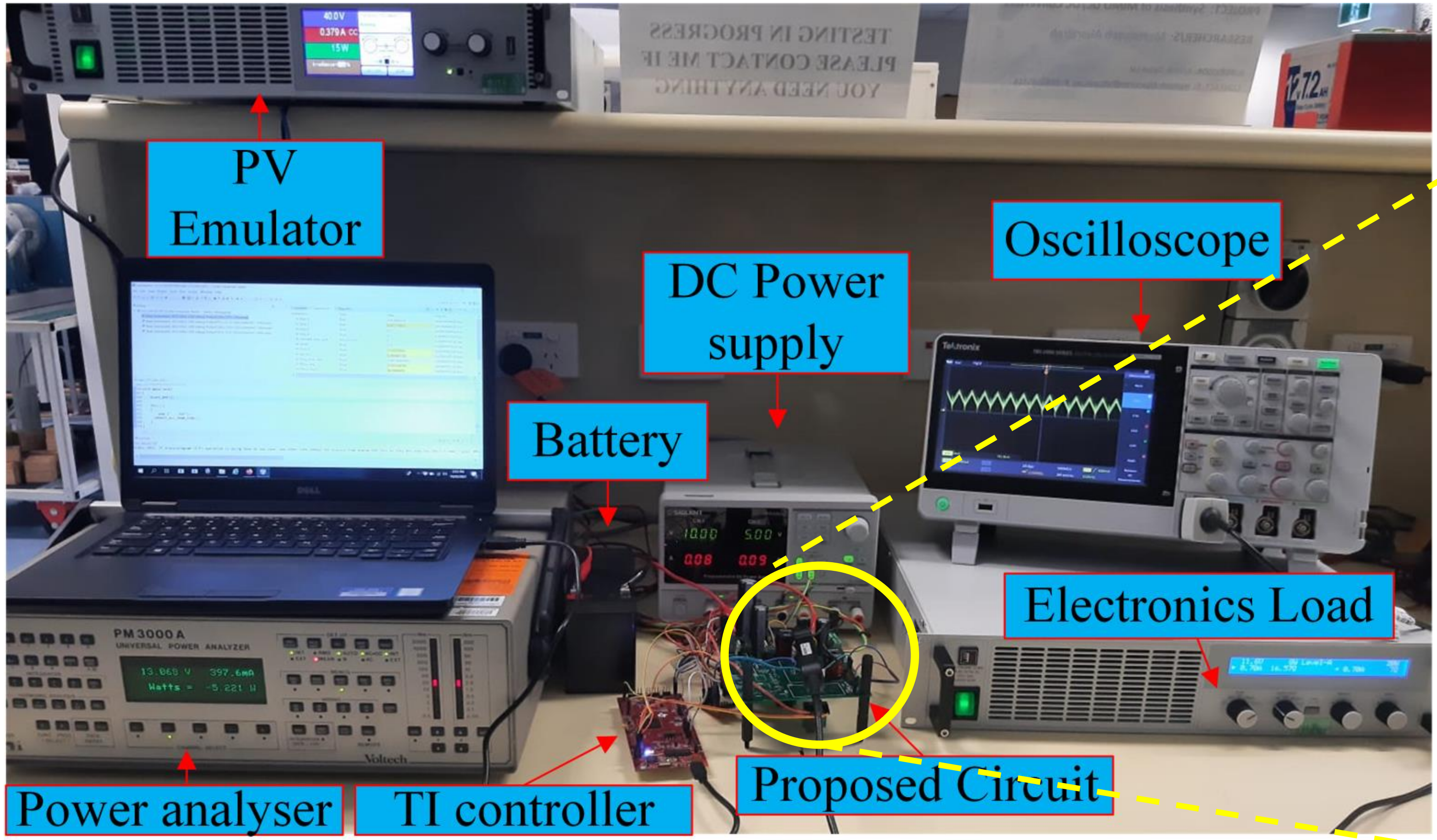
Buck converter

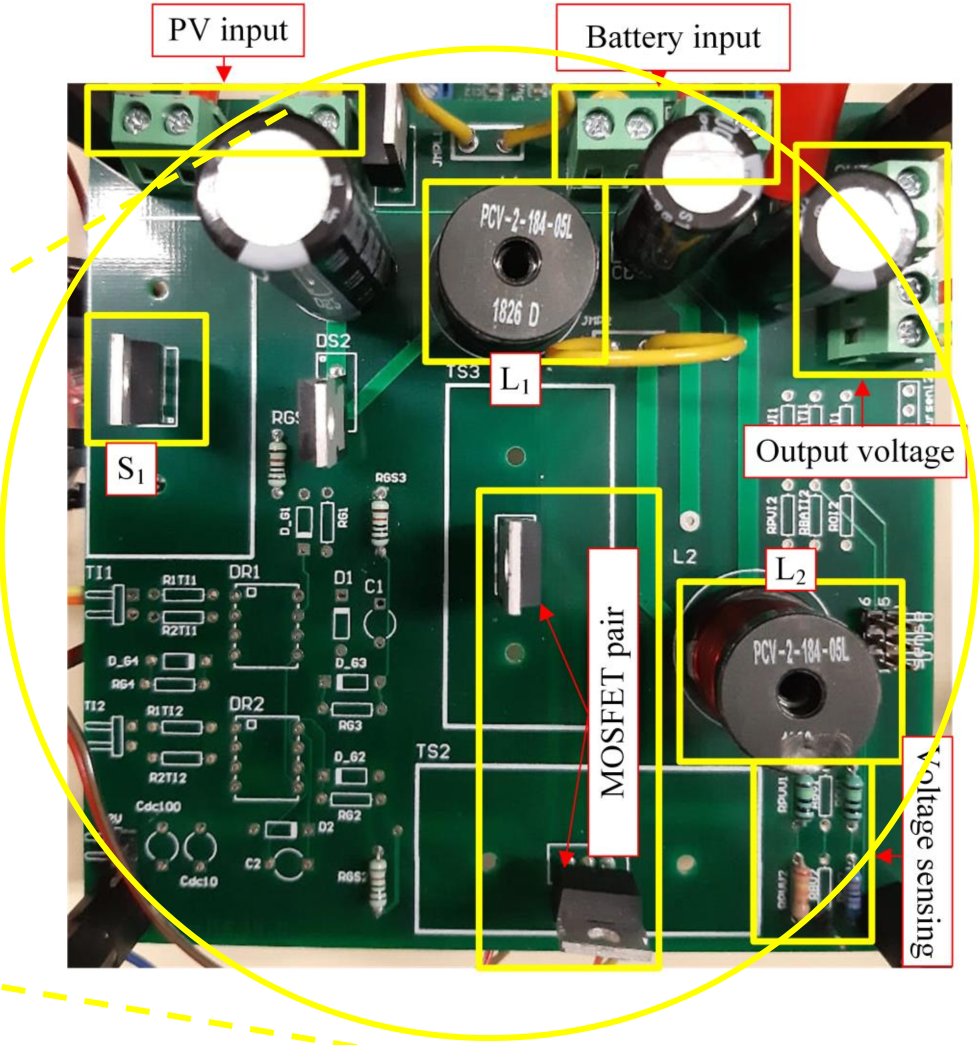


Boost converter

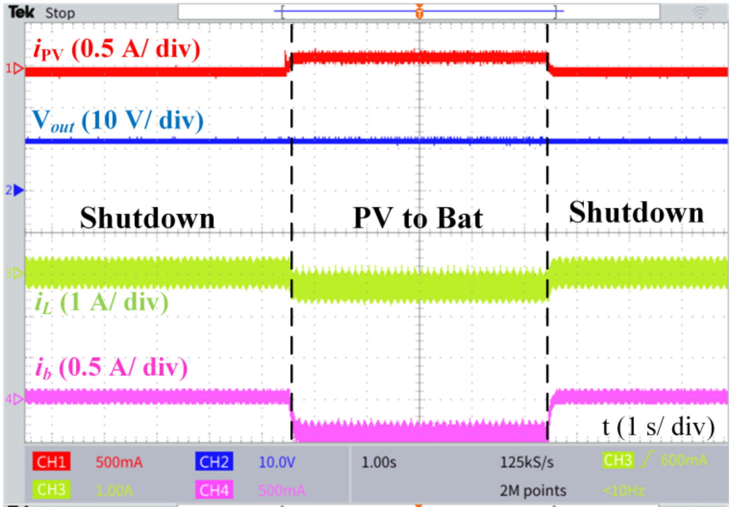


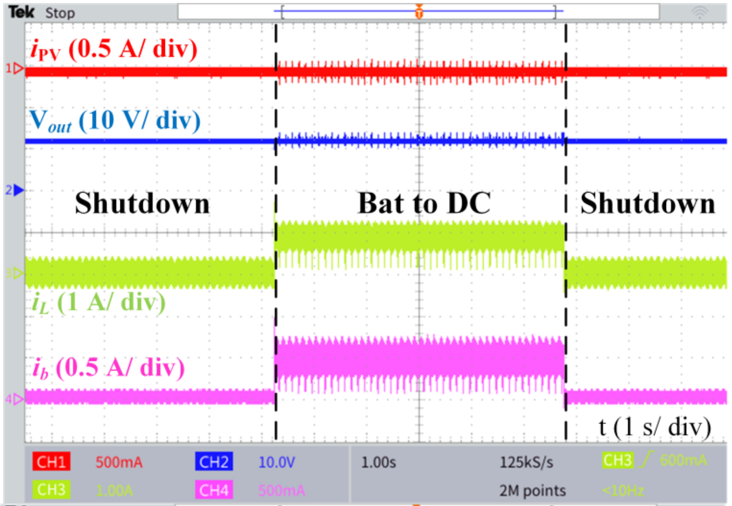
Experimental setup

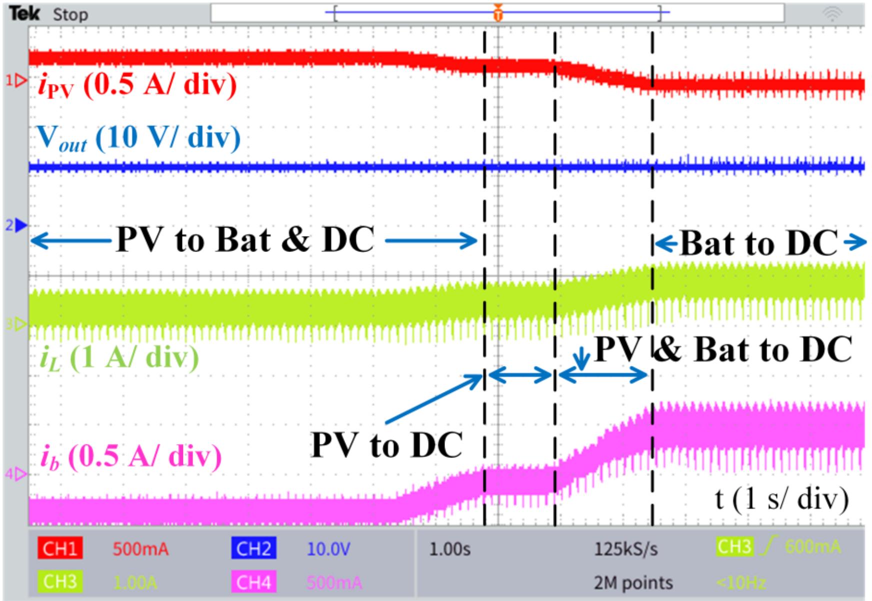


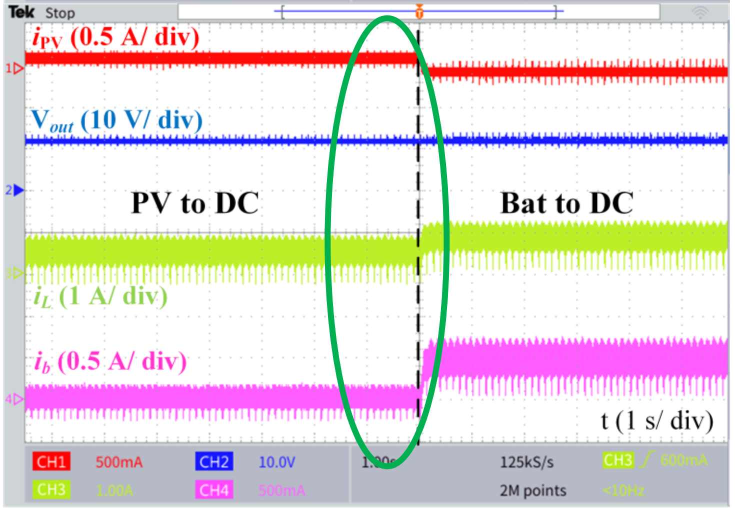


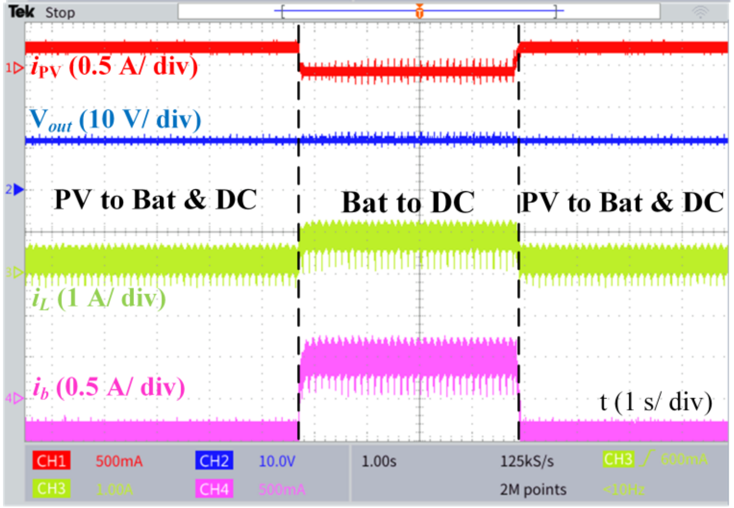
Experimental Results











Fast response in ms and smooth transition

Comparison between the proposed method and others

Reference	Modes	Delay	Overshoot	Settling time	Complex control	Selection Conditions	Modes Transition	Sensors
[60]	3	-	-	-	Mid	3	Simulation results	6
[61]	3	-	-	-	-	Not shown	Simulation results	5
[62]	3	-	-	-	Mid	3	Simulation results	Not considered
[63]	3	-	-	-	Mid	3	Simulation results	6
[64]	4	-	-	-	Mid	4	Not considered	5
[65]	4	-	-	-	Mid	3	One case only	5
[66]	4	-	-	-	-	3	Not considered	4
[51]	4	-	-	-	Mid	3	Not considered	6
[11]	5	No	10%	0.4 s	High	5	Experimental	6
[52]	4	No	40%	0.2 s	Mid	4	Experimental	6
[14]	7	Yes	20%	1 s	High	4	Experimental	5
[53]	7	Yes	No	1 s	High	4	Experimental	5
[57]	4	No	50%	0.6 s	Mid	4	Experimental	6
[58]	6	-	-	-	Mid	3	Simulation results	5
[59]	6	Yes	-	-	Mid	4	Experimental	6
[67]	3	No	10%	0.2 s	Mid	3	Experimental	6
[68]	3	No	10%	0.2 s	Low	2	Experimental	6
[69]	3	No	30%	0.3 s	Mid	3	Experimental	6
Proposed	7	No	10%	0.1 s	Low	2	Experimental	4

* Receiving PWM signal,

Short Summary

- In existing TPCs, transition between modes has an overshoot, long settling time, or a delay.
- Some existing TPCs have full control of seven modes with many switches/ less number of switches with limited control.
- Smooth and fast operation of all mode transitions in fully controlled manner

MPC Challenge #4

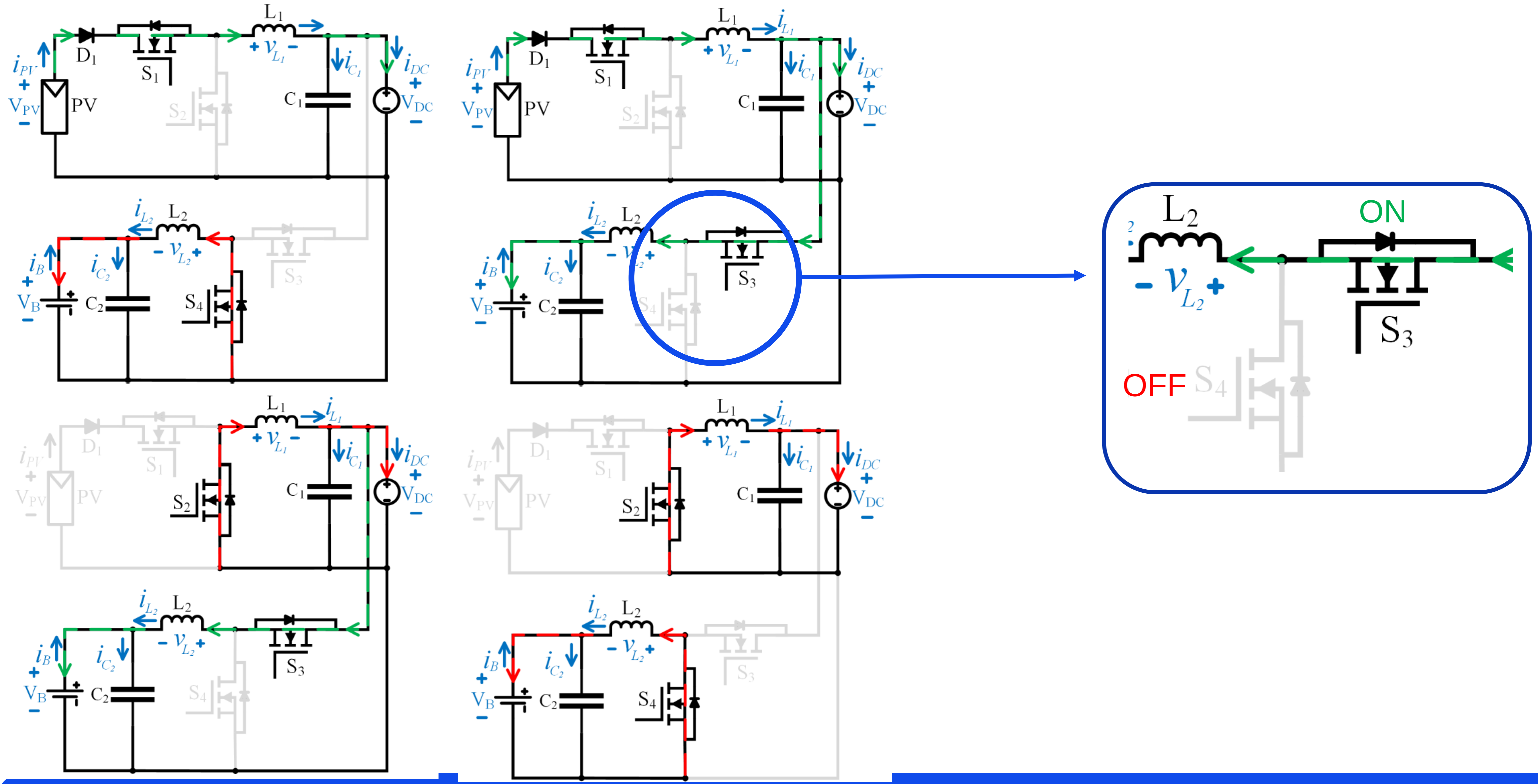
Multi-parametric Optimization and Compromises

Switching Look-up Table for Different Modes

Modes	Power	Active Components	State	Switch state ON	Switch state OFF	Duty condition	Fig
PV to DC bus	$P_{pv} = P_{DC}$	D_1, S_1, S_2, L_1 & C_1	I	$S_1{}^*$	$S_2{}^*$	–	–
			II	$S_2{}^*$	$S_1{}^*$		–
PV to battery	$P_{pv} = P_B$	All active except S_4	I	$S_1{}^*, S_3{}^\circ$	$S_2{}^*$	–	–
			II	$S_2{}^*, S_3{}^\circ$	$S_1{}^*$		–
PV to DC bus and battery	$P_{pv} = P_{DC} + P_B$	All active	I	$S_1{}^*, S_4{}^*$	$S_2{}^*, S_3{}^*$	$\frac{1}{D_3} \approx \frac{V_{DC}}{V_B}$	Fig. 5(a)
			II	$S_1{}^*, S_3{}^*$	$S_2{}^*, S_4{}^*$		Fig. 5(b)
			III	$S_2{}^*, S_3{}^*$	$S_1{}^*, S_4{}^*$		Fig. 5(c)
			IV	$S_2{}^*, S_4{}^*$	$S_1{}^*, S_3{}^*$		Fig. 5(d)
PV and battery to DC bus	$P_{pv} + P_B = P_{DC}$	All active	I	$S_1{}^*, S_4{}^*$	$S_2{}^*, S_3{}^*$	$\frac{1}{D_3} \geqslant \frac{V_{DC}}{V_B}$	Fig. 6(a)
			II	$S_1{}^*, S_3{}^*$	$S_2{}^*, S_4{}^*$		Fig. 6(b)
			III	$S_2{}^*, S_3{}^*$	$S_1{}^*, S_4{}^*$		Fig. 6(c)
			IV	$S_2{}^*, S_4{}^*$	$S_1{}^*, S_3{}^*$		Fig. 6(d)
PV and DC bus to battery	$P_{pv} + P_{DC} = P_B$	All active	I	$S_1{}^*, S_4{}^*$	$S_2{}^*, S_3{}^*$	$\frac{1}{D_3} \leqslant \frac{V_{DC}}{V_B}$	Fig. 7(a)
			II	$S_1{}^*, S_3{}^*$	$S_2{}^*, S_4{}^*$		Fig. 7(b)
			III	$S_2{}^*, S_3{}^*$	$S_1{}^*, S_4{}^*$		Fig. 7(c)
			IV	$S_2{}^*, S_4{}^*$	$S_1{}^*, S_3{}^*$		Fig. 7(d)
battery to DC bus	$P_B = P_{DC}$	S_3, S_4, L_2, C_1 & C_2	I	$S_3{}^*$	$S_4{}^*$	–	–
			II	$S_4{}^*$	$S_3{}^*$		–
DC bus to battery	$P_{DC} = P_B$	S_3, S_4, L_2, C_1 & C_2	I	$S_3{}^*$	$S_4{}^*$	–	–
			II	$S_4{}^*$	$S_3{}^*$		–

* Switch operates in PWM $^\circ$ Switch is fully ON

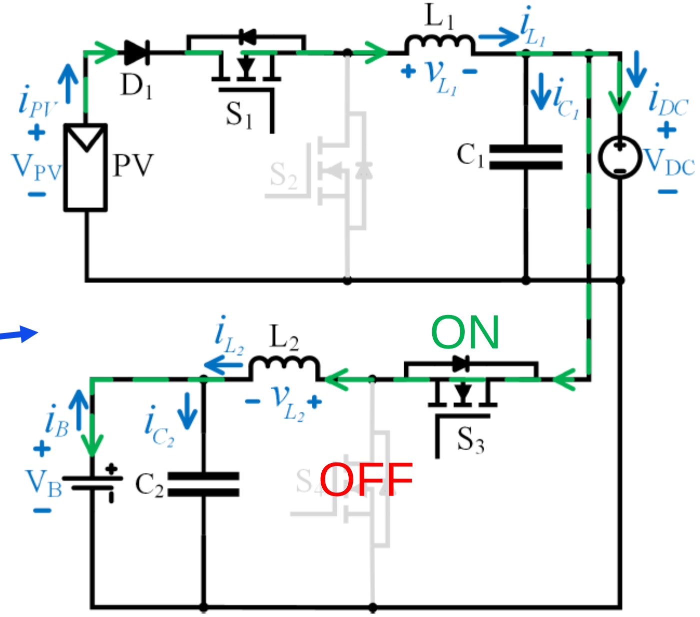
Example #1: Type II-IIB circuit

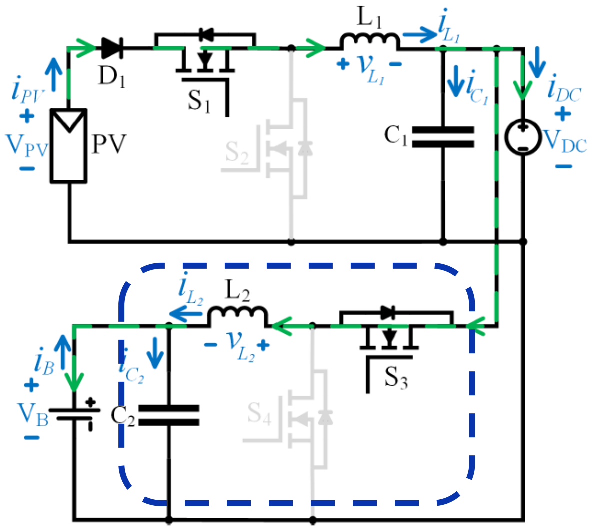


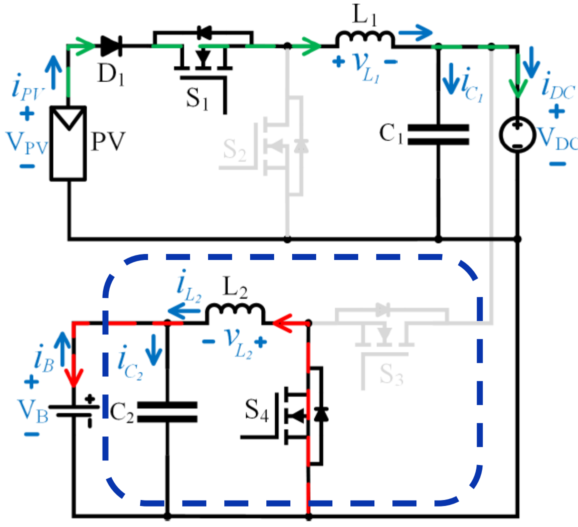
Different Switching patterns for the same Mode

EFFICIENCY COMPARISON AT DIFFERENT DUTY CYCLES.

Symbol	d_2=100%	d_2= 93%	d_2= 90%	d_2= 85%	d_2= 80%
V_{pv} (V)	147.9	151.1	153.18	156.26	158.46
I_{pv} (A)	1.959	1.9363	1.912	1.8524	1.7824
P_{pv} (W)	289.74	292.56	292.87	289.46	282.44
V_B (V)	52.989	51.741	50.914	49.424	48.081
I_B (A)	2.4943	1.8703	1.457	0.712	0.04
P_B (W)	132.17	96.773	74.183	35.182	1.9434
V_{DC} (V)	53.459	54.628	55.39	56.527	57.337
I_{DC} (A)	2.7294	3.3139	3.6952	4.2633	4.6687
P_{DC} (W)	145.91	181.03	204.68	240.99	267.69
S_1 losses	4.5679	4.7867	4.8787	5.0308	5.0735
S_2 losses	5.8323	6.4618	6.6331	7.0274	7.2689
S_3 losses	1.1671	3.1394	2.6438	1.3809	0.4
S_4 losses	0	0.792	0.172	0.148	0.28
Efficiency	96.01%	94.81%	95.11%	95.31%	95.38%

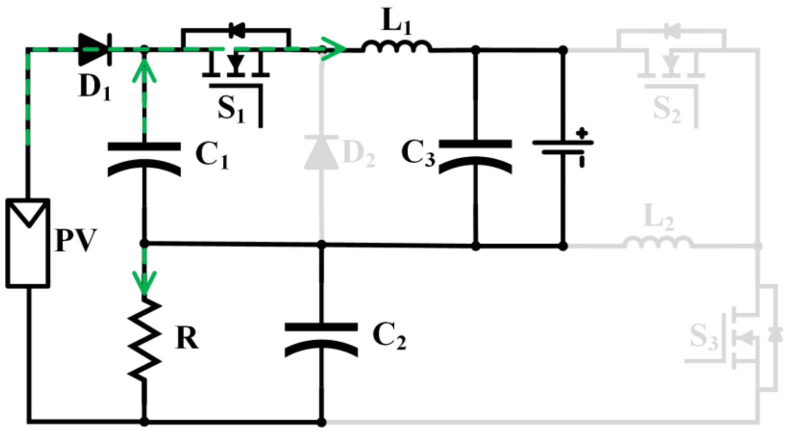


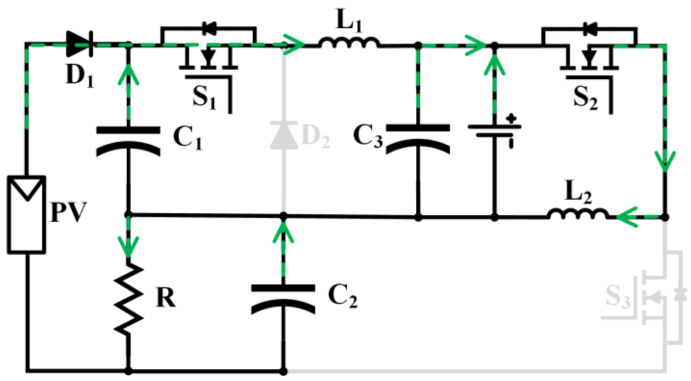


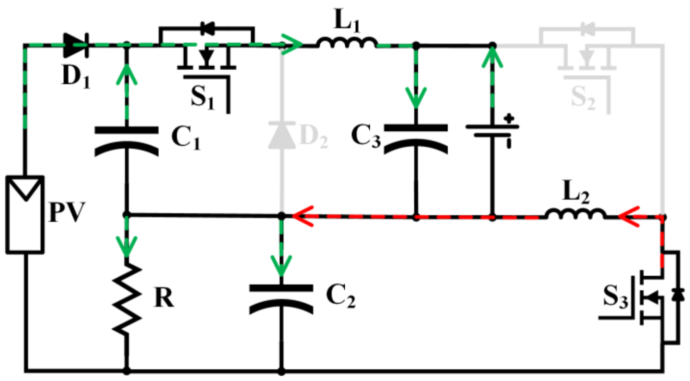


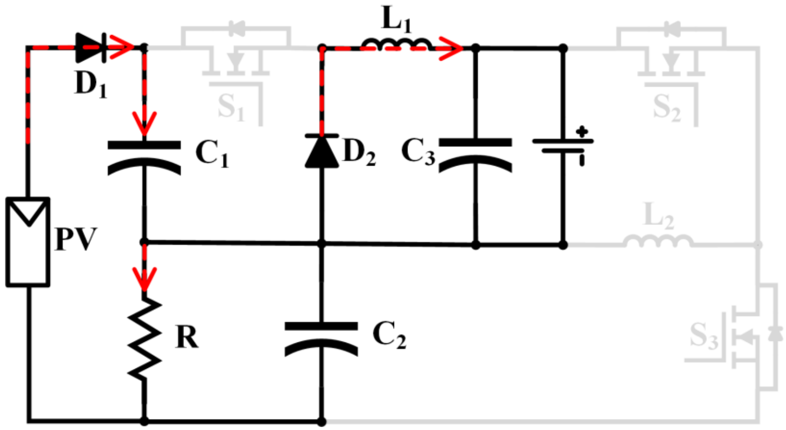
Receiving PWM signal with Duty d_2

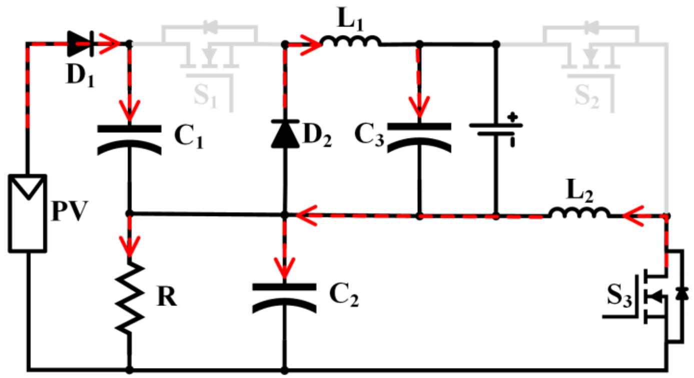
Example #2: Type I-III-I circuit

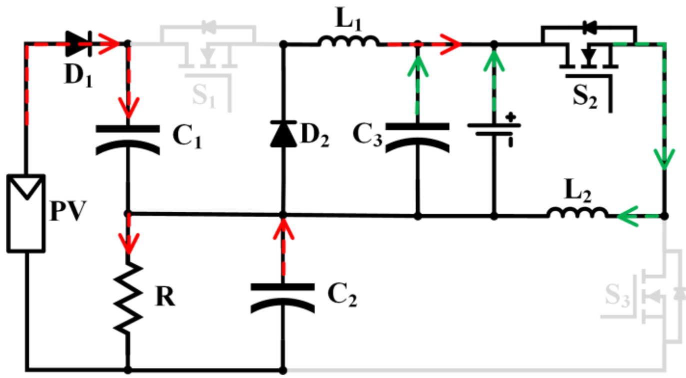












UTS

H. Aljarajreh, D. D. -C. Lu, Y. P. Siwakoti and C. K. Tse, "A Nonisolated Three-Port DC–DC Converter With Two Bidirectional Ports and Fewer Components," in *IEEE Transactions on Power Electronics*, vol. 37, no. 7, pp. 8207-8216, July 2022, doi: 10.1109/TPEL.2022.3146837.

Different switching patterns comparison

Symbol	R6020ENX
P_{pv} (W)	292.27
P_B (W)	188.4
P_{DC} (W)	100.7
S_1 losses	2.0387
D_1 losses	1.2854
S_2 losses	0
S_3 losses	0
Total losses	3.3241
Efficiency	98.86%

PV TO BAT AND DC WHERE ALL SWITCHES ARE ACTIVE AND d_2 VARIES

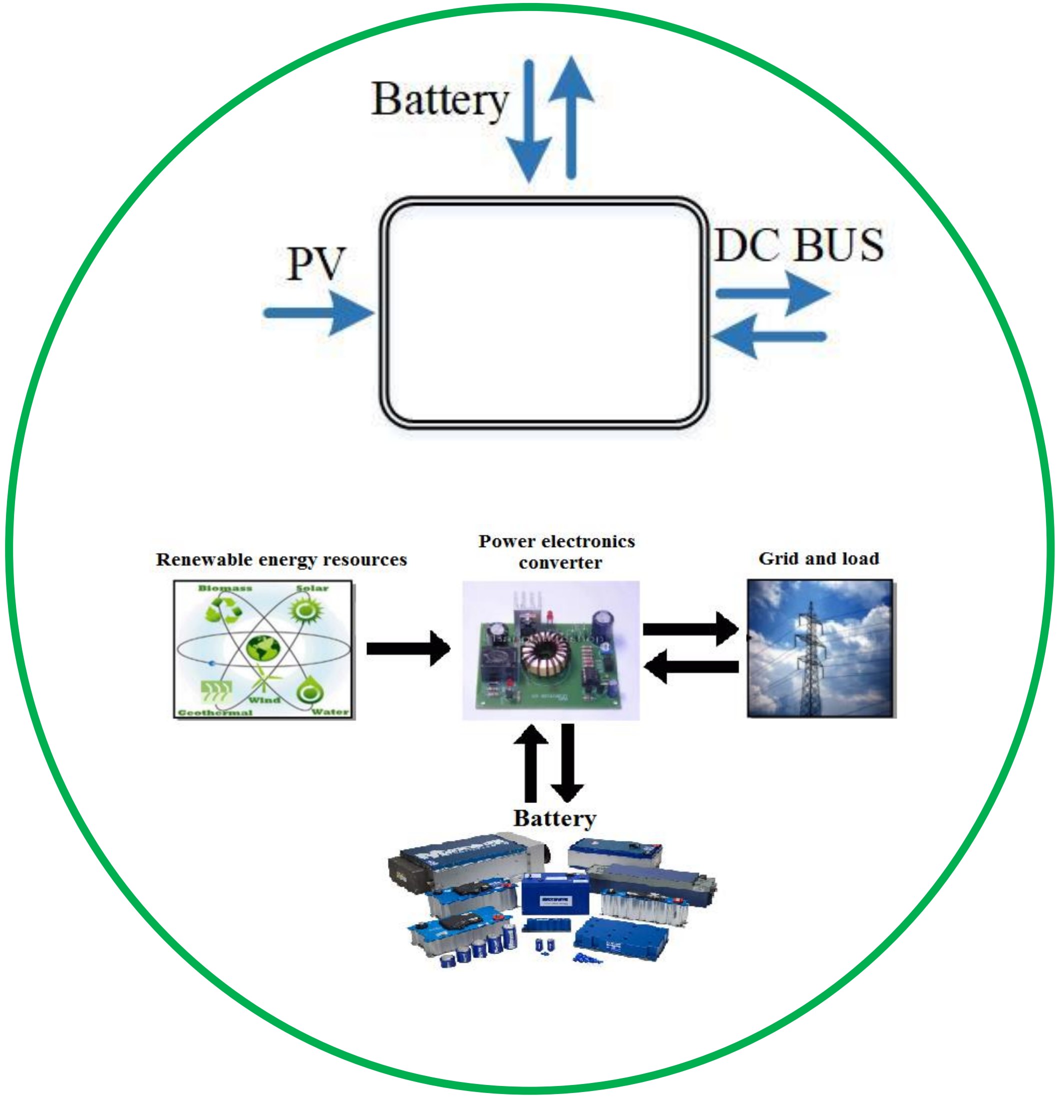
Symbol	d_2 = 4.6 us	d_2 = 4.8 us	d_2 = 5 us	d_2 = 5.2 us
V_{pv} (V)	150.36	149.7	148.21	146.1
I_{pv} (A)	1.9428	1.9479	1.9574	1.9669
P_{pv} (W)	292.12	291.6	290.1	287.36
V_B (V)	54.582	53.768	52.071	49.947
I_B (A)	3.2909	2.8842	2.0354	0.973
P_B (W)	179.62	155.08	105.99	48.622
V_{DC} (V)	52.164	52.944	54.462	56.111
I_{DC} (A)	2.0822	2.472	3.2308	4.0553
P_{DC} (W)	108.62	130.88	175.96	227.5
S_1 losses	2.0076	2.0012	1.9807	1.9636
D_1 losses	1.2844	1.2892	1.2945	1.298
S_2 losses	0.733	2.5011	4.946	7.856
S_3 losses	0.035	0.0924	0.218	0.411
Total losses	4.06	5.8839	8.4392	11.5286
Efficiency	98.61%	97.98%	97.09%	95.99%

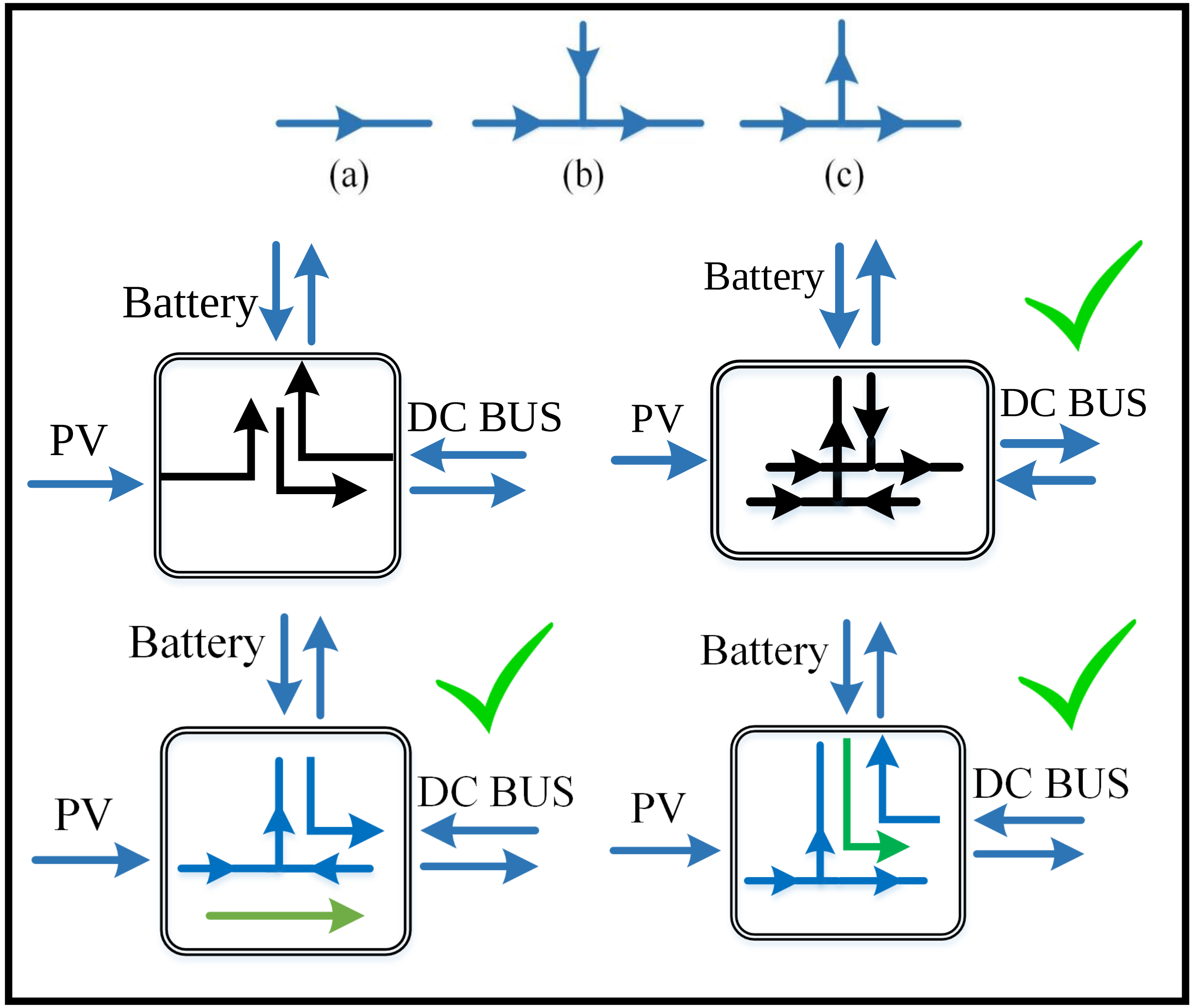
Short Summary

- Each mode of operation could be obtained from different switching patterns
- In the first example, maximum efficiency could be achieved when the S_3 is always ON and S_4 is OFF.
- In the second example, maximum efficiency could be achieved when S_1 is receiving PWM signal while S_2 and S_3 are OFF.
- In contrast, it will limit the control dimension.

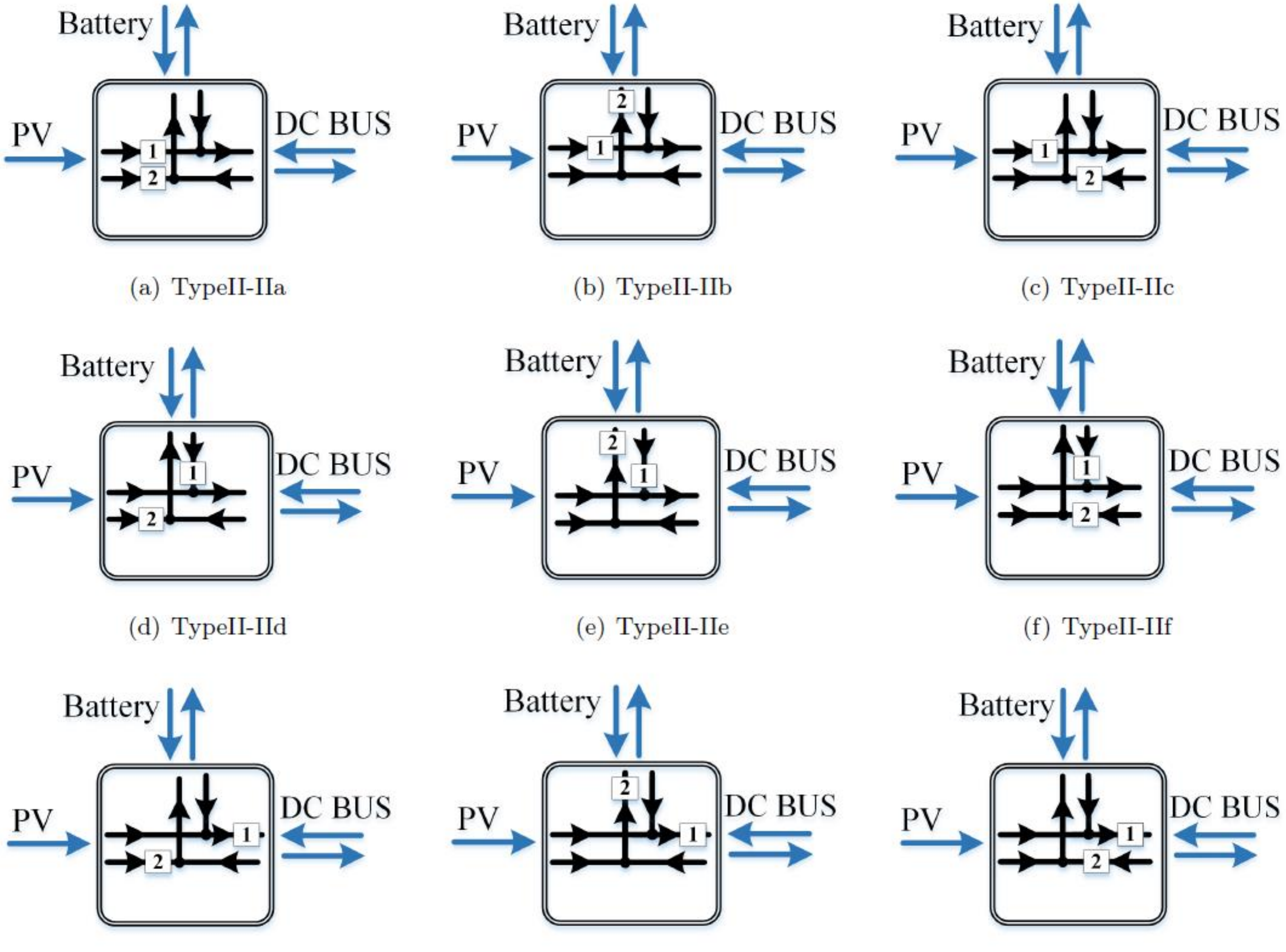
- Existing and Future Applications of Multiport Converters (MPCs)
- Major Challenges with MPCs and Some Solutions
- Tool to Derive and Develop MPC Topologies
- Reliability and Fault-tolerant Operations of MPCs

Power flow graphs





C. K. Tse, M. H. L. Chow and M. K. H. Cheung, "A family of PFC voltage regulator configurations with reduced redundant power processing," in *IEEE Transactions on Power Electronics*, vol. 16, no. 6, pp. 794-802, Nov 2001.

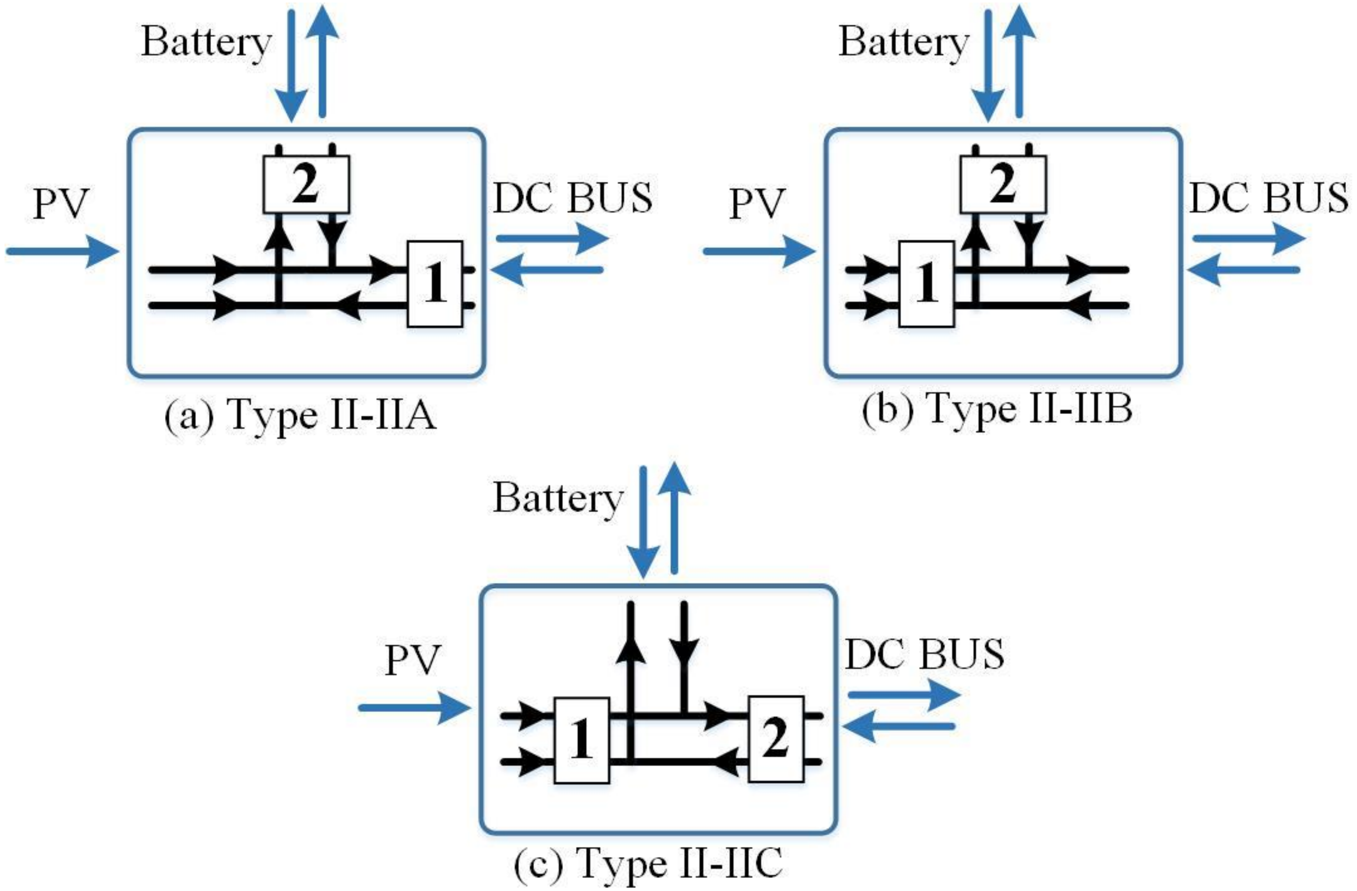


(a) TypeII-IIa (b) TypeII-IIb (c) TypeII-IIc

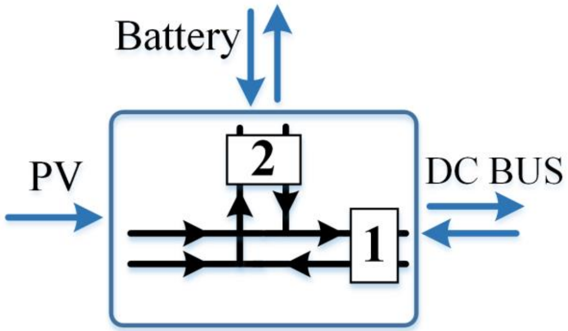
(d) TypeII-IId (e) TypeII-IIe (f) TypeII-IIf

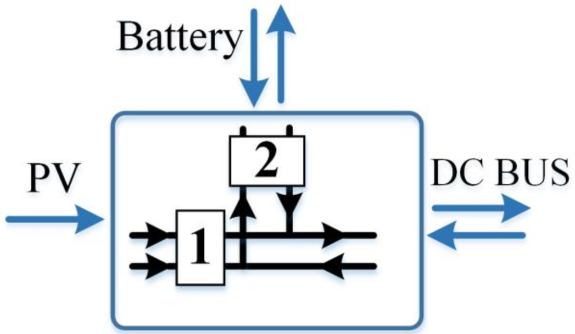
(g) TypeII-IIg (h) TypeII-IIh (i) TypeII-IIi

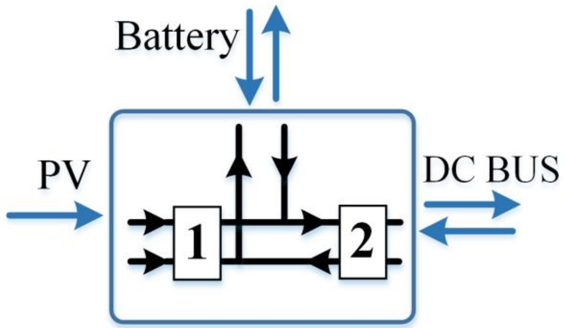
Practical implementation configurations of Type II-II

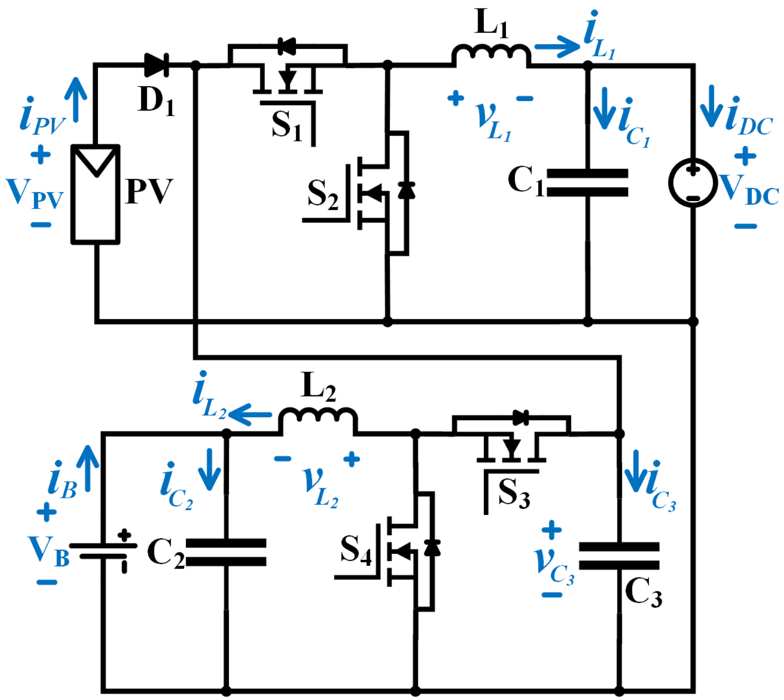


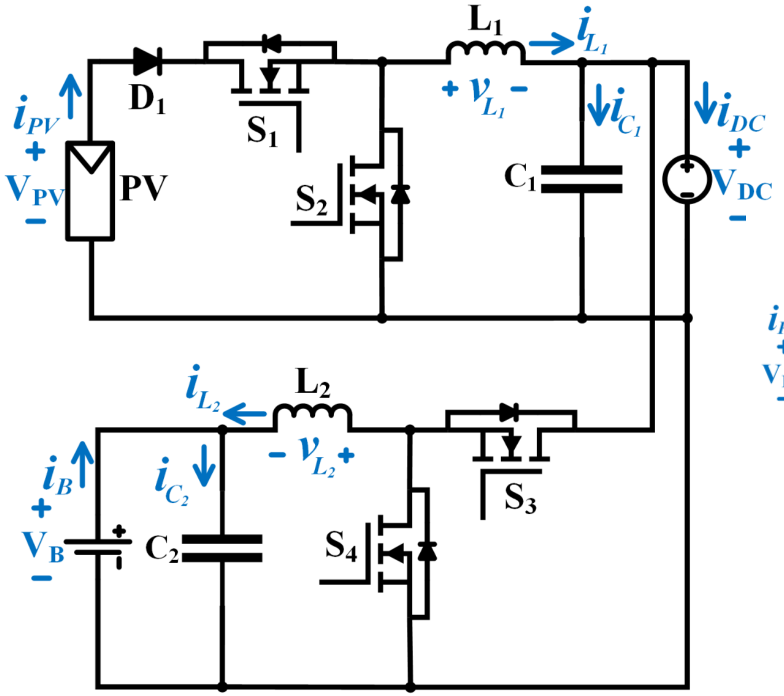
Example circuits of Type II-II

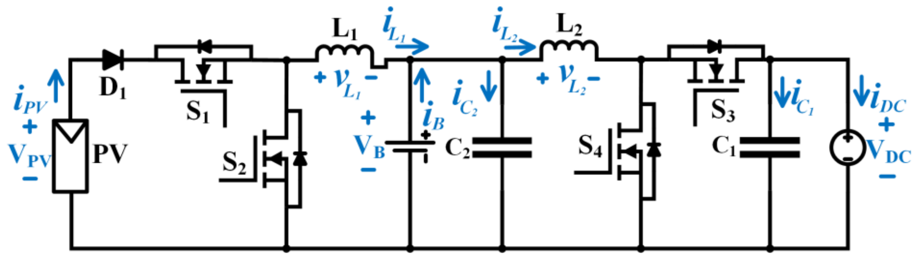




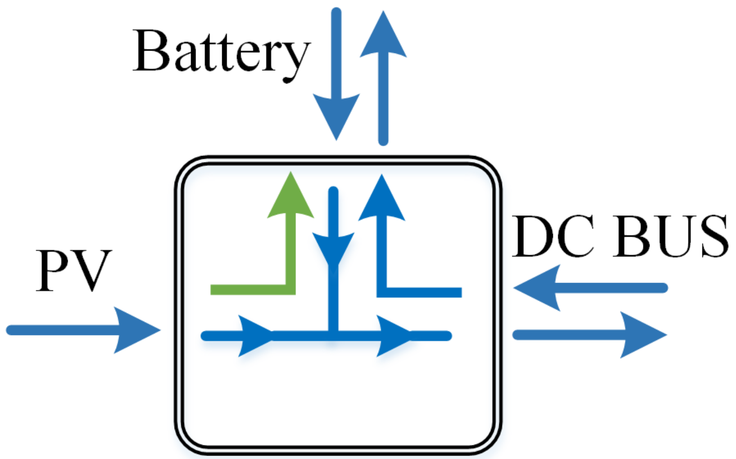


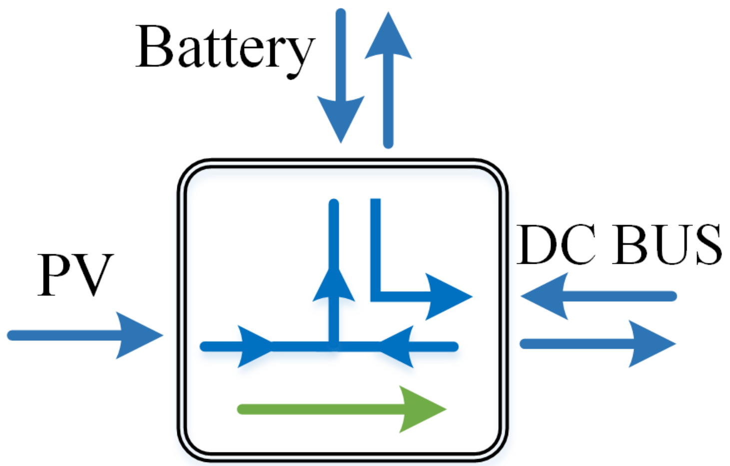




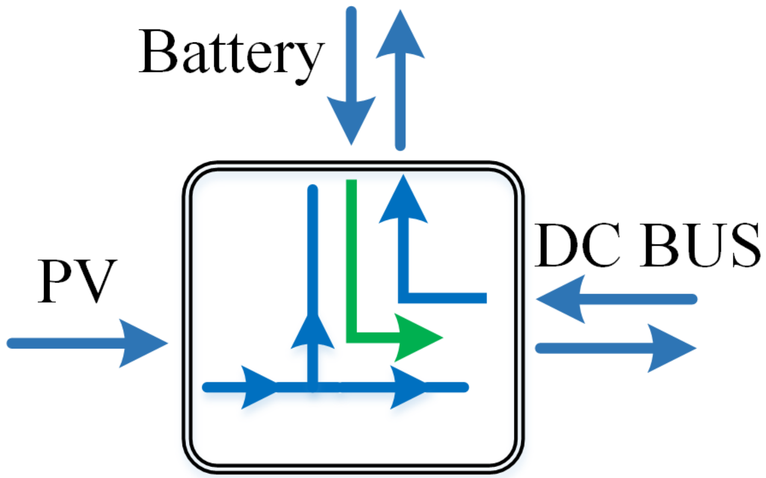


All possible power flow graphs of two Type I and Type II :

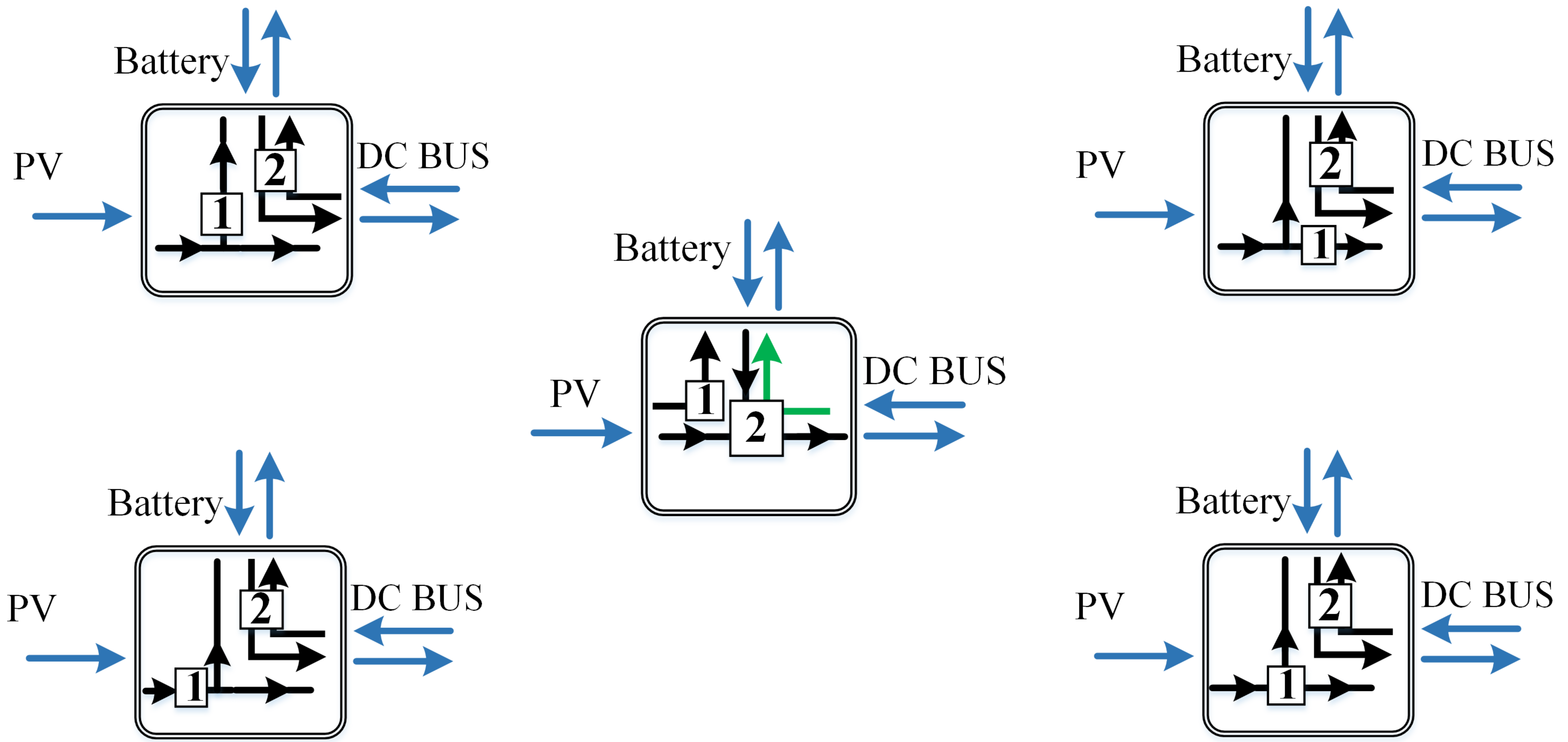




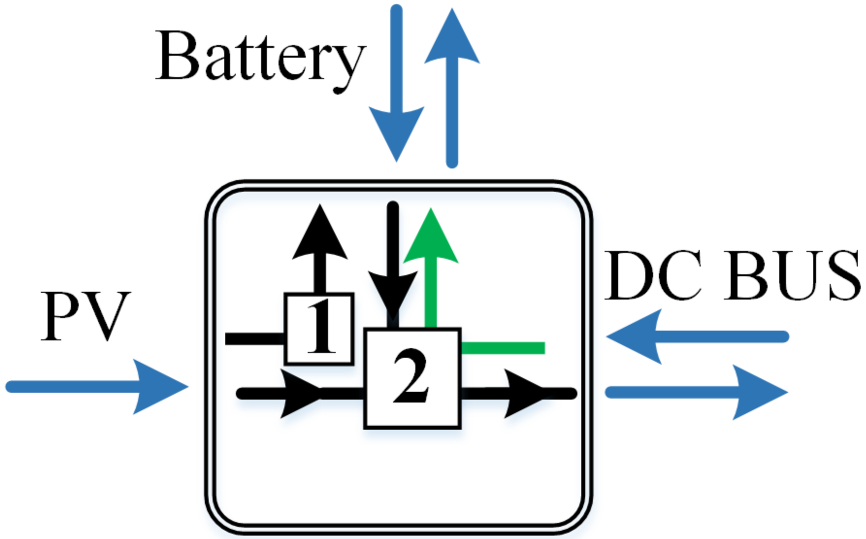
One power flow graph of two Type I and Type III:

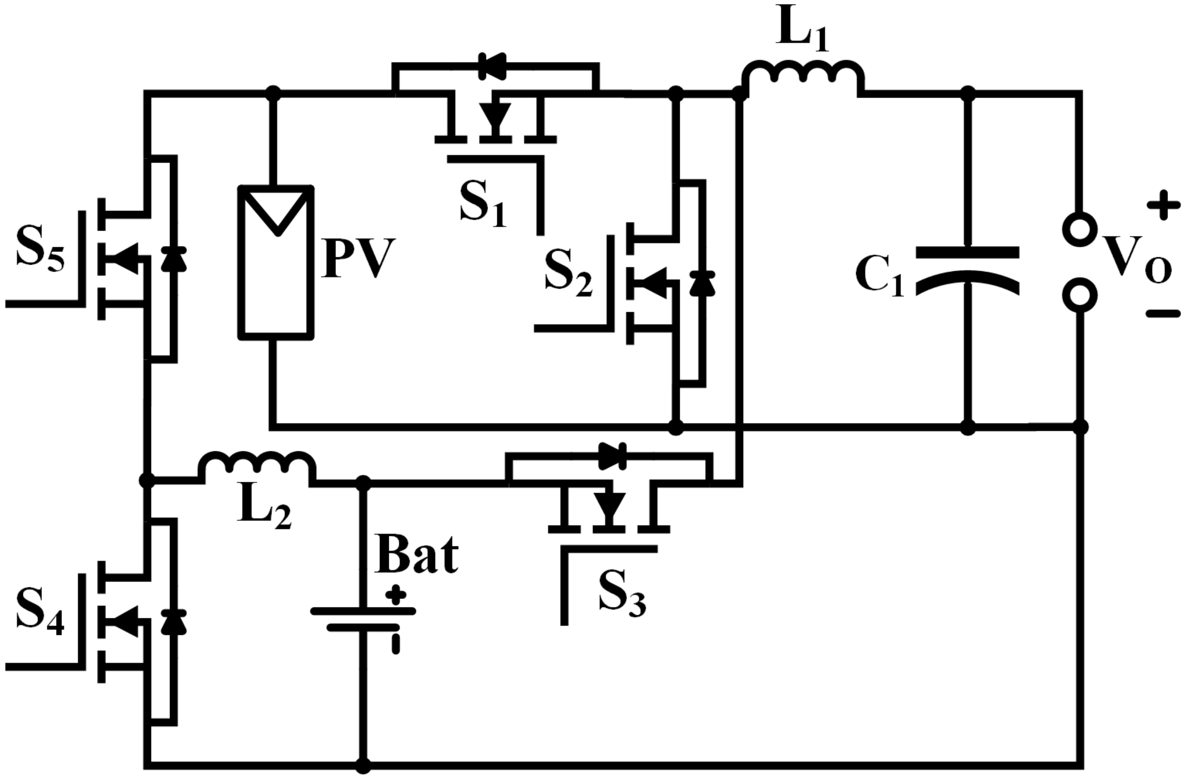


Two converters are placed in appropriate paths of the power flow:



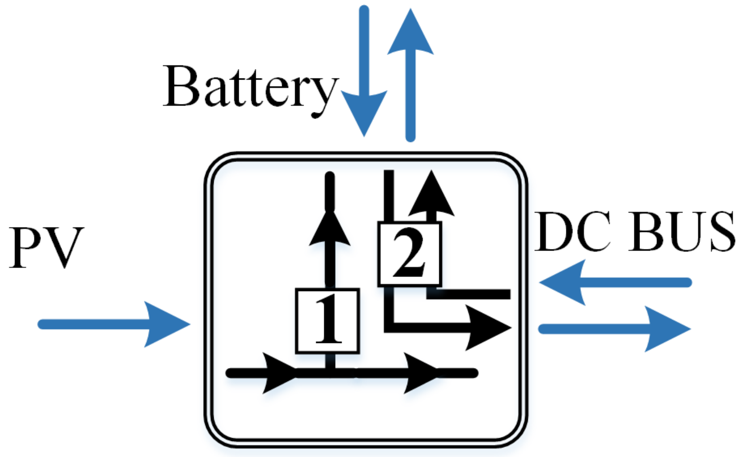
Type I-II-IA

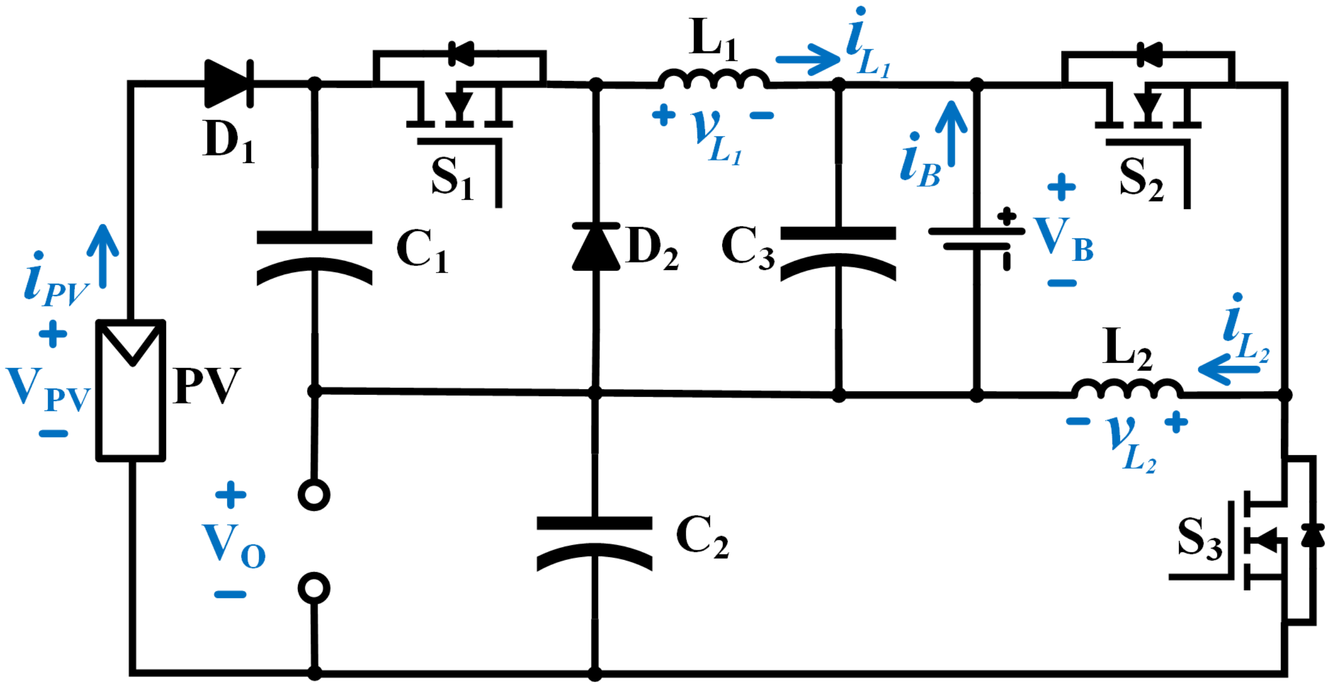




- Advantage: Single power processing
- Limitation: PV and battery to DC bus Mode

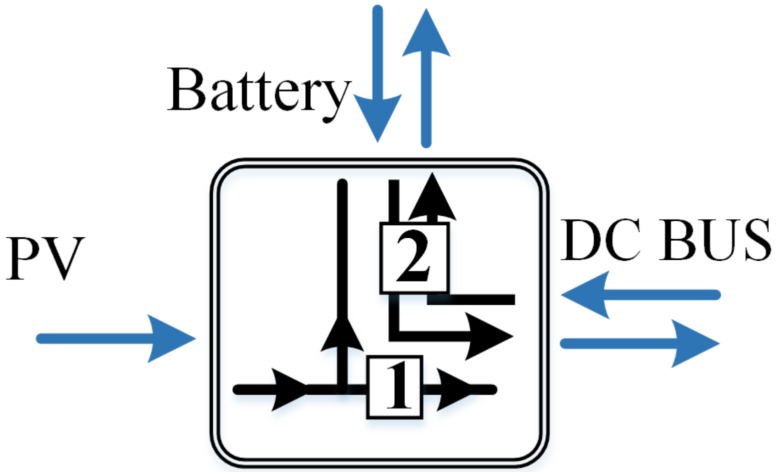
Type I-III-IA

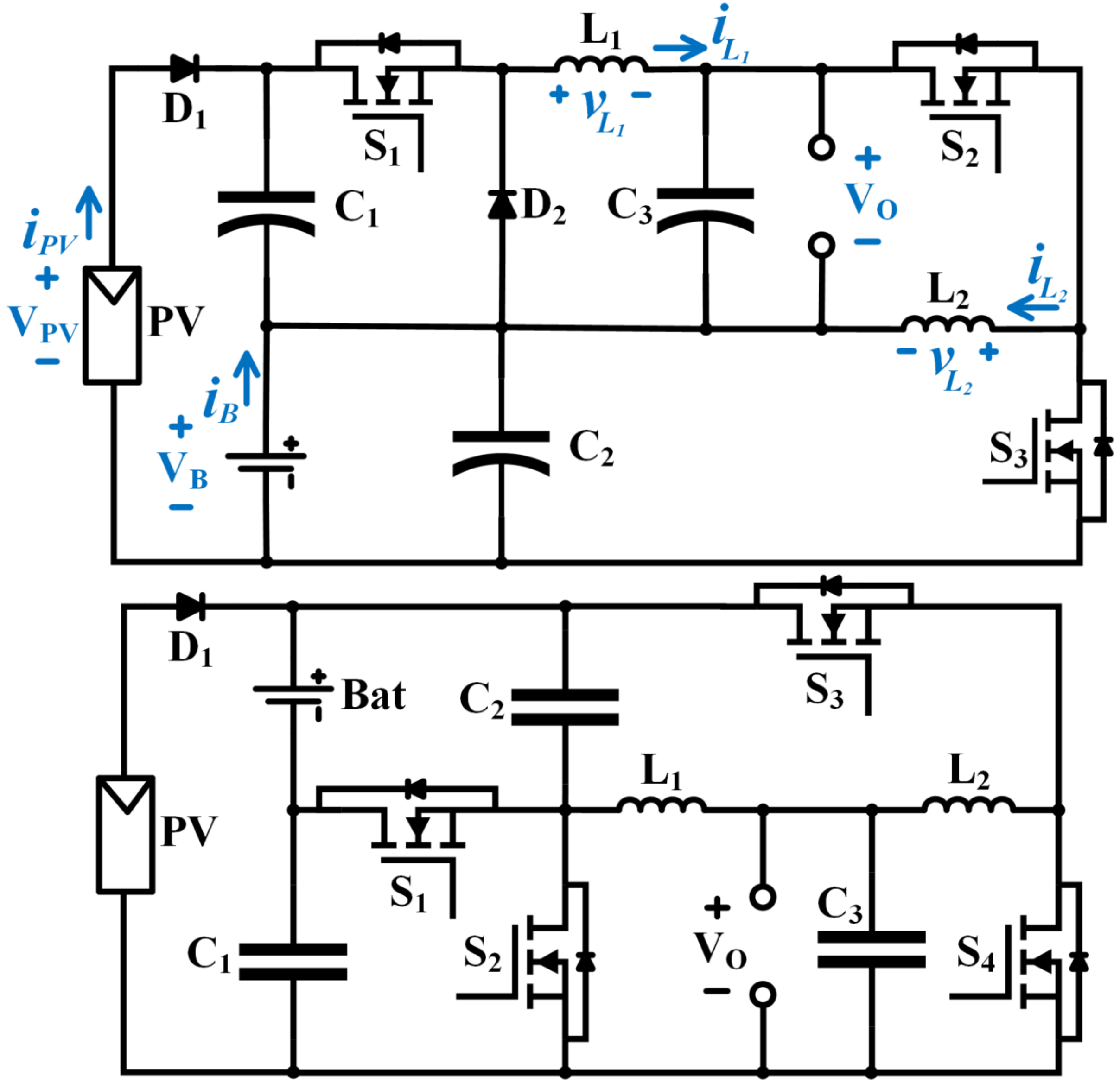




- Advantage: 4 Semiconductor devices
- Limitation: PV to battery Mode

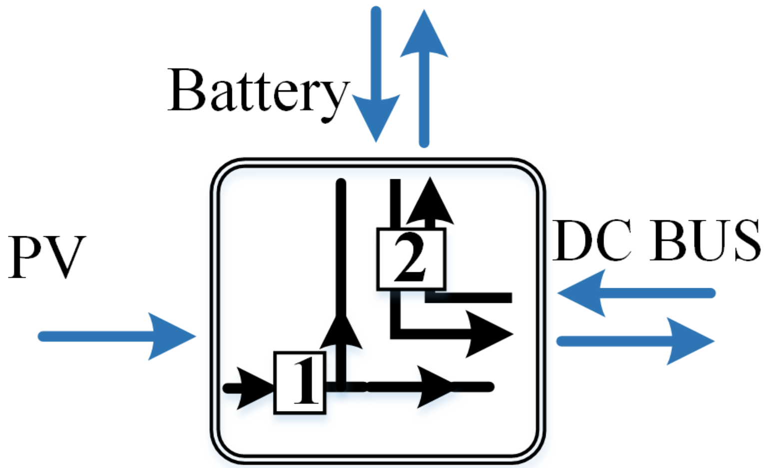
Type I-III-IB

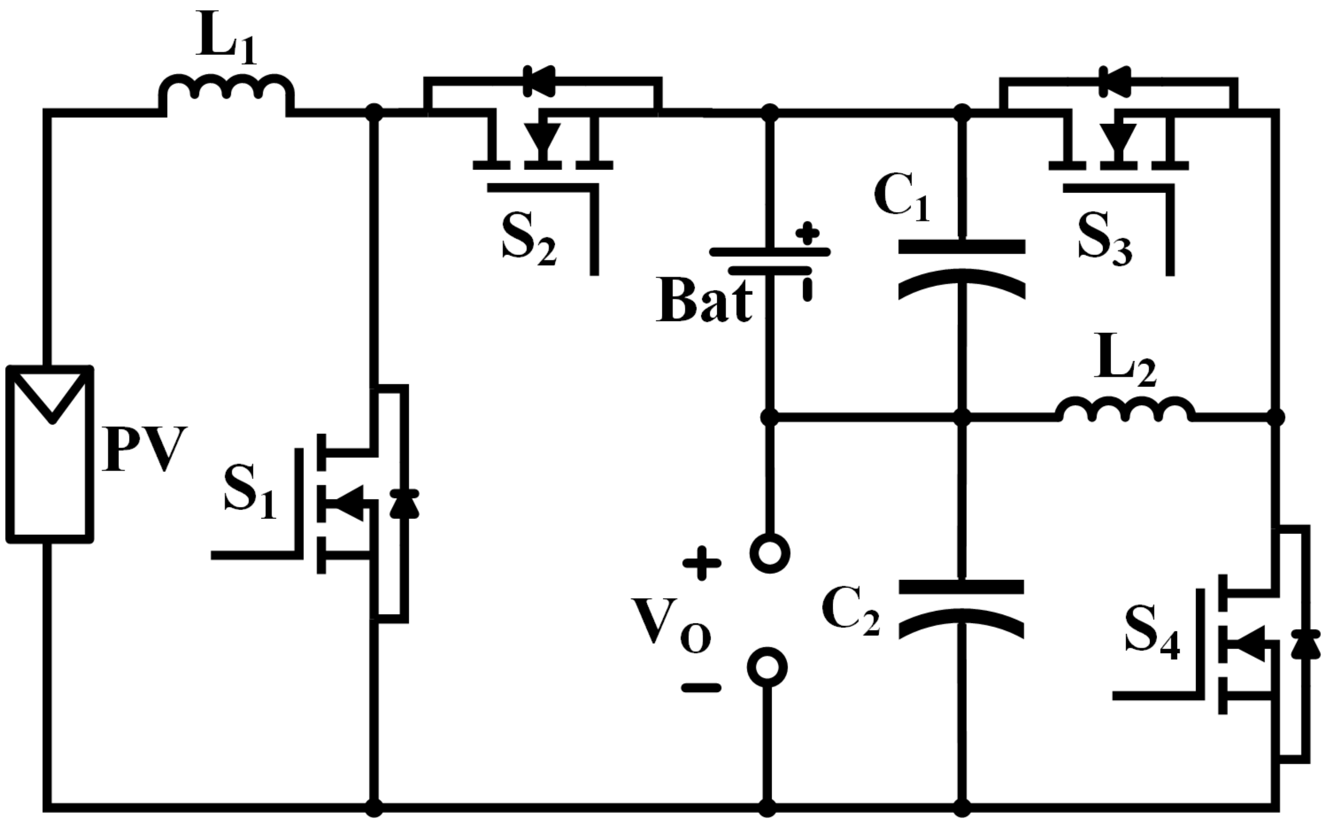




- Advantage: 4 Semiconductor devices
- Limitation: PV to DC bus Mode

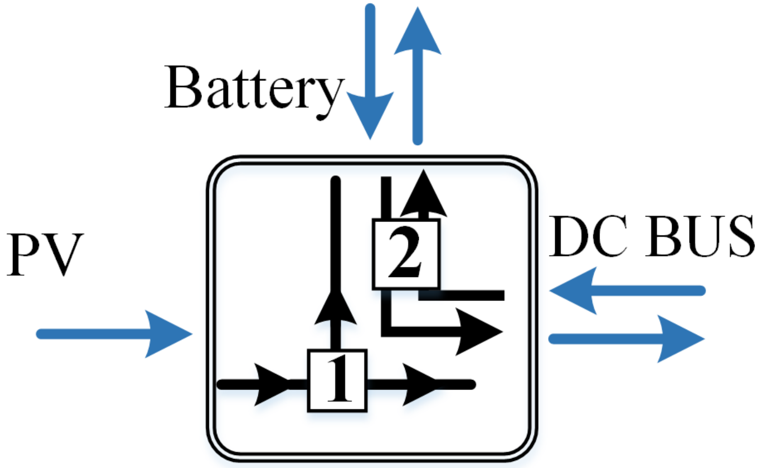
Type I-III-IC

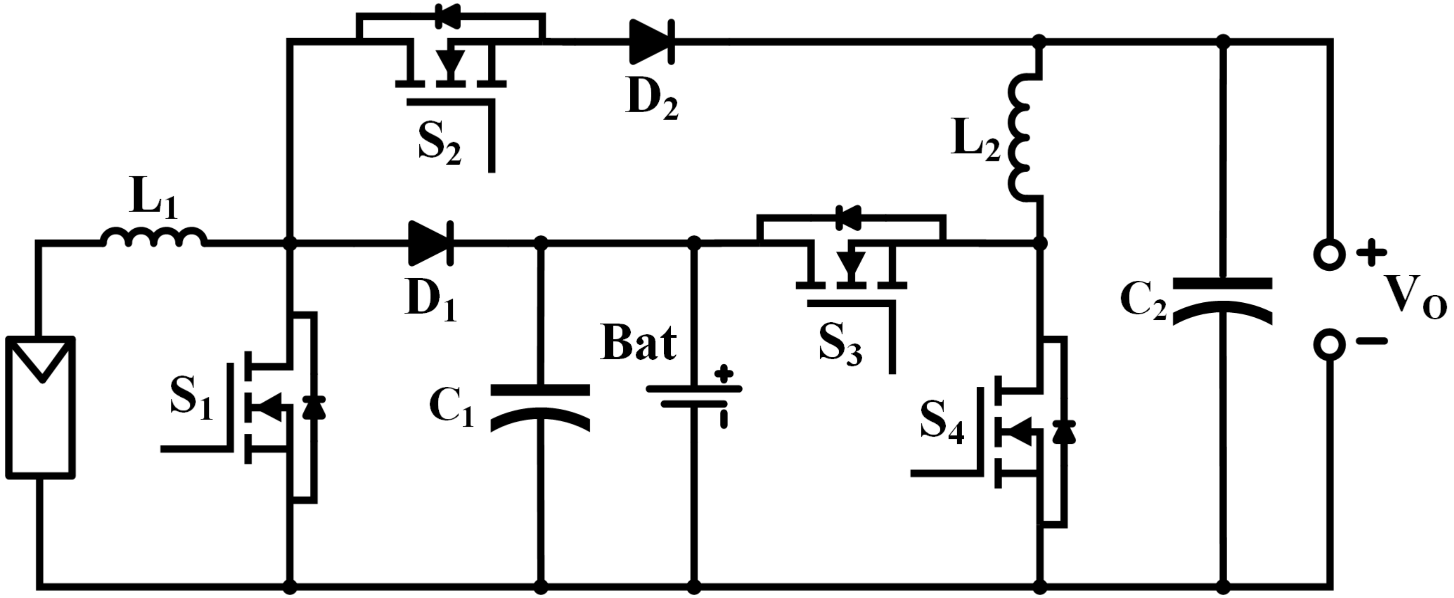




- Advantage: 4 Switches
- Limitation: PV to battery Mode

Type I-III-ID

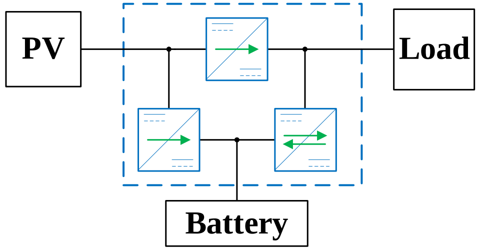




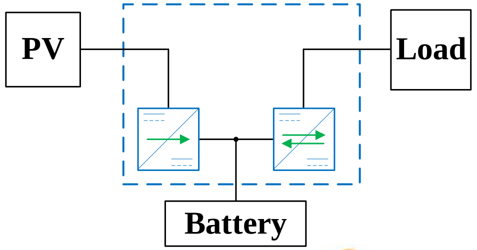
- Advantage: Single power processing
- Limitation: 4 Switches and 2 Diodes

Cheng, T. and Lu, D.D.C., 2017. Three-port converters with a flexible power flow for integrating PV and energy storage into a DC bus. *J. Power Electron*, *17*(6), pp.1433-1444.

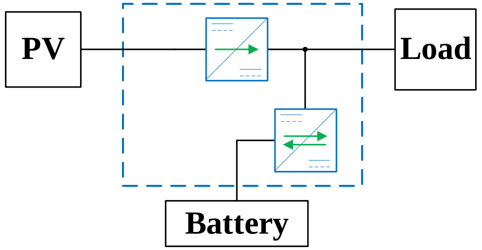
A systematic topological study to derive all possible Three-Port Converters (TPCs)



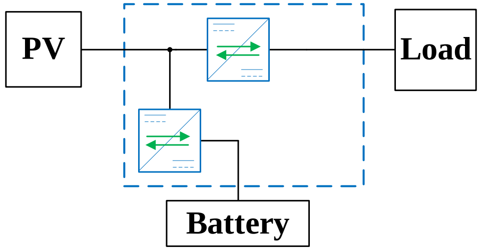
- Efficiency
- Simplicity
- Control



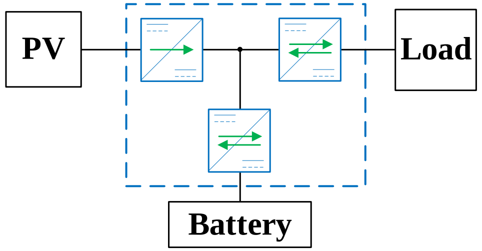
- Efficiency
- Simplicity
- Control



- Efficiency
- Simplicity
- Control



- Efficiency
- Simplicity
- Control



- Efficiency
- Simplicity
- Control

- Comprehensive guidelines for researchers.
- Best configuration for specific application

Short Summary

- A topological study to derive all possible TPC configurations by using power flow graphs is presented.
- Power flow graphs technique produces more efficient design
- Some practical power flow configurations have been analysed and verified experimentally

Existing and Future Applications of Multiport Converters (MPCs)

Major Challenges with MPCs and Some Solutions

Tool to Derive and Develop MPC Topologies

Reliability and Fault-tolerant Operations of MPCs

Reliability and FT of MPCs

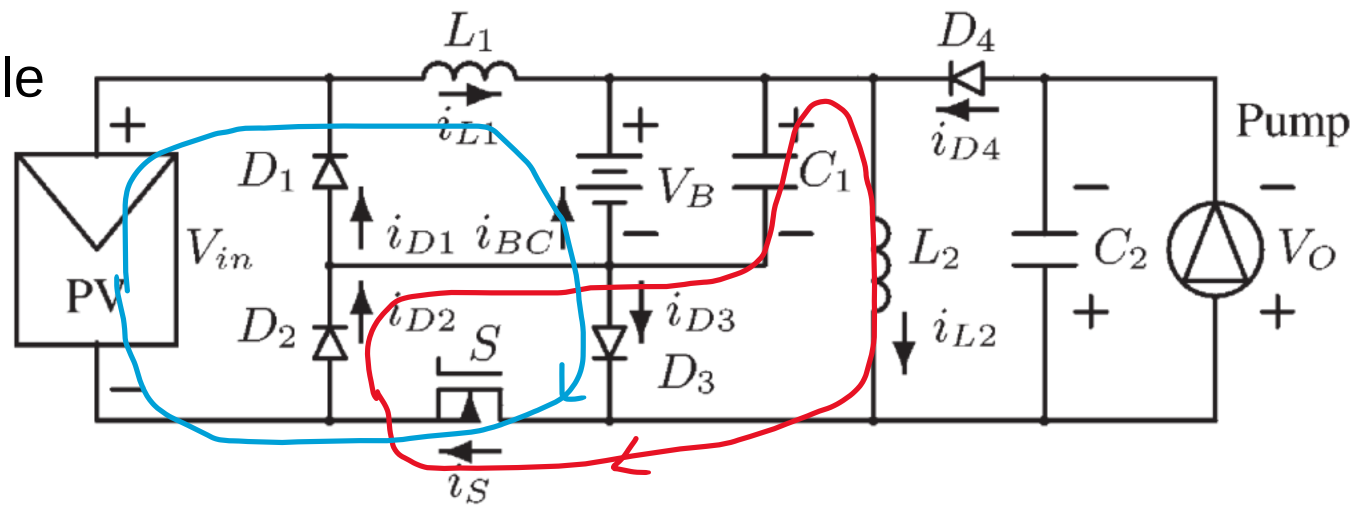
How component stress translates into failure calculations

Lifespan Comparison

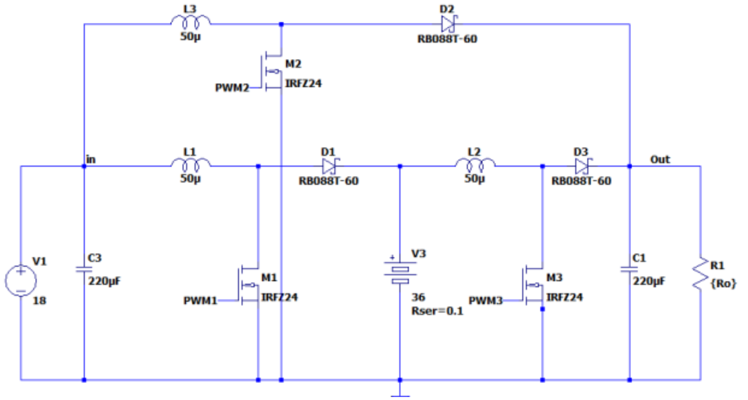
5 years　10 years　15 years　20 years

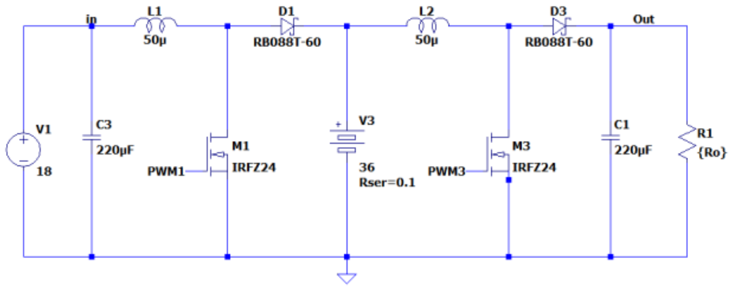
Are MPCs reliable?

- Sharing of components inevitably increases voltage or current stress
- How to have a fair comparison?
- How to make MPC more reliable while reducing the component count?

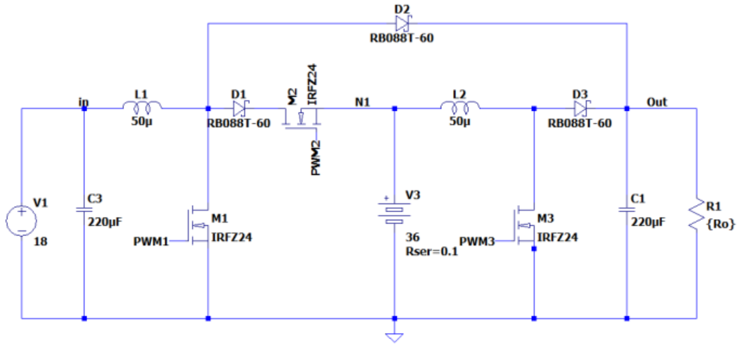


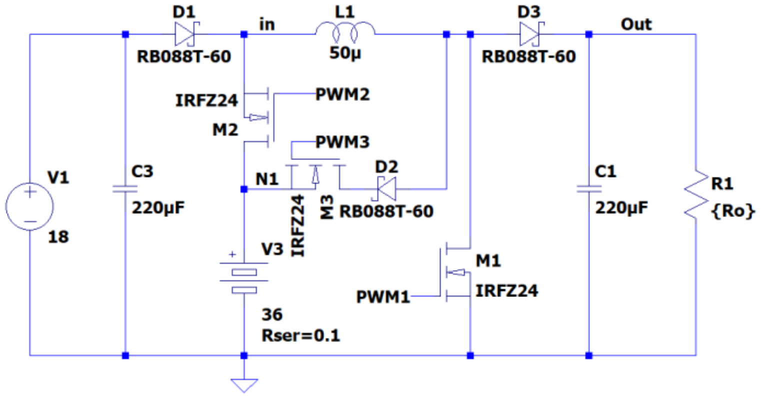
Six Representative MPC Topologies



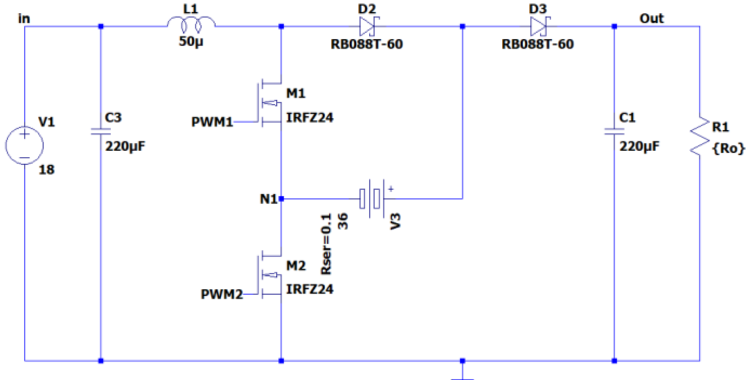


T. Cheng and D. D.-C. Lu, "Three-Port Converters with a Flexible Power Flow for Integrating PV and Energy Storage into a DC Bus," *Journal of Power Electronics*, vol. 17, no. 6, pp. 1433–1444, 2017. [Online]. Available: https://koreascience.or.kr/article/JAKO201734158606268.page

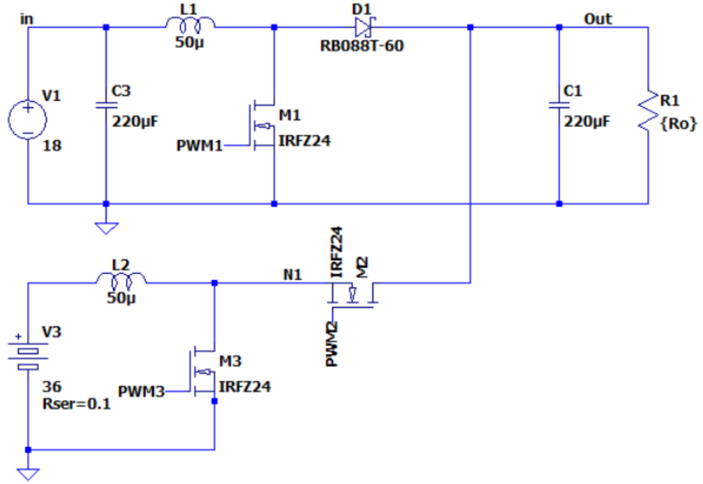




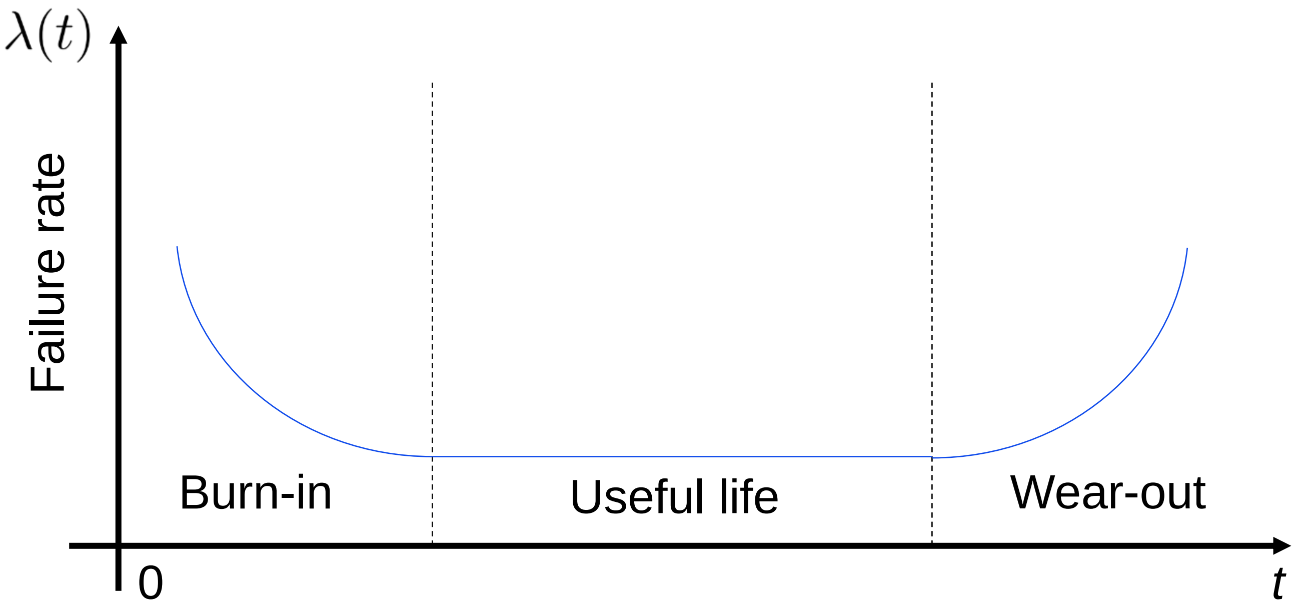
H. Wu, K. Sun, S. Ding, and Y. Xing, "Topology Derivation of Nonisolated Three-Port DC–DC Converters From DIC and DOC," *IEEE Transactions on Power Electronics*, vol. 28, no. 7, pp. 3297–3307, 2013.



Q. Tian, G. Zhou, R. Liu, X. Zhang, and M. Leng, "Topology synthesis of a family of integrated three-port converters for renewable energy system applications," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 7, pp. 5833–5846, 2021.



Reliability Assessment Tool

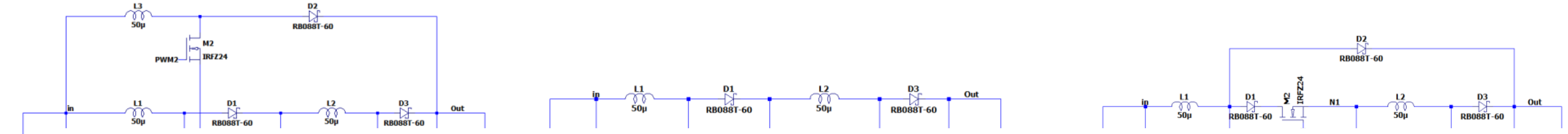


Mean Time To Failure (MTTF)

$$\boxed{\mathrm{MTTF} = \frac{1}{\lambda}}$$

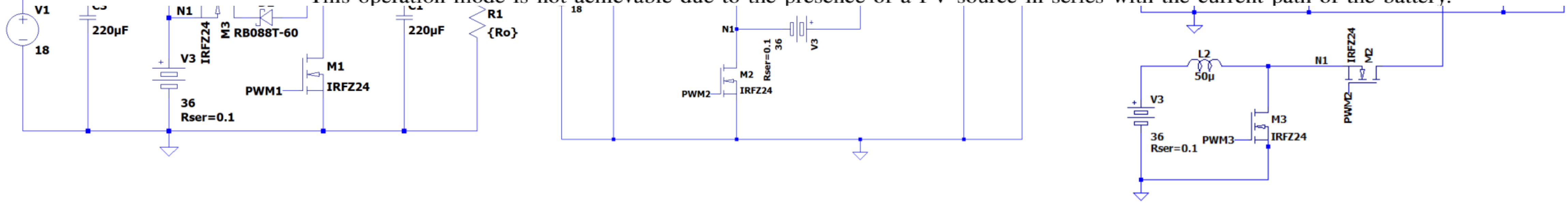
MIL-HDBK-217F

Calculated MTTF Based on MIL-HDBK-217F



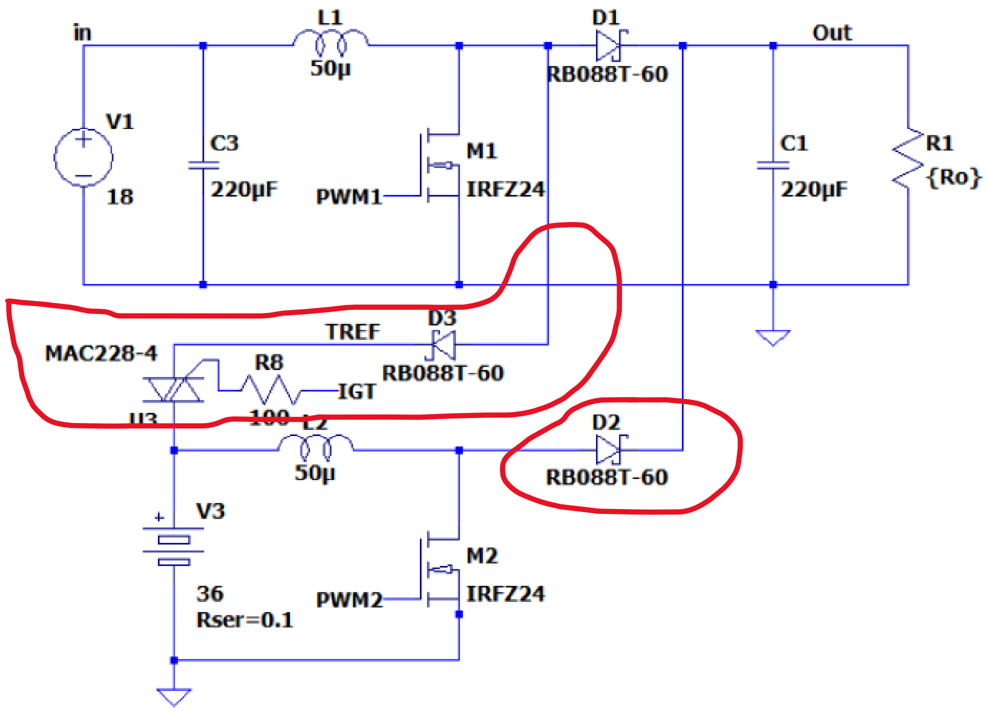
Converter Topology	MTTF in 10^5 hours						
	PV → load	PV → battery	Battery → load	PV → battery (25%) and load (75%)	PV → battery (75%) and load (25%)	PV (75%) and battery (25%) → load	PV (25%) and battery (75%) → load
3 SISO boost converters	1.57	1.63	1.82	1.69	1.72	1.69	1.81
2-stage cascaded boost converters	1.71	1.77	2.02	1.73	1.74	1.84	1.98
DISO+SISO boost converters	1.57	1.48	1.82	1.55	1.51	1.70	1.81
Single-inductor integrated boost converter	1.53	1.49	1.74	1.54	1.50	1.55	1.69
Single-inductor two-switch boost converter	1.46	1.38	N/A[a]	1.49	1.59	1.63	1.97
Parallel-connected boost-based converters	1.58	1.48	1.77	1.54	1.51	1.67	1.78

[a] This operation mode is not achievable due to the presence of a PV source in series with the current path of the battery.



Improving MPC Reliability

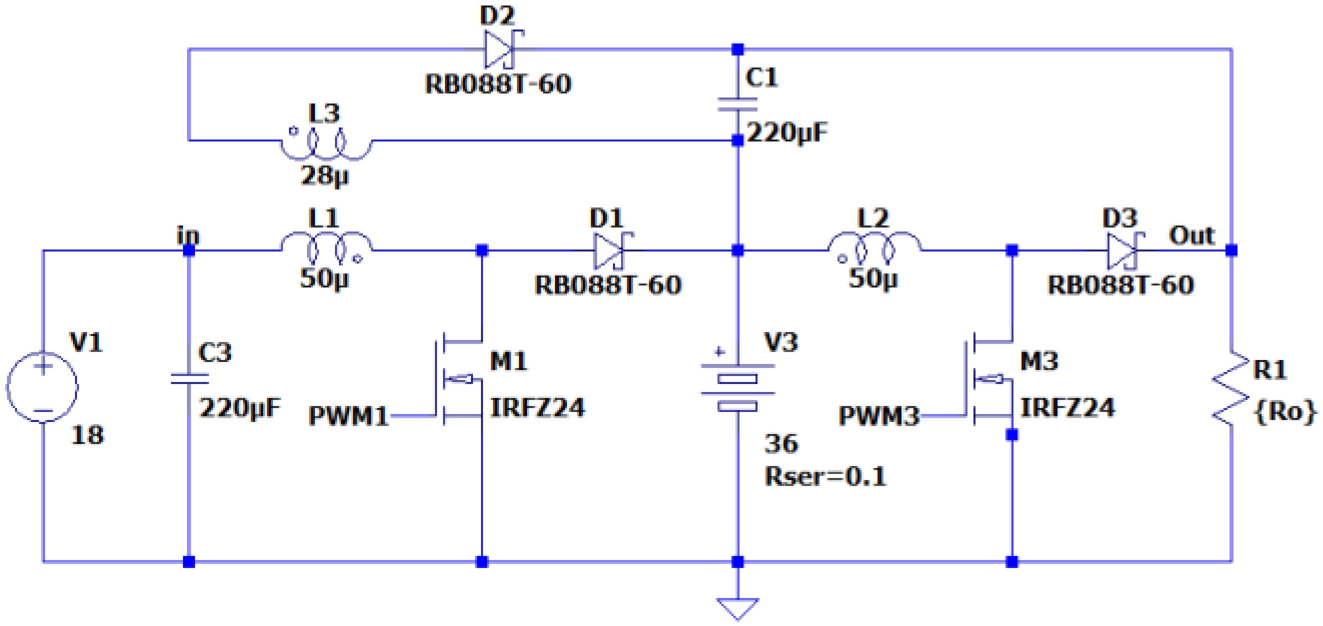
- Using more reliable devices
- Correlation between efficiency and reliability



Converter Topology	MTTF in 10^5 hours						
	PV → load	PV → battery	Battery → load	PV → battery (25%) and load (75%)	PV → battery (75%) and load (25%)	PV (75%) and battery (25%) → load	PV (25%) and battery (75%) → load
2-stage cascaded boost converters	1.71	1.77	2.02	1.73	1.74	1.84	1.98
Parallel-connected boost-based converters	1.58	1.48	1.77	1.54	1.51	1.67	1.78
Parallel-connected boost-based converters with a TRIAC	1.72	1.76	2.01	1.74	1.77	1.87	1.99

Improving MPC Reliability

- Reduce voltage stress on key devices
- Consider less power processing



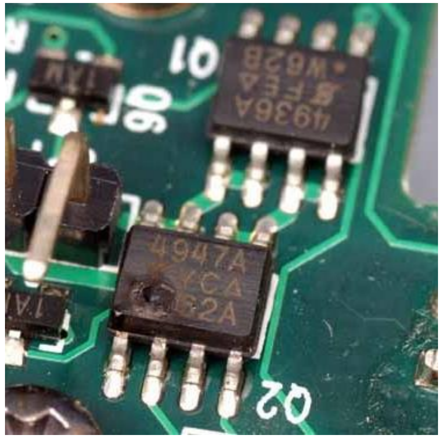
Short Summary

- Component stress (both electrical and thermal) is the key to PEC reliability
- Reliable PEC designs should look into converter structure, soft-switching, static and active thermal management and component selection
- Reliability assessment based on standards is useful for some static comparison
- Physics-of-failure (PoF) provides a more realistic and dynamic PEC reliability assessment

Fault-Tolerant Operations of MPCs

Developing MPCs with FT feature to increase reliability

Common Types and Causes of Fault of Devices

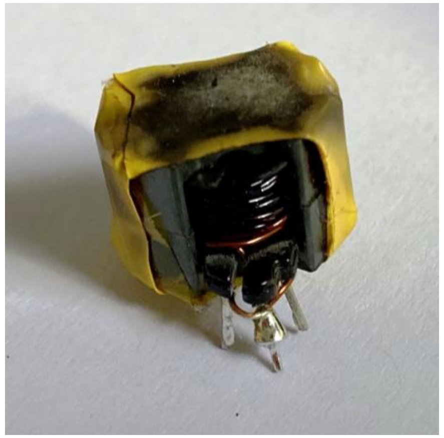


Power Semiconductor

- Open-circuit fault due to bond lifting and solder fatigue
- Short-circuit fault due to excessive voltage spike, excessive current surge or over-temperature (SOA)

Electrolytic Capacitor

- Capacitance dropped and ESR increased significantly due to dry-out as water in the electrolyte evaporated
- Bulging due to overheating and over-voltage

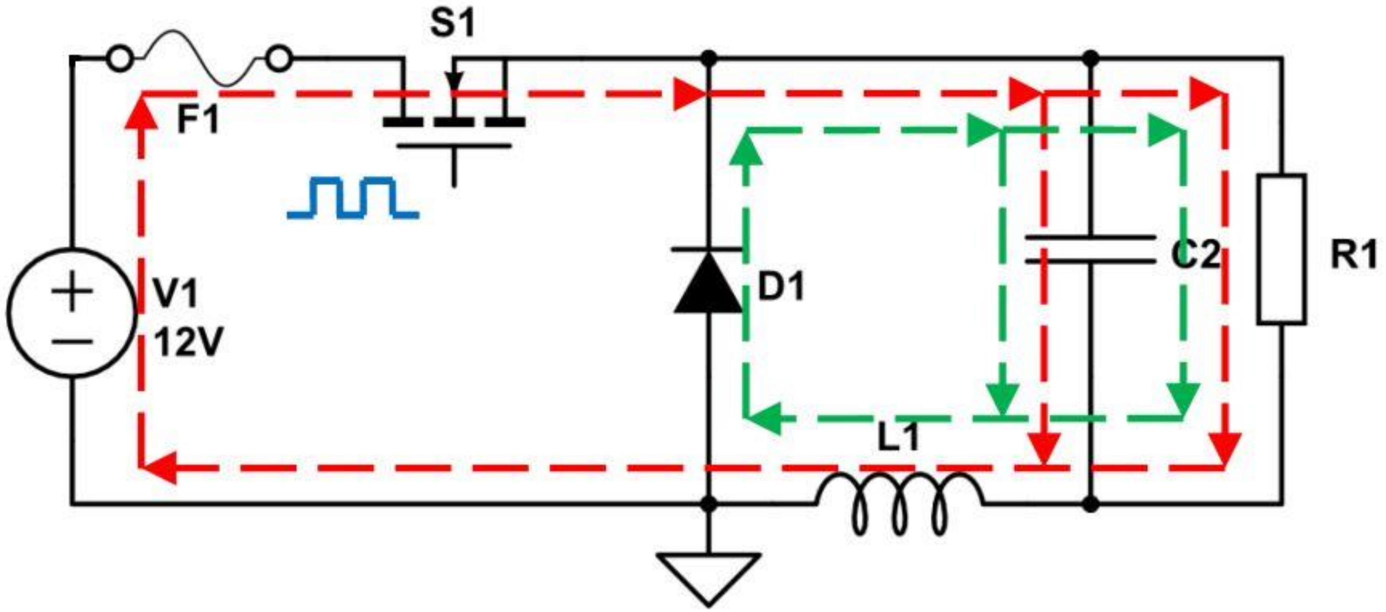


Magnetics (HF inductor/transformer)

- Thermal-related failure due to design-to-limit. Inductance dropped significantly
- Insulation-related wear-out due to thermal stress, moisture and dust levels. Windings short-circuited which reduces inductance further

PEC Failure due to Component Failure

- Effects of component failure on power electronic converter (PEC) operation
  - Power transistor
  - Power diode
  - Inductor
  - Capacitor

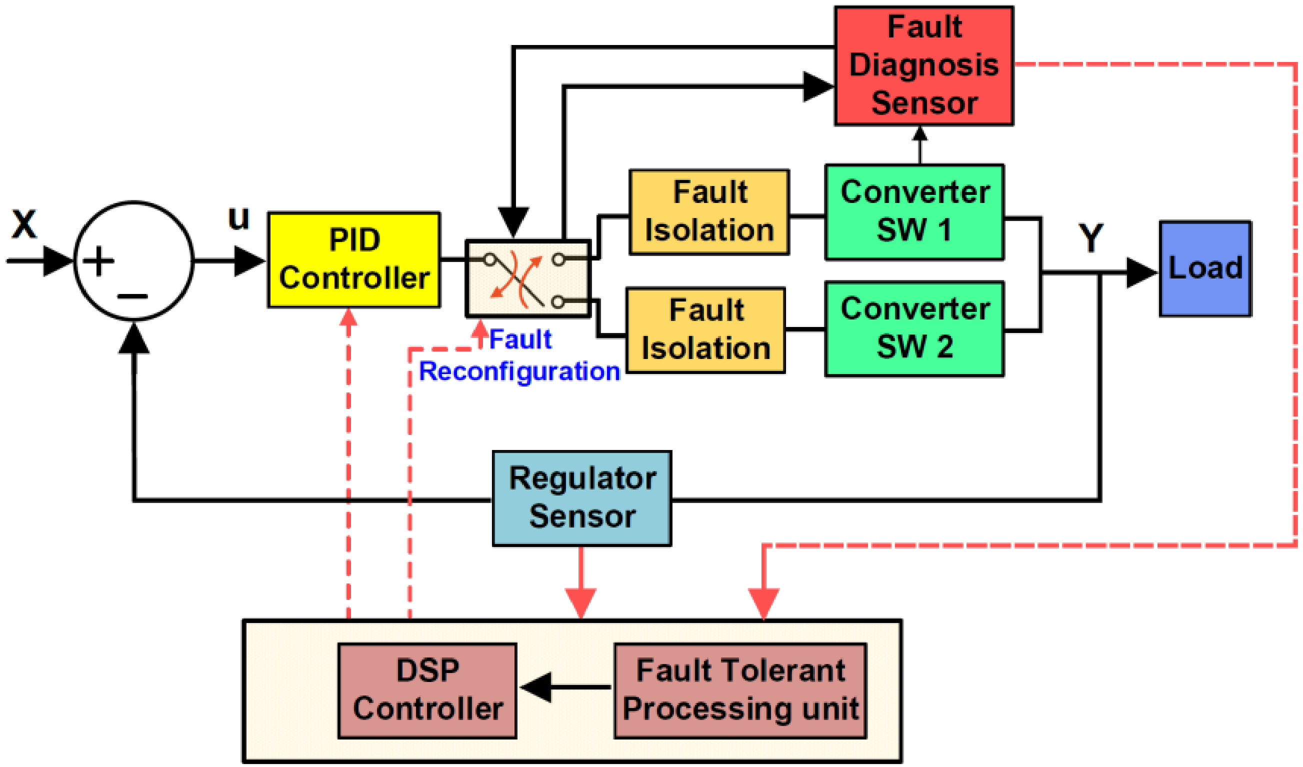


Why Fault-tolerant Operation?

- Isn’t replacing the failed module(s) sufficient?
- When to replace? (e.g., difficult during flight mission) – Timing
- Is continuous, uninterrupted power system operation essential?

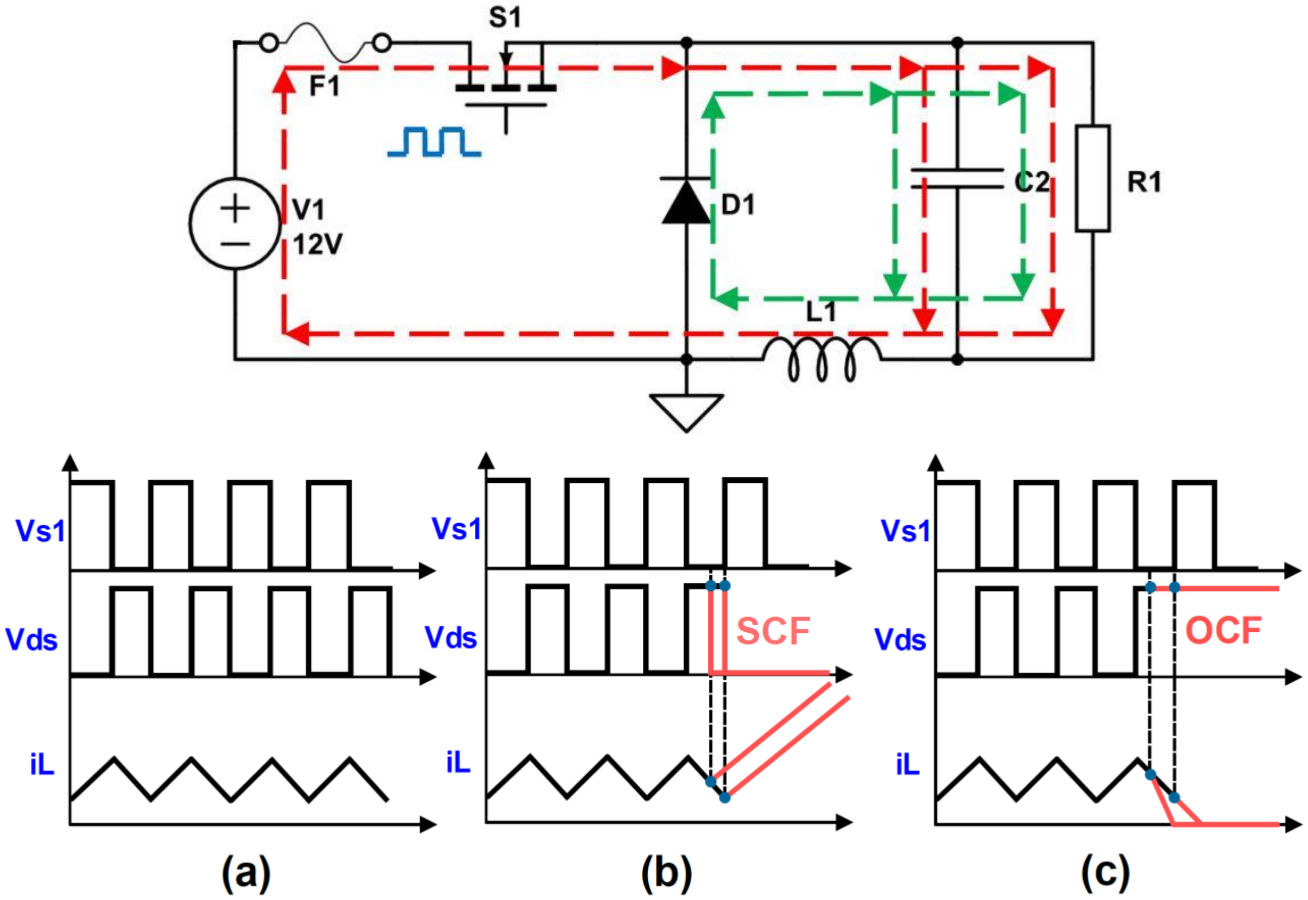
Overview of Fault-Tolerant PEC System

- Fault diagnosis
- Fault isolation
- Fault reconfiguration
- Redundancy is a key element for fault-tolerant PEC operation



Fault Detection and Diagnosis

- Short-circuit fault (SCF) of S1 that causes inductor saturation and excessive peak current in the circuit
- Open-circuit fault (OCF) of S1 isolates electrically the circuit from the source
- Differential voltage across the MOSFET (Vds) and comparison with gate signal (Vs1) to distinguish between normal and fault conditions

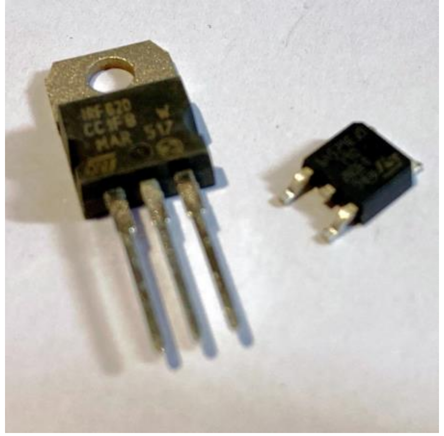


Fault Isolation Devices

Circuit Breaker

https://au.rs-online.com/web/p/electronic-circuit-breakers/7681079

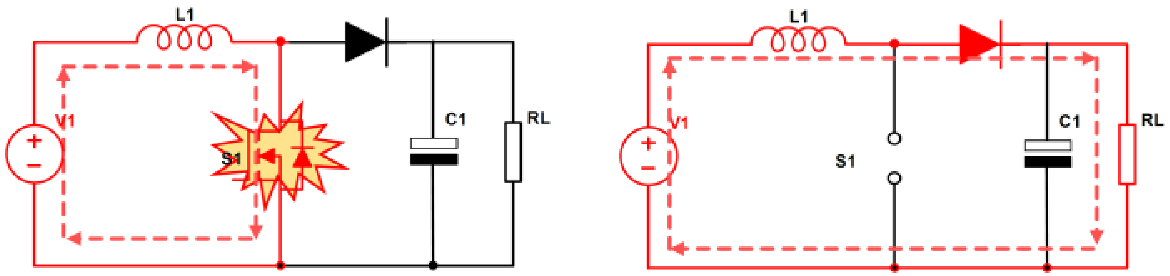
Fuses



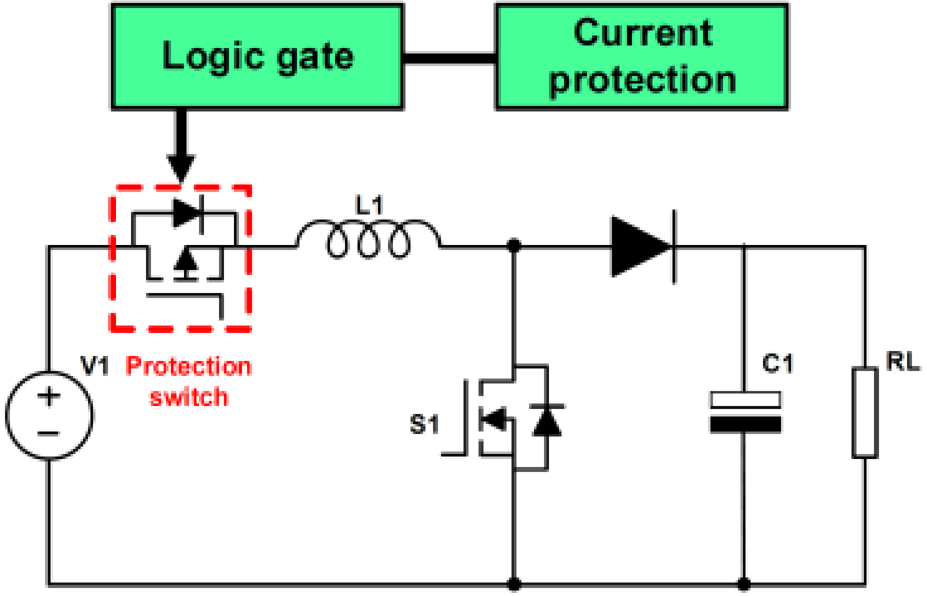
Power Transistors

Fault Isolation – Power Transistor

- Fuse cannot isolate switch fault in some converter topologies
- Power transistor provides both fault isolation and reverse-current blocking functions



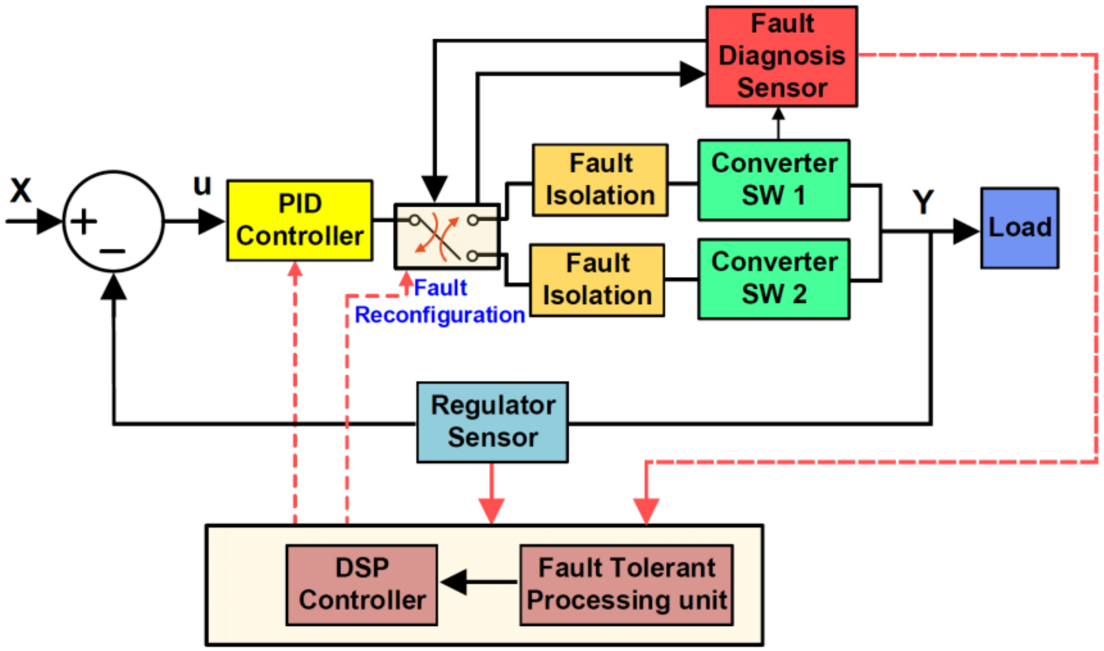
Fuse unable to protect the circuit even it is blown

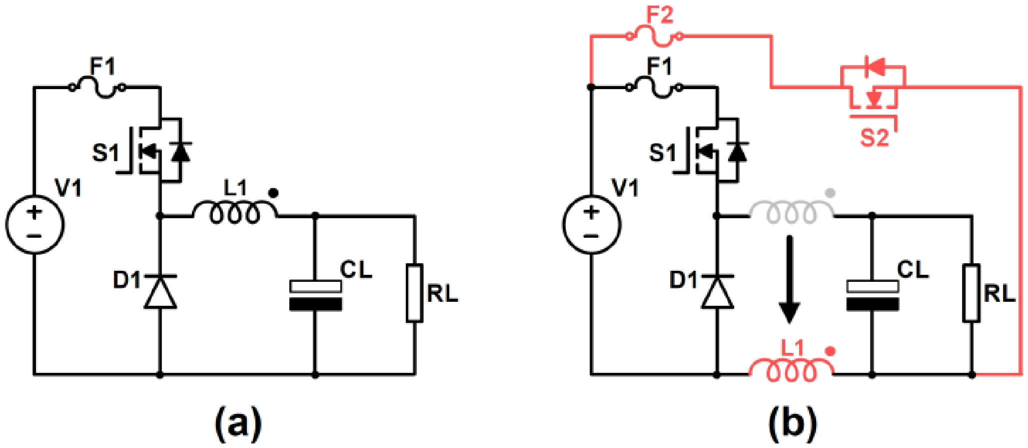


A boost converter with a PMOS to protect the circuit

Fault Reconfiguration on Two-level PEC

- Redundancy can also be implemented on circuit level to save space and cost

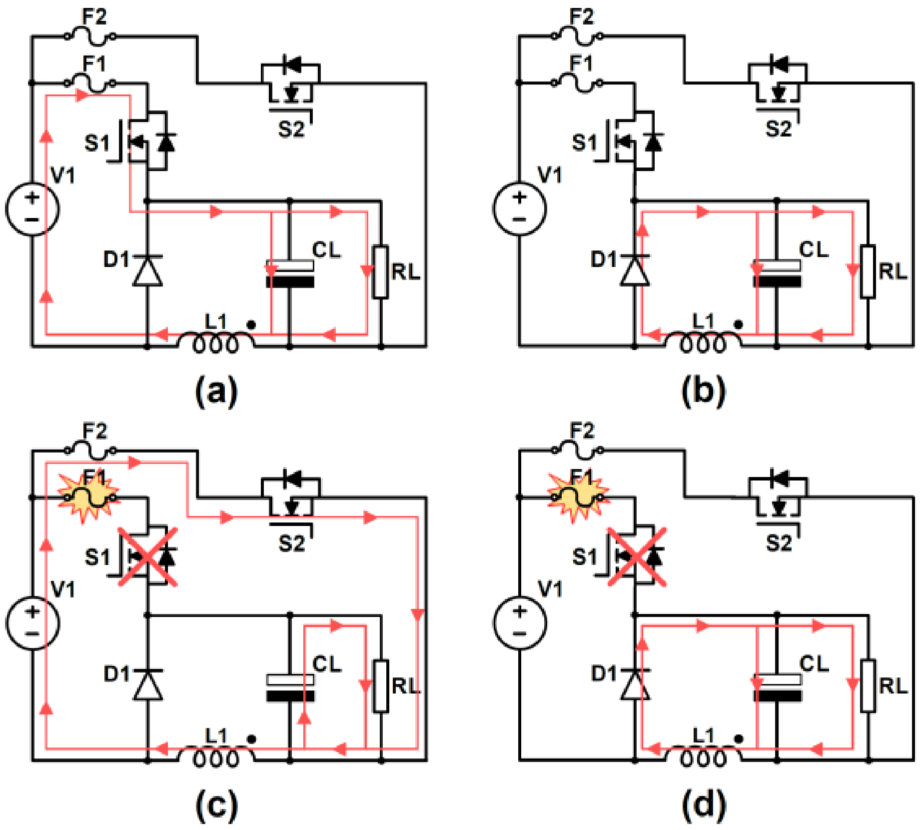




Two PECs, which form a FT converter, share the diode, inductor and output capacitor

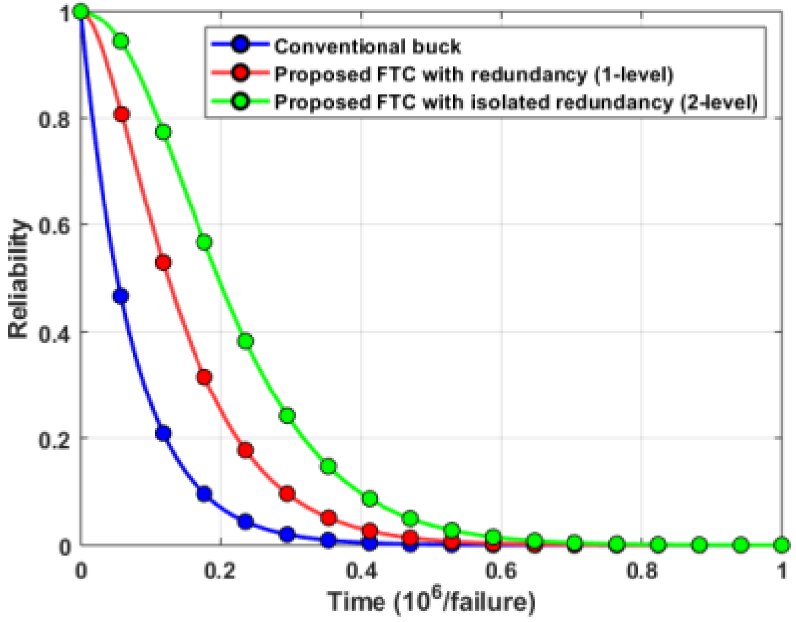
Fault Reconfiguration on Two-level PEC

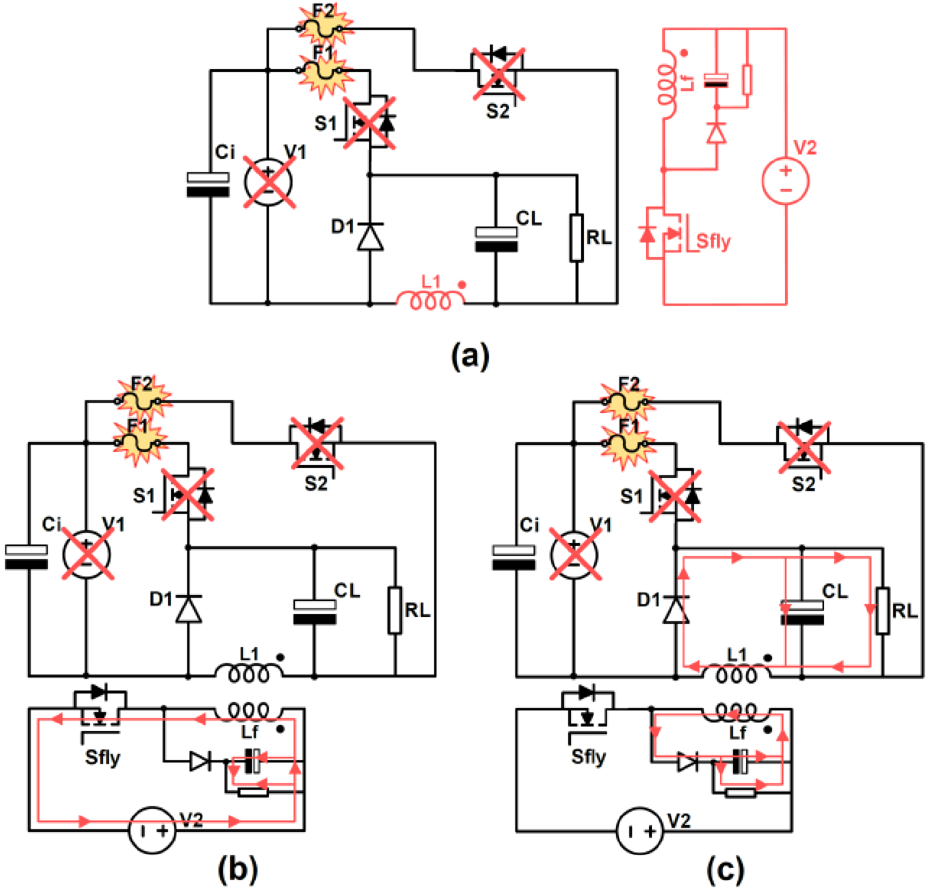
- Fuse-MOSFET pair used
- SCF translates to OCF
- Integrated boost, buck and buck-boost converter, i.e. voltage step-up and step-up conversion



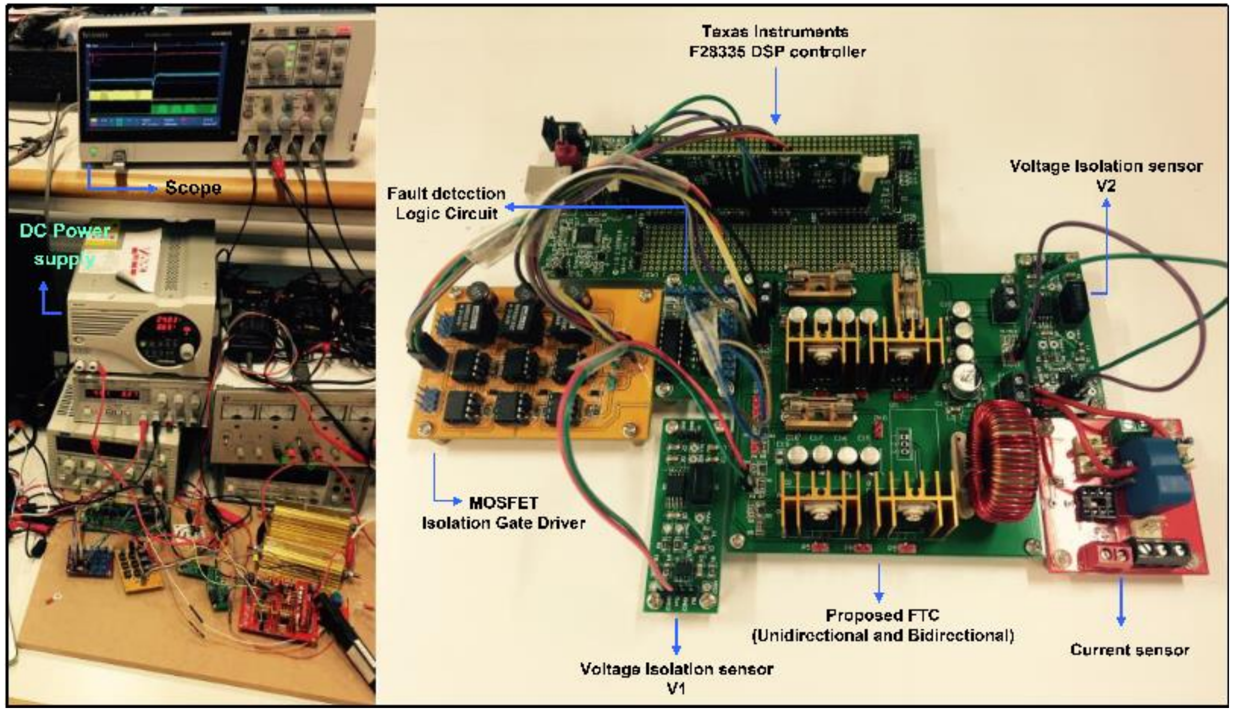
Fault Reconfiguration on Two-level PEC

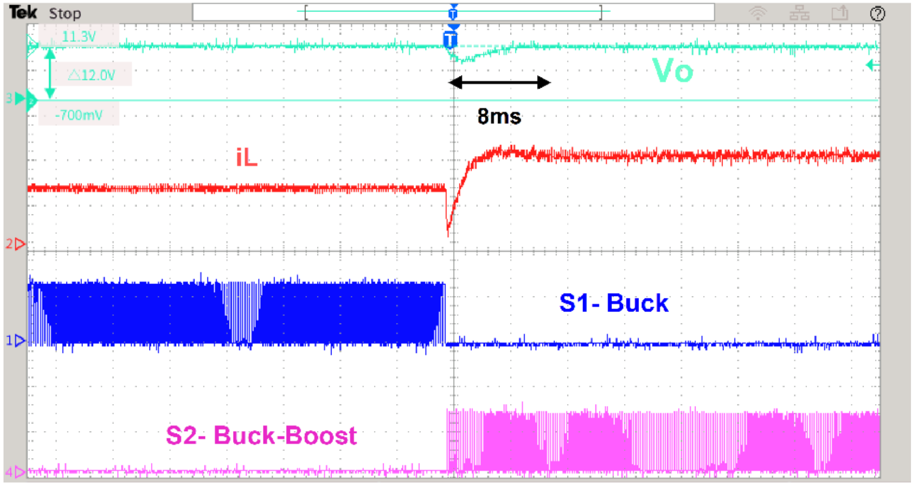
- Isolated fault-tolerant operation
- Single-ended converter topology such as flyback converter

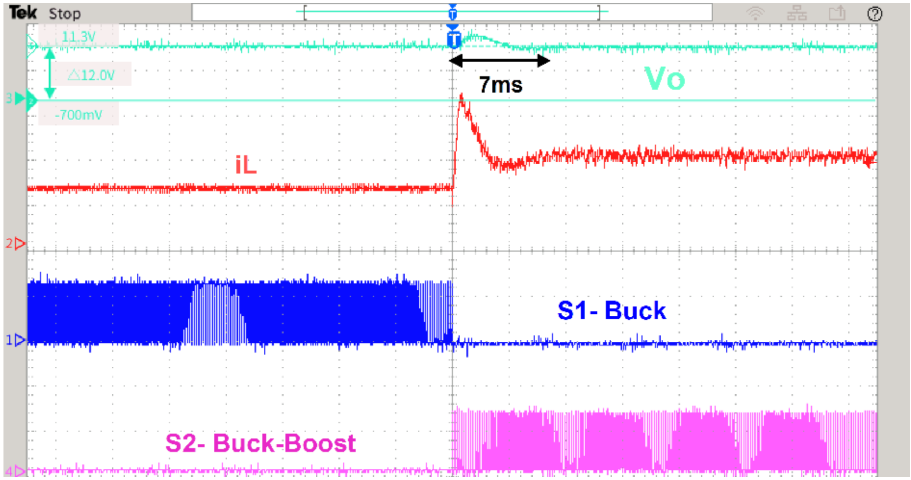




Experimental Verification

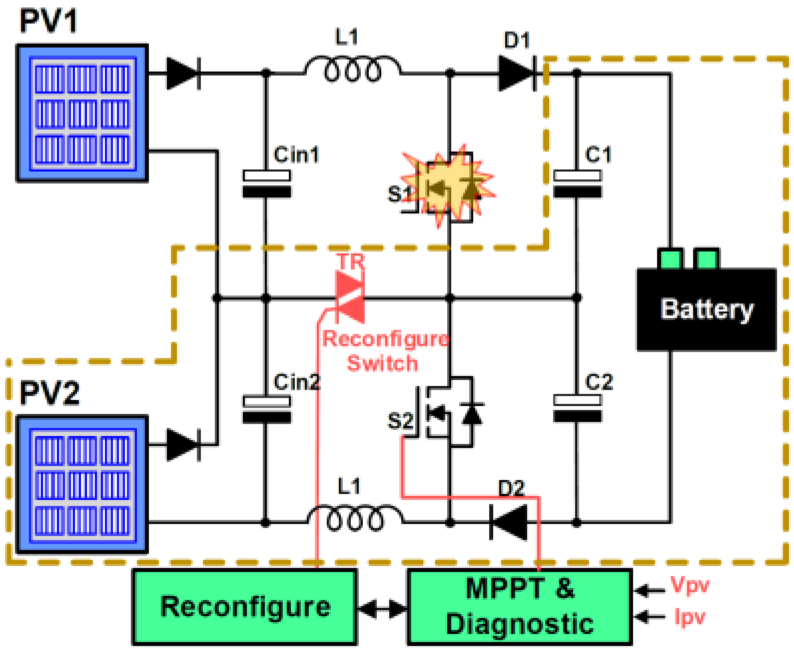






Fault Reconfiguration on Multi-level PEC

- TR is ON during normal operating condition; PV1 and PV2 have individual MPPTs
- TR is OFF when one of the switches is at a fault (OCF); PV1 and PV2 run in series and PV performance is degraded due to power mismatch



E. Ribeiro, A. J. M. Cardoso and C. Boccaletti, "Fault-Tolerant Strategy for a Photovoltaic DC--DC Converter," in IEEE Transactions on Power Electronics, vol. 28, no. 6, pp. 3008-3018, June 2013, doi: 10.1109/TPEL.2012.2226059.

Short Summary

- Fault-tolerant (FT) operation of PEC is required in some applications where continuous power supply is critical to successful mission
- Fault-detection, fault-isolation and fault-reconfiguration form the three core steps in achieving fault-tolerant operation of PEC
- FT PEC improves overall reliability of the power electronic system
- FT design can be achieved via new circuitry or module redundancy approach

Current and Future Research on Reliability of MPCs

Concluding Remarks

- Multiport converters (MPCs) have great potential to provide cost-effective, efficient and compact power electronics solutions to various (and emerging) applications.
- Challenges of MPCs include strong coupling among ports, reduced degrees of control freedom and operation modes, control complexity and compromise, and reliability, which require a holistic investigation and comprehensive analysis, leading to innovative ideas and designs.
- Converter derivation tools such as power flow graphs facilitate the MPC design process systematically, taking into account different operation and control criteria.
- Fault-tolerant operation of MPCs is important to extend the lifetime of the power system and minimize the incidents (and consequences) due to failure of power converters.

Potential Research Topics for MPCs

- Multidisciplinary reliability assessment (microelectronics, electrical engineering, mechanical engineering and chemical engineering). Examples are vibration and humility.
- More reliable MPCs while offering cost-effectiveness, compactness and highly efficient power conversion
- Automated converter and control design process with expert input
- Smart diagnosis, communication and control with the integrated fault-tolerant operation

Any Questions?

Dylan D.-C. Lu | Professor
School of Electrical and Data Engineering
Faculty of Engineering & IT

THE UNIVERSITY OF TECHNOLOGY SYDNEY
CB11.09.123 | Ultimo | NSW | 2007
T +61 2 9514 2674
E dylan.lu@uts.edu.au
W https://profiles.uts.edu.au/dylan.lu