Advances in Micro-inverter Technology

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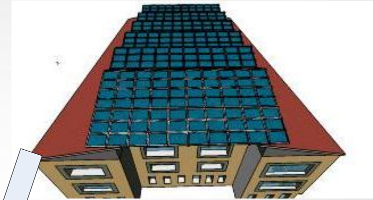
Outline

- Introduction
  - Three-phase vs. Single-phase Micro-inverter
- Micro-inverter Control Based Soft Switching Technique
- Micro-inverter Efficiency Improvement
- Conclusion

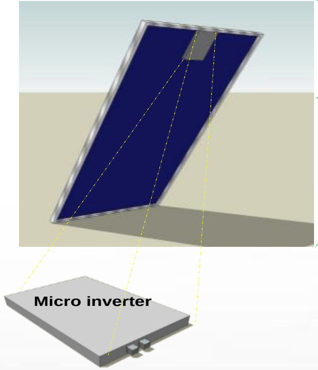
Solar Farm Based on Three-phase Micro-inverters:

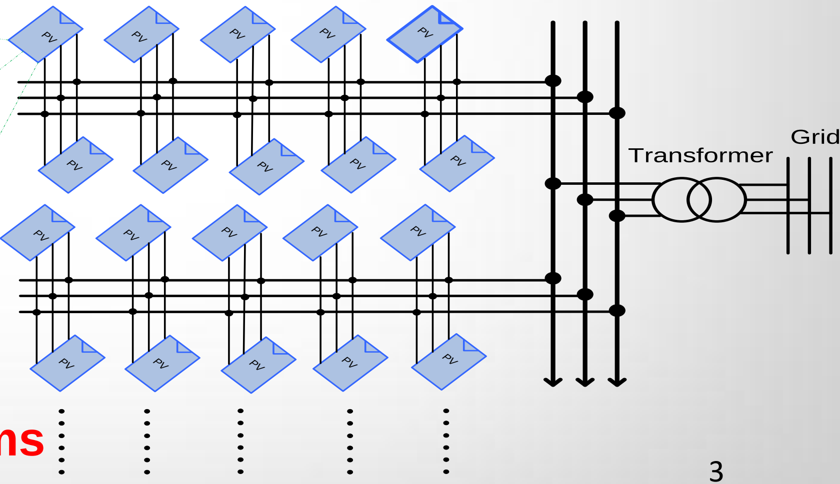
- What is Micro-inverter?
  - It converts and controls the DC power from each PV module into grid-compliant AC power.
- Three-phase vs. Single-phase :
  - Minimized Power Decoupling Capacitance
  - Eliminated the need of an expensive custom AC cable
  - Improved Reliability
  - Reduced Cost ($/W)

Open Area PV Power Plant (Large scale)



Top-roof PV Power Plant (Small scale)





Courtesy of Petra Systems

PV Power Plant:

Micro Inverter based:

- MPPT for each PV panel
- Ease of installation and maintenance (plug and play)
- No DC cabling
- Flexibility in system expansion
- Possible cost reduction due to mass production

- High cost of inverter
- Low efficiency (power conversion)
- Harsh operation conditions
- Long life time required(>25 Year)

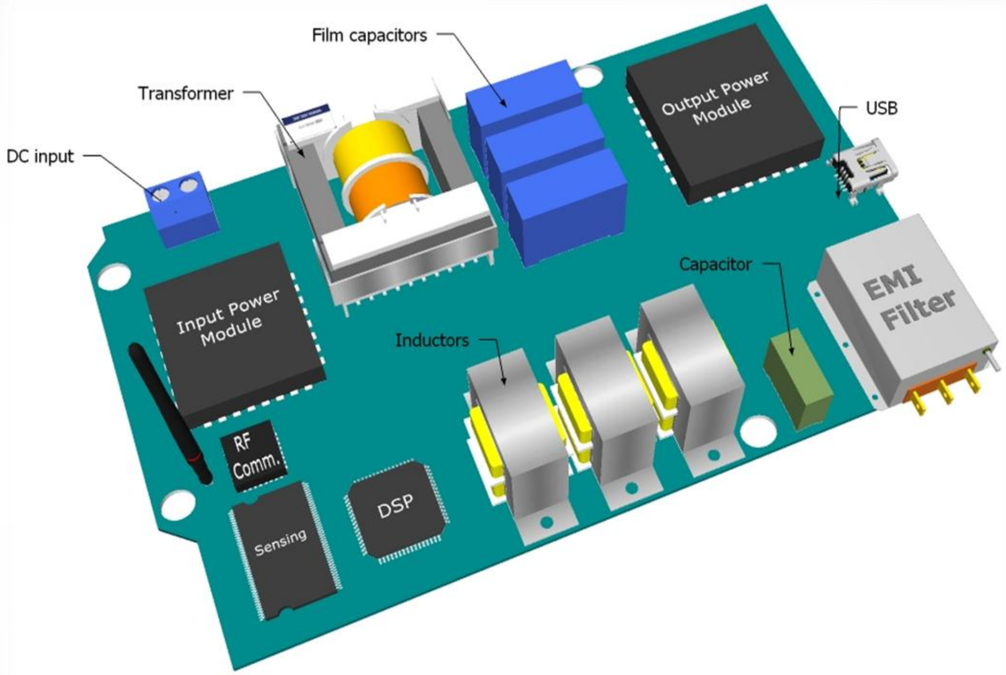
Centralized Inverter based:

- Low cost of inverter
- High efficiency (power conversion)

- MPPT for the PV array, not for each panel (low efficiency in power harvest)
- Complex DC wiring
- Power harvest affected a lot when inverters fail
- Laborious installation

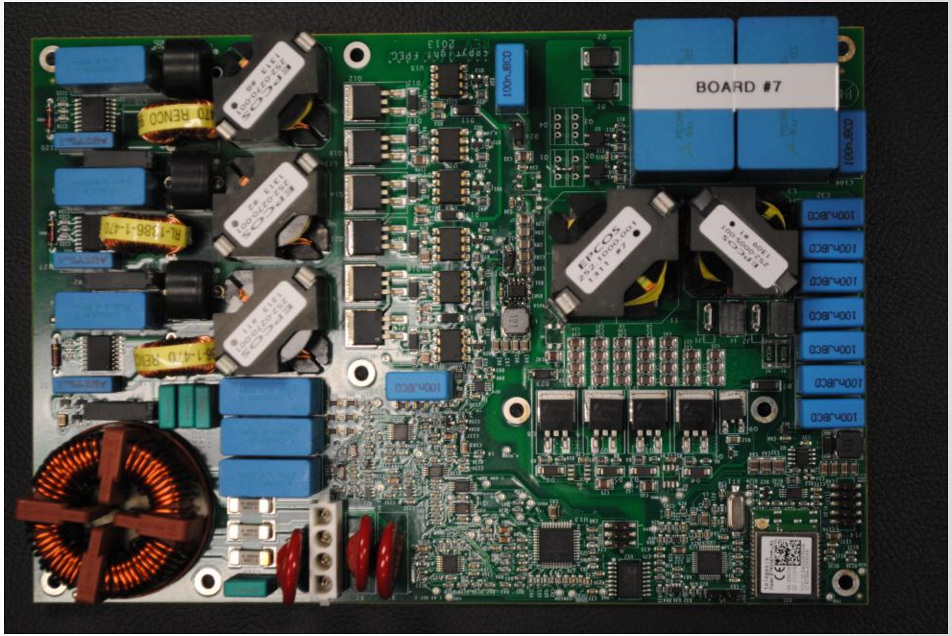
Development Targets for Three-phase Micro-inverter:

- High efficiency comparable to those of centralized inverter(>96%)
- Low cost (0.3$/W)
- High reliability (25 Year Warranty)
- Low profile to be fit into PV panel (Power Density > 12W/in3)



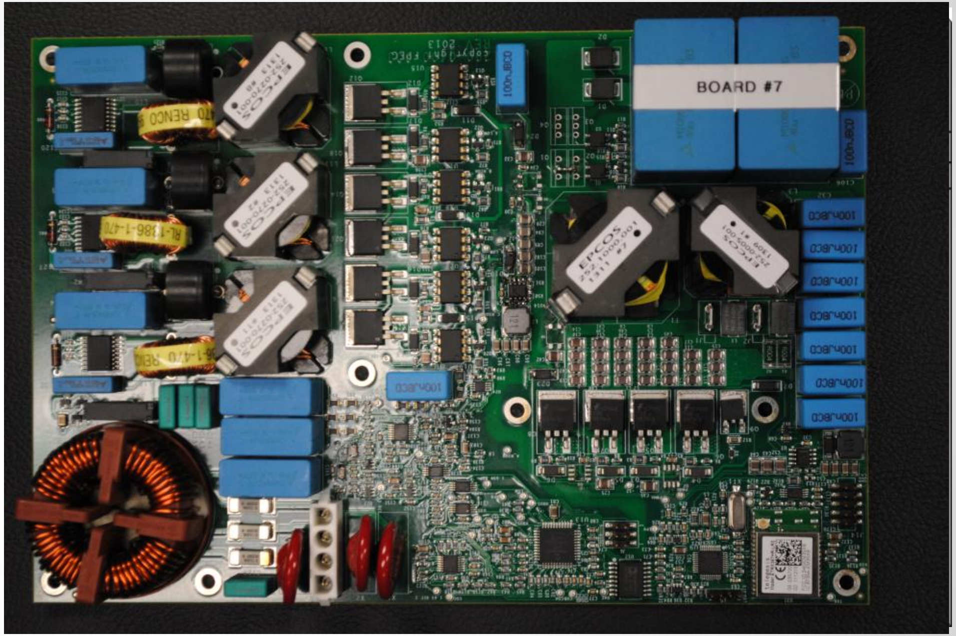
Three-phase Micro-inverter Prototype:

- Overview:
  - 400W Nominal Output Power
  - 50 VDC Nominal Input Voltage
  - 208 VAC Three-phase Output Voltage
  - 60Hz Output Frequency
  - Two Stage Topology



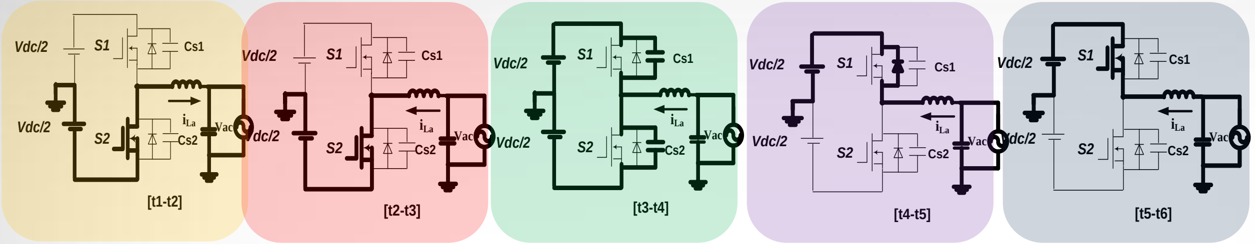
System Architecture:

- Two Stage Topology:
  - LLC Resonant DC/DC Converter
  - Three-phase Half Bridge DC/AC Stage



Control Based Soft Switching Technique:

- Transition from switch S2 to S1



- Hybrid Control is a combination of predictive control and hardware reset

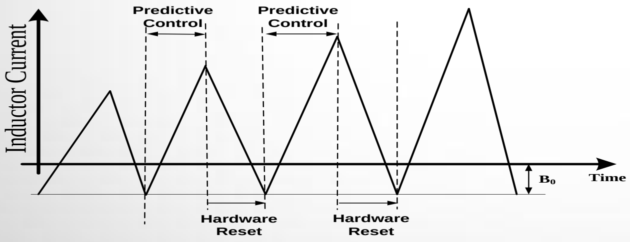


Figure. Hybrid BCM Current Control

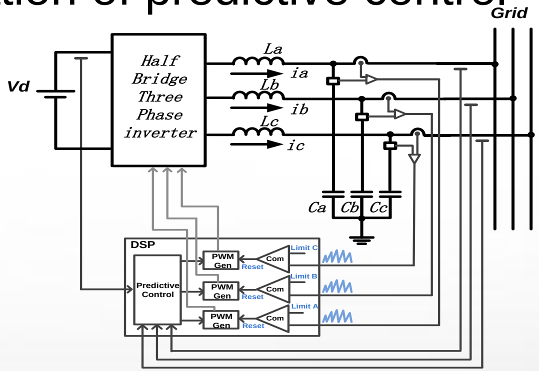


Figure. DSP Implementation of Hybrid BCM Current Control

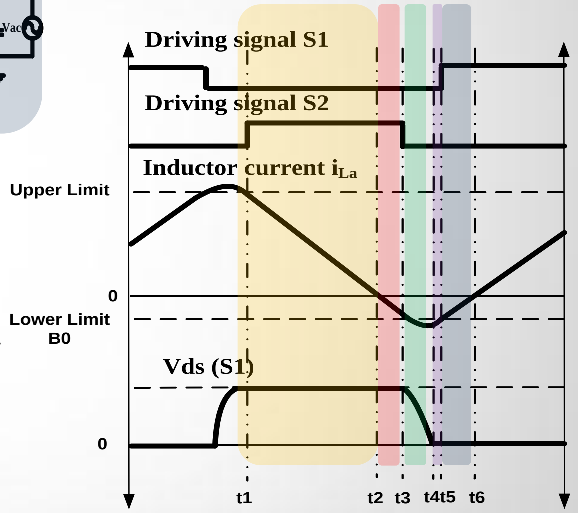


Figure. Current and Voltage Waveforms for ZVS BCM Current Control

Cost Reduction (0.28$/W):

- Inductors
  - (3~14mH→270uH)
  - (0.013J→0.0019J)
- MOSFETs

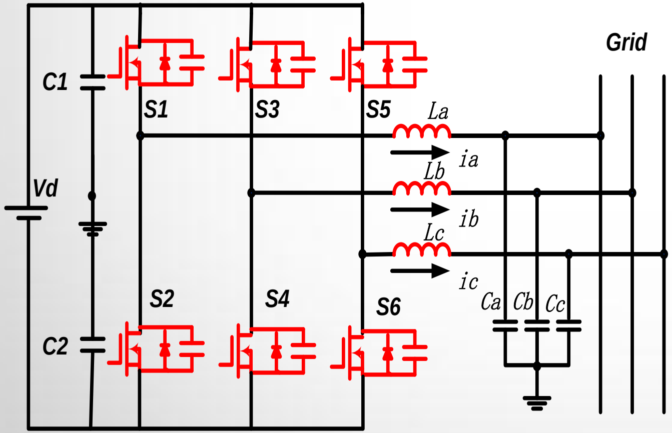
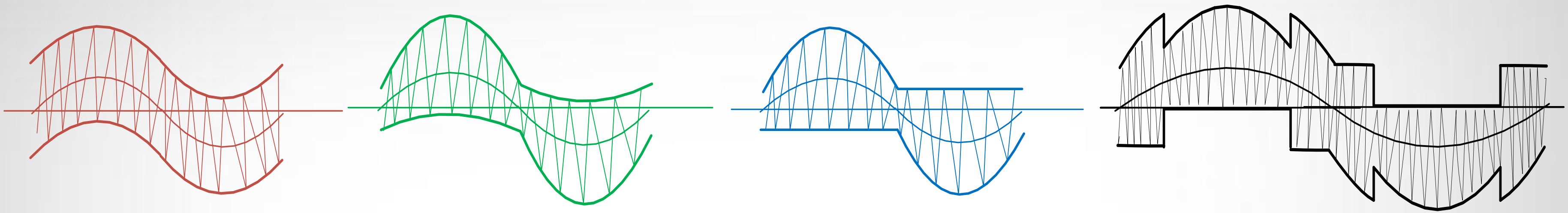


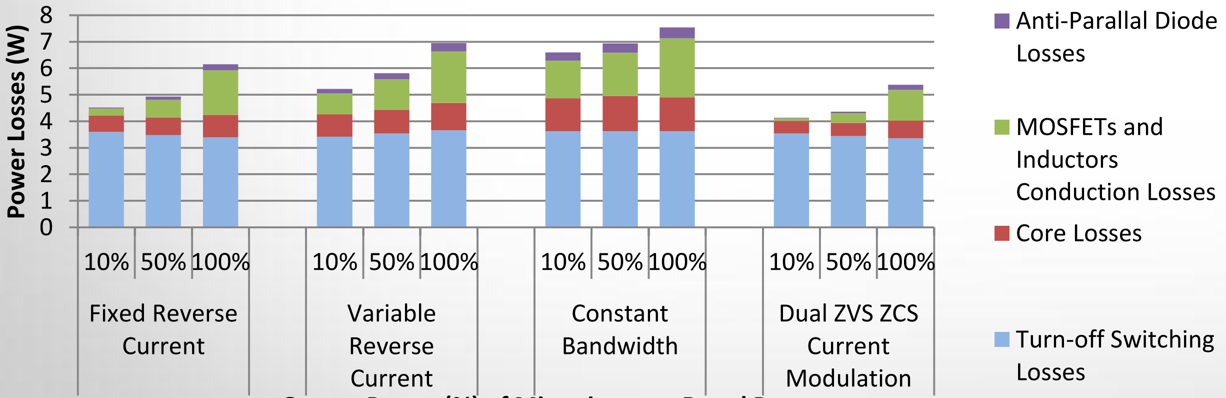
Table. Bill of Materials

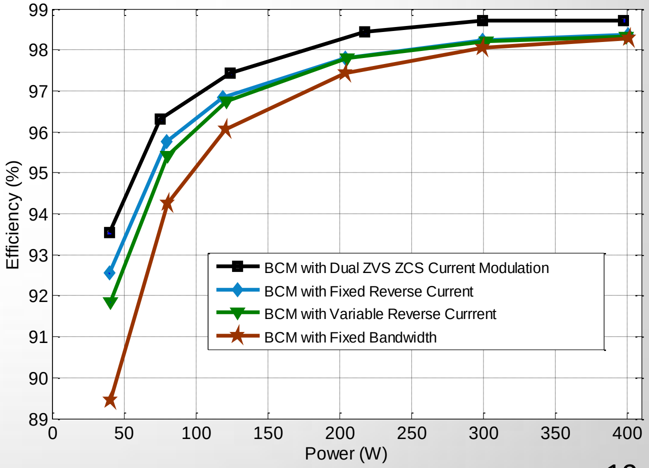
67	3	RES, 3.32K, 1/10	YAGEO	RC0603FR-073K32L	R23,R84,R87	0.0027	0.0081
68	5	RES, 51 OHMS, 1	YAGEO	RC0603FR-0751RL	R26,R31,R33,R34,R35	0.0027	0.0135
69	1	RES, 100K, 1/10'	YAGEO	RC0603FR-07100KL	R28	0.0027	0.0027
70	1	RES, 4.7K, 1/10W	ROHM	MCR03EZPJ472	R29	0.00384	0.00384
71	4	RES, 330, 1/10W	YAGEO	RC0603FR-07330RL	R40,R43,R45,R47	0.0027	0.0108
72	10	RES,1M,1/4W,.5	KOA SPEER	HV732BTTD1004D	R52,R54,R74,R76,R94,R95,R96,R97,R100,R101	0.07523	0.7523
73	3	RES, 4.7 OHMS,	YAGEO	RC1206JR-074R7L	R53,R59,R63	0.00447	0.01341
74	6	RES, 22 OHMS, 1	YAGEO	RC1206JR-0722RL	R56,R60,R66,R67,R73,R78	0.00447	0.02682
75	4	RES, 22.1K, 1/10	SUSUMU	RG1608P-2212-B-T5	R57,R68,R85,R90	0.10342	0.41368
76	3	RES, 22 OHMS, 1	STACKPOLE	OD220JE	R80,R81,R82	0.05	0.15
77	4	RES, 12K, 1/10W	YAGEO	RT0603FRE0712KL	R83,R92,R99,R109	0.00635	0.0254
78	3	RES, 4.99K, 1/10	YAGEO	RC0603FR-074K99L	R86,R102,R147	0.0027	0.0081
79	3	RES, 18K, 1/10W	YAGEO	RC0603FR-0718KL	R89,R91,R103	0.0027	0.0081
80	2	RES, 2M, 1/10W	SUSUMU	RG1608P-2005-B-T5	R93,R126	0.027	0.054
81	1	RES, 2.87k, 1/10	YAGEO	RC0603FR-072K87L	R106	0.0027	0.0027
82	3	RES, 8.66K, 1/10	YAGEO	RC0603FR-078K66L	R107,R115,R122	0.0027	0.0081
83	1	RES, 3.01K, 1/10	YAGEO	RC0603FR-073K01L	R108	0.0027	0.0027
84	3	RES, 64.9K, 1/10	YAGEO	RC0603FR-0764K9L	R113,R117,R125	0.0027	0.0081
85	3	RES, 15 OHMS,1	SUSUMU	RC0603FR-0715RL	R119,R120,R121	0.00171	0.00513
86	1	RES, 47K, 1/8W,	YAGEO	RC0603FR-0747KL	R129	0.00171	0.00171
87	1	RES, 120K, 1/10'	YAGEO	RC0603FR-07120KL	R131	0.00171	0.00171
88	1	RES,301K,1/4W,	YAGEO	RC1206FR-07301KL	R132	0.00378	0.00378
89	1	RES, 75K, 1/10W	YAGEO	RC0603FR-0775KL	R133	0.00171	0.00171
90	1	RES,180K,1/10W	YAGEO	RC0603FR-07180KL	R134	0.00171	0.00171
91	1	RES, 1.24K, 1/10	YAGEO	RC0603FR-071K24L	R139	0.00171	0.00171
92	1	RES, 499, 1/10W	YAGEO	RC0603FR-07499RL	R142	0.00171	0.00171
93	3	RELAY,SPST,5A,	ZETTLER	AZ921-1A-12DE	SW1,SW2,SW3	0.9	2.7
94	1	TRANSFORMER	FAB PART		T1	3	3
95	3	XFMR,CURRENT	ICE COMP	CT12007	T2,T3,T4	0.8	2.4
96	0	IC,MOSFET DRV	PANASONIC	APV1121S	U1,U3	1.2035	0
97	2	IC,GATE DRIVE,I	MICREL	MIC4103YM	U2,U6	2.142	4.284
98	3	RECT,SCHOTTKY	MICRO COMM	CDBHD260-G	U4,U5,U8	0.5768	1.7304
99	2	IC, SW REG, TPS	TI	TPS5410D	U7,U14	1.8	3.6
100	1	IC,MICROPROC,	ST	STM32F103C8T7	U9	2.5	2.5
101	1	IC,SNGL OP AM	NATIONAL	LMV771MG	U10	0.50625	0.50625
102	1	IC, TEMP SENSO	NATIONAL	LM94022	U11	0.394	0.394
103	1	IC,DIG ISO,10MI	ALOG DEVIC	ADuM1401BRW	U12	2	2
104	1	IC,PROC,DSPIC3	MICROCHIP	DSPIC33FJ16GS504	U13	2.48	2.48
105	6	IC,OPTO,SGL CH	AVAGO	HCPL-3180-360E	U15,U16,U17,U18,U19,U20	0.65	3.9
106	3	IC,HALL EFFECT,	ALLEGRO	ACS716KLATR-6BB-T	U21,U22,U23	1.69	5.07
107	1	IC,OP AMP,DUA	TI	LMV772MM	U24	0.72	0.72
108	2	IC,QUAD OP AM	TI	OPA4322AIPWR	U25,U30	1.068	2.136
109	3	IC,OP AMP,SING	TI	OPA353NA	U26,U27,U28	1	3
110	1	IC,VOLT REF,AD	DIODES INC	TLV431AFTA	U29	0.2175	0.2175
111	1	MODULE,RF,ZIG	TELEGESIS	ETRX357HR-LRS	U31	8.37	8.37
112	1	IC, DUAL COMP,	ST	TS393IPT	U32	0.16	0.16
113	3	IC,DUAL COMAR	TI	LMV393IPWR	U33,U34,U35	0.13	0.39
114	1	IC,EEPROM,8KX	MICROCHIP	24LC64T-I/OT	U36	0.33	0.33
115	1	XTAL,8 MHZ,-40	ABRACON	ABLS-8.000MHZ-K4T	XT1	0.25	0.25
116	2	DIODE,ZENER,3	ON SEMI	1SMA5914BT3G	**D23,D24**	0.05	0.1
117	1	PWB,DOE 400W	FAB PART			6	6
						TOTAL	**114.05962**

Micro-inverter Efficiency Improvement:

- Break-down power loss analysis of different current modulation schemes
- Proposed dual-mode ZVS ZCS current modulation scheme

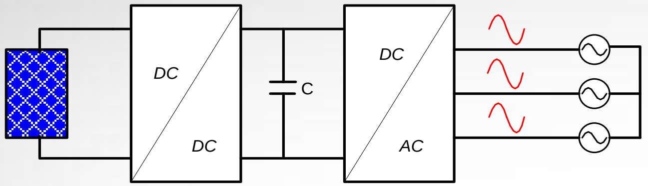




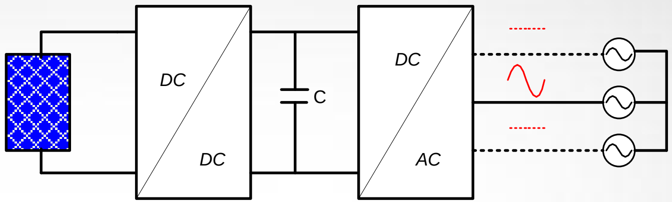


Light Load Efficiency Enhancement:

- Phase Skipping Control:



Normal Operation



Phase Skipping Control

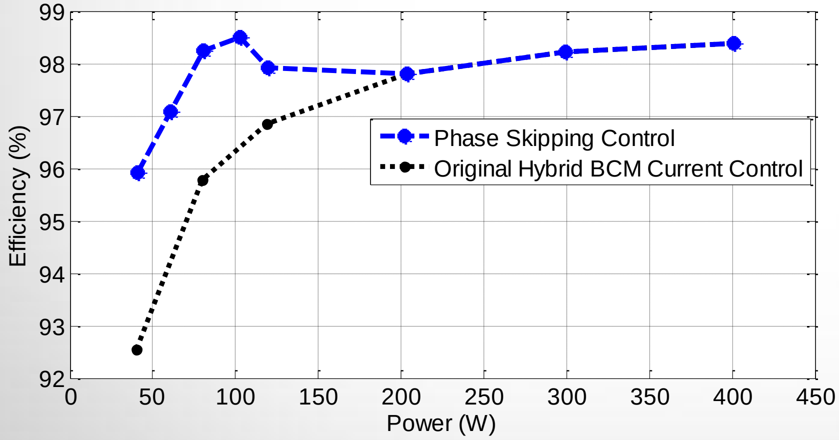


Figure. Converter Efficiency versus Output Power

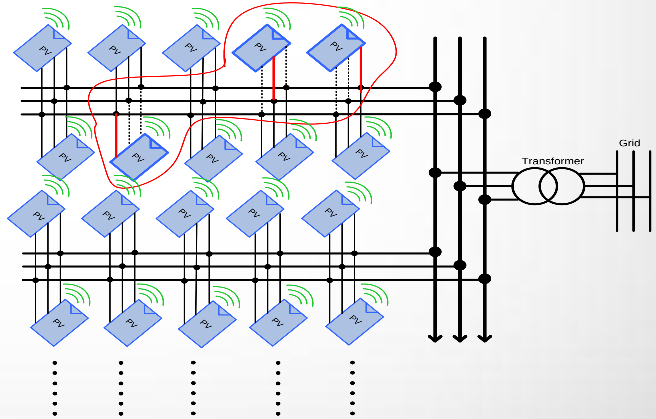


Figure. Solar Farm Architecture based on Three Phase Micro-inverter, Three Micro-inverters are Operating in Phase Skipping Mode

Conclusion:

- A soft switching three-phase micro-inverter has been proposed. It has the advantage of high efficiency, high power density and low cost.
- To further improve the efficiency of the micro inverter a new current modulation scheme combining the ZVS and ZCS operations was proposed.
- A phase skipping method has been proposed to maintain high power conversion efficiency across the entire load range of the three-phase micro-inverter
- System total CEC efficiency of 96% was achieved

Thank you.

Recent Journal Publications:

[1] A. Amirahmadi, U. Somani, L. Chen, N. Kutkut, I. Batarseh "Light Load Efficiency Enhancement of Three-phase ZVS Micro-Inverter" Submitted *to IEEE Transactions on Power Electronics*, 2014

[2] A. Amirahmadi, L. Chen, U. Somani, N. Kutkut, I. Batarseh "High Efficiency Dual Mode Current Modulation Method for Low Power DC/AC Inverters" *IEEE Transactions on Power Electronics*, vol. 29, no. 6, pp. 2638-2642, June 2014.

[3] A. Amirahmadi , H. Hu, A. Grishina, Q. Zhang, L. Chen, U. Somani, I. Batarseh "Hybrid ZVS BCM Current Controlled Three-Phase Micro-inverter" *IEEE Transactions on Power Electronics*, vol. 29, no. 4, pp. 2124-2134, 2014.

[4] L. Chen, A. Amirahmadi, Q. Zhang, N. Kutkut, I. Batarseh "Design and Implementation of Three-phase Two-stage Grid-connected Module Integrated Converter" Published *in IEEE Transactions on Power Electronics*, 2014

[5] L. Chen, H. Hu, Q. Zhang, A. Amirahmadi, I. Batarseh "Boundary Mode Forward-Flyback Converter with Efficient Active LC Snubber Circuit" *IEEE Transactions on Power Electronics*, vol. 29, no. 6, pp. 2944-2958, June 2014

[6] Q. Zhang, C. Hu, L. Chen, A. Amirahmadi, N. Kutkut, I. Batarseh "A Center Point Iteration MPPT Method With Application on the Frequency-Modulated LLC Microinverter" *IEEE Transactions on Power Electronics*, vol. 29, no. 3, pp. 1262-1274, 2014

Recent Conference Publications:

[1] A. Amirahmadi , H. Hu, A. Grishina, L. Chen, J. Shen, I. Batarseh, " Improving Output Current Distortion in Hybrid BCM Current Controlled Three-phase Micro-inverter" IEEE Energy Conversion Congress and Exposition (ECCE 2013), pp.1319-1323, 2013

[2] A. Amirahmadi, H. Hu, A. Grishina, L. Chen, J. Shen, I. Batarseh "Hybrid Control of BCM Soft-switching Three Phase Micro-inverter" IEEE Energy Conversion Congress and Exposition (ECCE 2012) pp. 4690-4695, 2012

[3] X. Fang, H. Hu, L. Chen, A. Amirahmadi, J. Shen, I. Batarseh "Operation Analysis and Numerical Approximation for the LLC DC-DC Converter", IEEE Applied Power Electronics Conference and Exposition (APEC2012), pp. 870-876, 2012

[4] D. Zhang, Q. Zhang , A. Grishina, A. Amirahmadi , J. Shen, I. Batarseh "A Comparison of Soft and Hard-switching Losses in Three Phase Micro-inverters" ECCE 2011, pp 1076-1082, Arizona, US, 2011

[5] A. Grishina, H. Hu, D. Zhang, A. Amirahmadi , J. Shen, I. Batarseh " A New Quasi Resonant DC Link for Single Phase Micro-inverter" IEEE Energy Conversion Congress and Exposition (ECCE 2012), pp 3221-3225, 2012

[6] F. Chen, Q. Zhang, A. Amirahmadi, I. Batarseh, "Design and implementation of three-phase gridconnedted two-stage module integrated converter" IEEE 14th Workshop on Control and Modeling for Power Electronics (COMPEL), pp. 1-8, 2013

[7] C. Hu, L. Chen, Q. Zhang, J. Shen, A. Amirahmadi, I. Batarseh, D. Xu "Current Dual-loop control for RPI with LCL filter in Micro-inverter" IEEE Applied Power Electronics Conf.(APEC), pp. 2907-2912, 2013

[8] A. Amirahmadi, U. somani, L. Chen, N. Kutkut, I. Batarseh"Variable Boundary Dual Mode Current Modulation Scheme for Three-phase Micro-inverter", Accepted at IEEE Applied Power Electronics Conference and Exposition 2014

[9] L. Chen, Q. Zhang, A. Amirahmadi, I. Batarseh"Modeling and Analysis of DC-Link voltage for Three-phase Four-Wire Two-Stage Micro-inverter", Accepted at IEEE Applied Power Electronics Conference and Exposition 2014

[10] U. somani, C. Jourdan, A. Amirahmadi, A. Grishina, H. Hu, I. Batarseh"Phase Skipping Control to Improve Light Load Efficiency of Three Phase Micro-Inverters", Accepted at IEEE Applied Power Electronics Conference and Exposition 2014

Recent Patents Pending:

[1] A. Amirahmadi, H. Hu, I. Batarseh, Soft Switching Current Control for High Efficiency Power Inverters (Pending)

[2] U. Somani, A. Amirahmadi , C. Jourdan, I. Batarseh, Phase Skipping Control to Improve Light Load Efficiency of Three-phase Grid tied Micro-inverter (Pending, Application No.: 61/820,266)

[3] H. Hu, I. Batarseh, A. Amirahmadi, A New PV System Architecture Based on Three-phase Micro Inverter for PV Solar Farm and Commercial Applications (Pending, Application No.:61/820,287)

[4]Q. Zhang, F. Chen, I. Batarseh, Maximum Power Point Tracking for Resonant Inverters based on Center Points Iteration Technique (Pending,Application No. :61/820,295)