

MHz High Efficiency High Density DC-DC Converters for Datacenter Applications

Xinke Wu Ph. D



High Density High Efficiency Power Converters



Power Management Innovation Consortium



Space & Satellite



More/Full Electric Aircraft



Super Computer



EV/HEV

High Density
High Efficiency



Power System of IDC



Radar Power supply



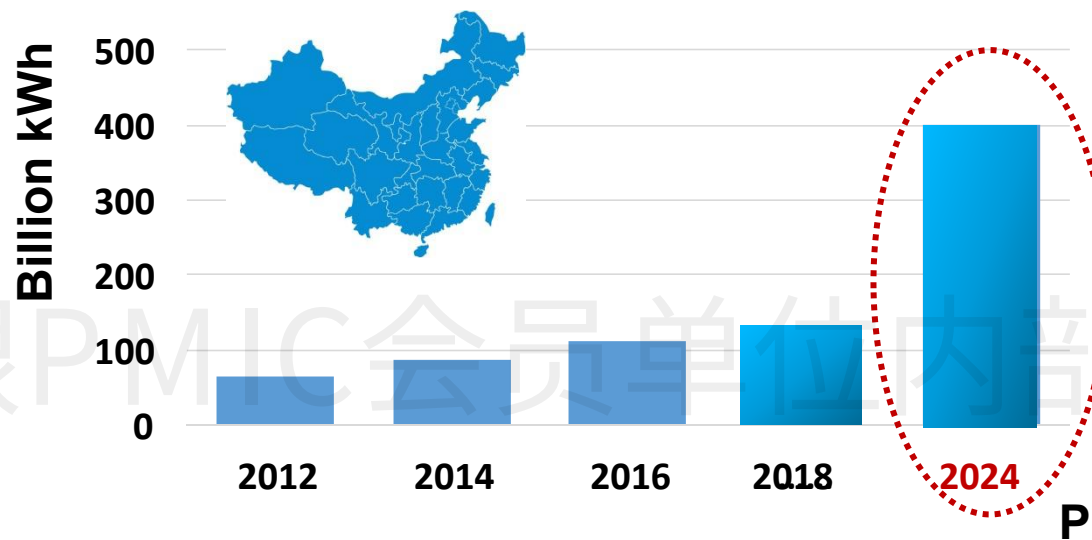
5G Base station



Portable Devices



Power Consumption of Data Center in China



- ❑ > 400 billion kWh
- ❑ 5%-8% Total Electric Power

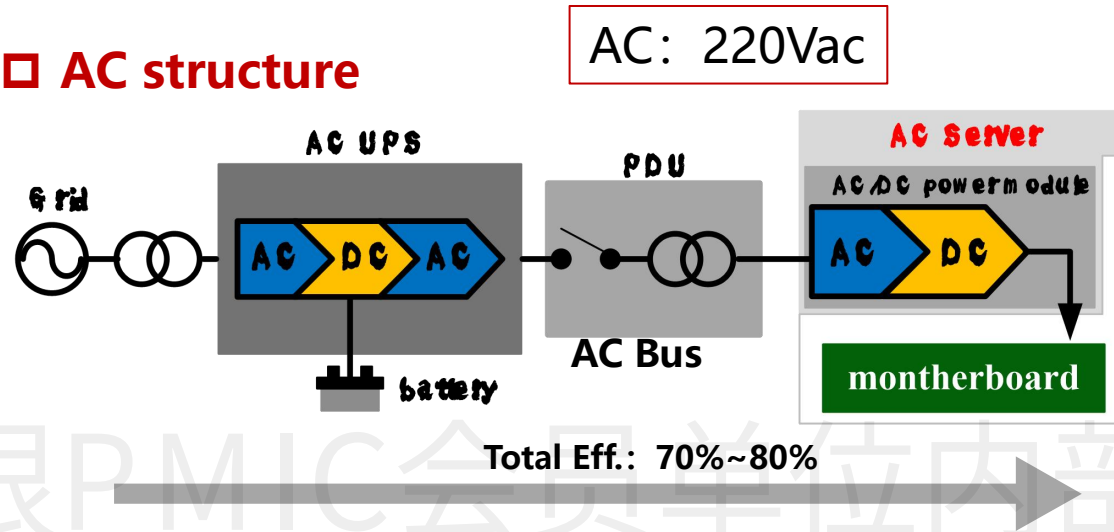
[1] 吕天文. 人工智能浪潮下的数据中心趋势分析, 2018, <http://www.gdctech.org/c41581.jsp>

[2] 闫志强, 中国能源报. 数据中心粗放发展节能降耗潜力大, 2016, http://paper.people.com.cn/zgnyb/html/2016-05/30/content_1684451.htm

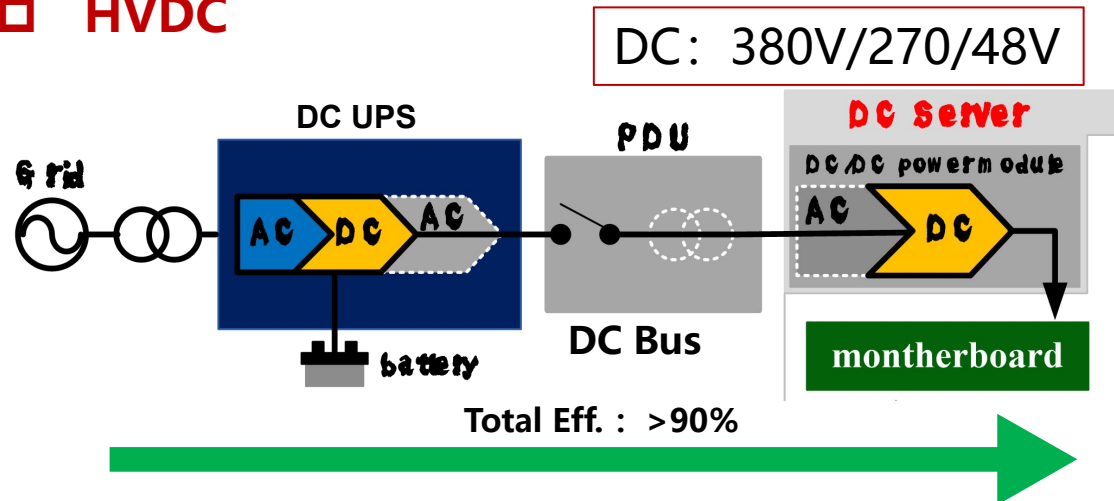
- 1. Introduction of power architectures of internet datacenter**
- 2. MHz high efficiency 48V-12V/6V power converters for 48V bus**
 - 2.1 State of the art of DC-DC converter for 48 Bus in server and other applications.
 - 2.2 Unregulated DCX for applications with low Bus voltage
 - 2.3 Tight regulated DC-DC converter (RDCX) for 48V-12V in server
- 3. MHz high efficiency 380V-48/12V power converters**
 - 3.1 Unregulated DC-DC techniques
 - 3.2 EMI design considerations of planar PCB transformer
 - 3.3 Tight regulated 380V-12V conversion
- 4. Conclusions**

Power Architectures of IDC

□ AC structure

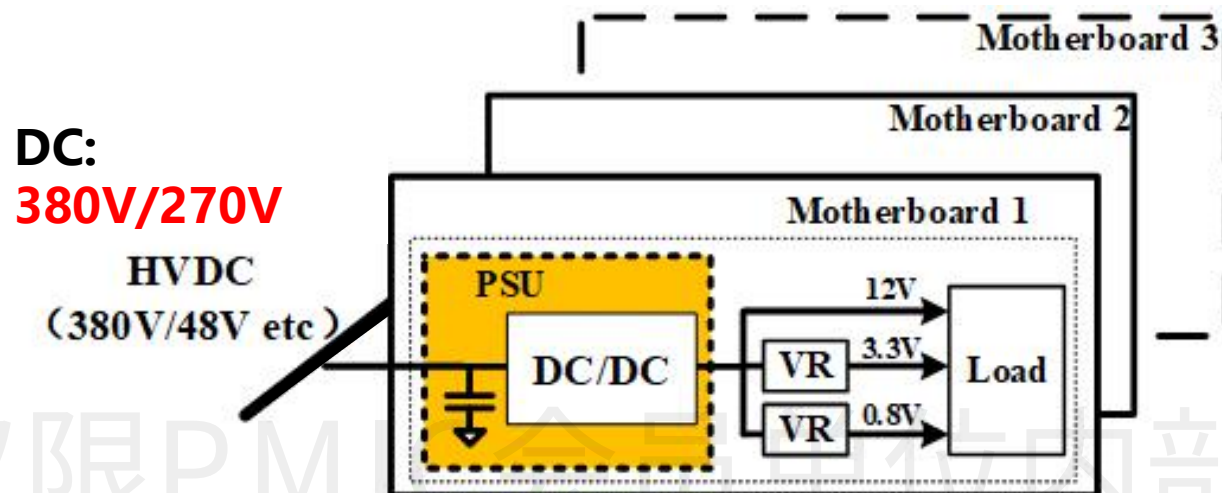


□ HVDC

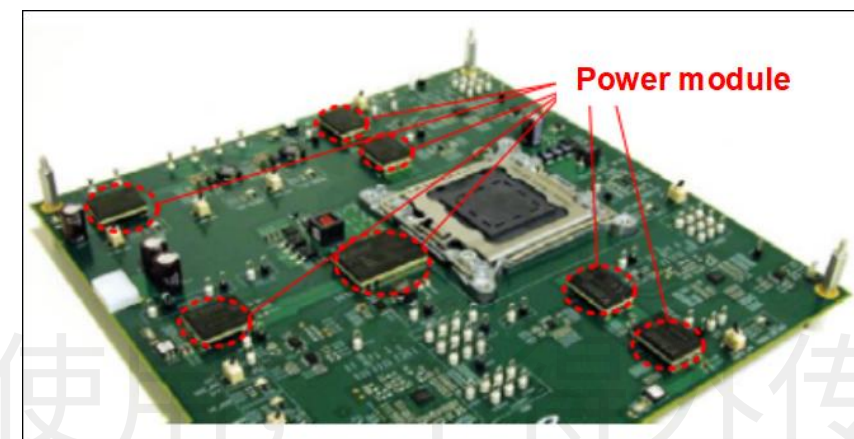


- ◆ Reduced power stages
- ◆ Lower distribution losses

380V input DCX feeding motherboard



Embedded high voltage bus dc/dc module



Motherboard

380V-12V DC/DC

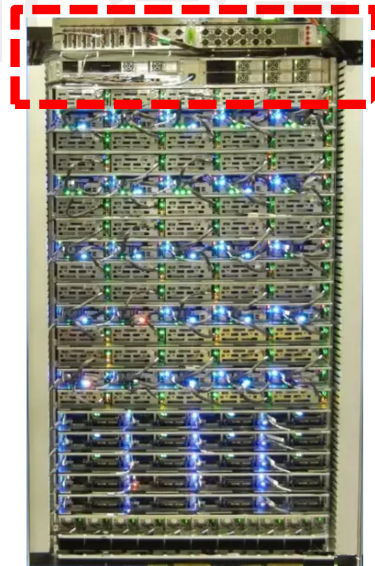
- ❑ Ultra high density
- ❑ Ultra high efficiency

48V DC Bus for IDC

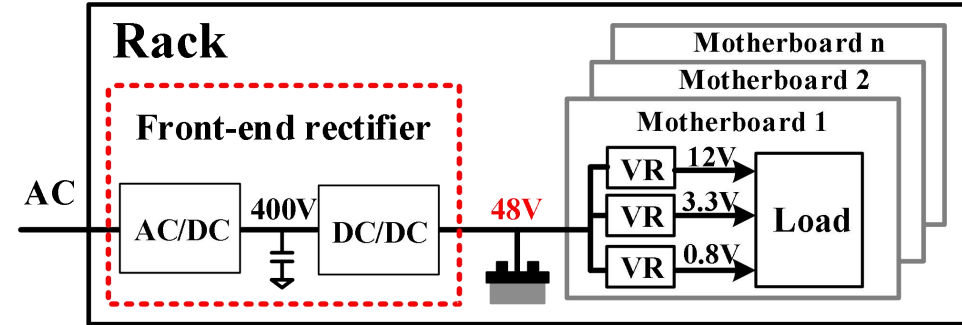


Datacenter of Google

Front-end
rectifier



48V-bus rack of Google

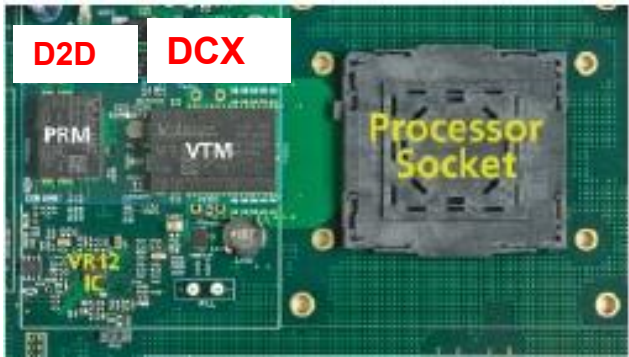
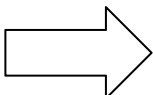
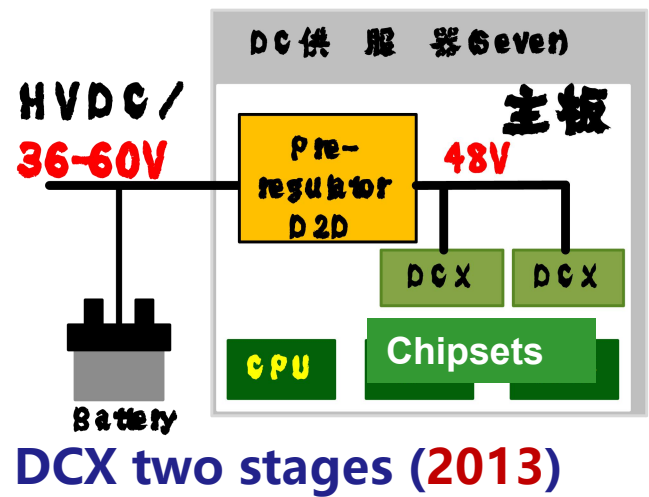
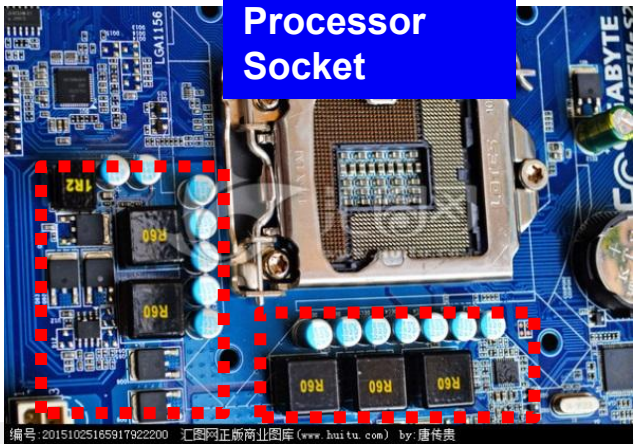
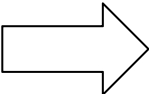
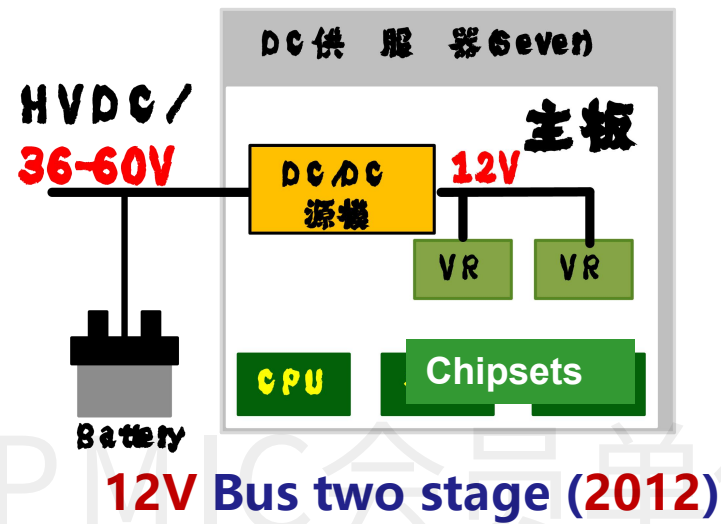


Power architecture of 48V rack

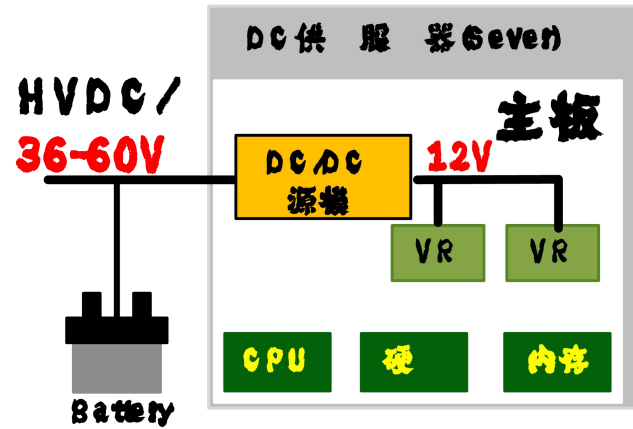
Challenges: Limited area for power supply
Load increase

Demands: High efficiency
High power density

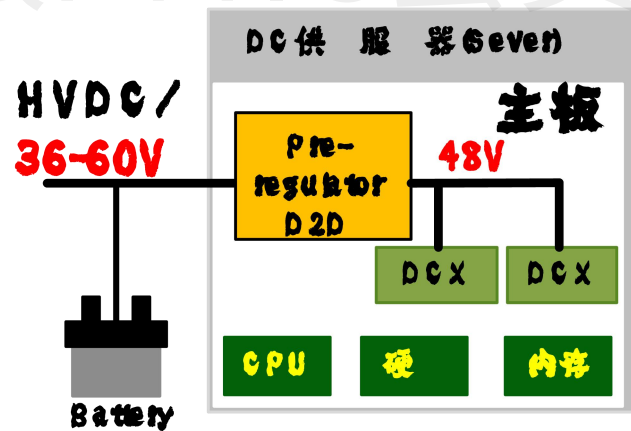
48V DC Bus for IDC



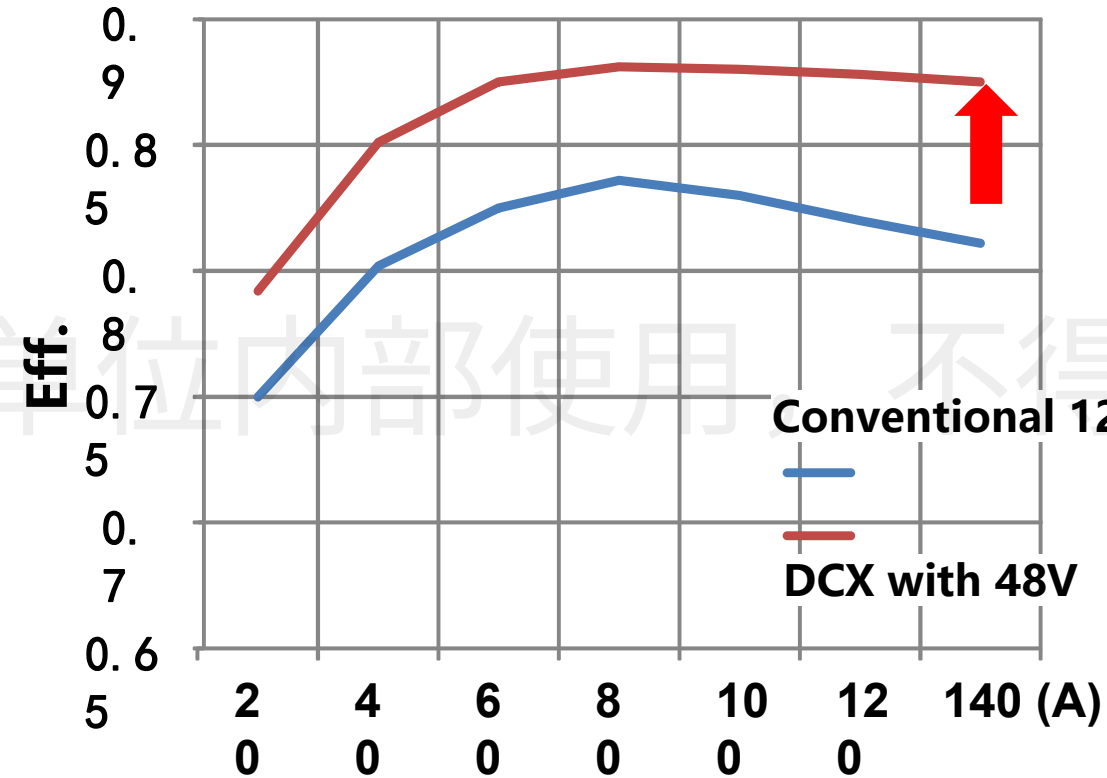
Efficiencies of different power architectures



12V two stage structure

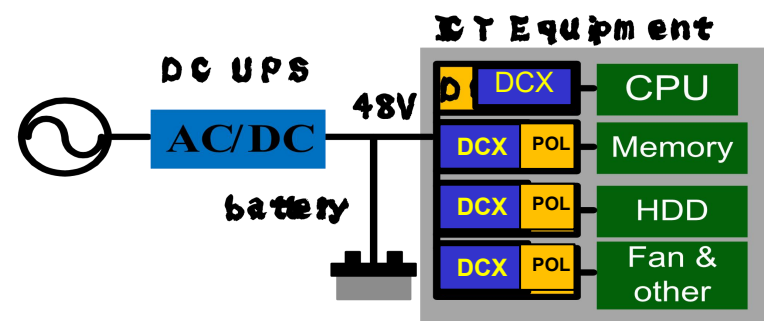


48V DCX two stage

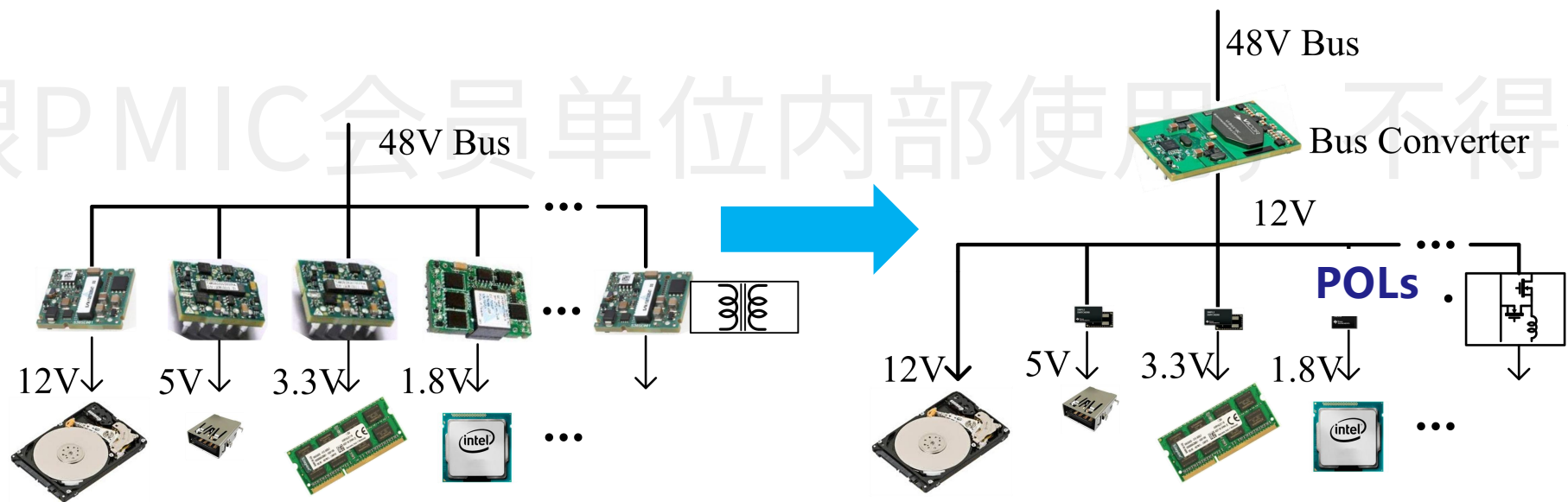


- Higher Efficiency
- Higher Density

48V input DCX Feeding POL



Server racks



Conventional isolated D2Ds

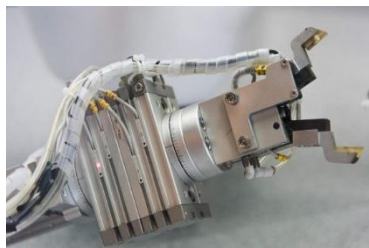
Intermedia bus



Low power low profile isolated power supply system **PMIC**

Power Management Innovation Consortium

Industry robotics



Unregulated Intermediate Bus Architecture (**IBA**)

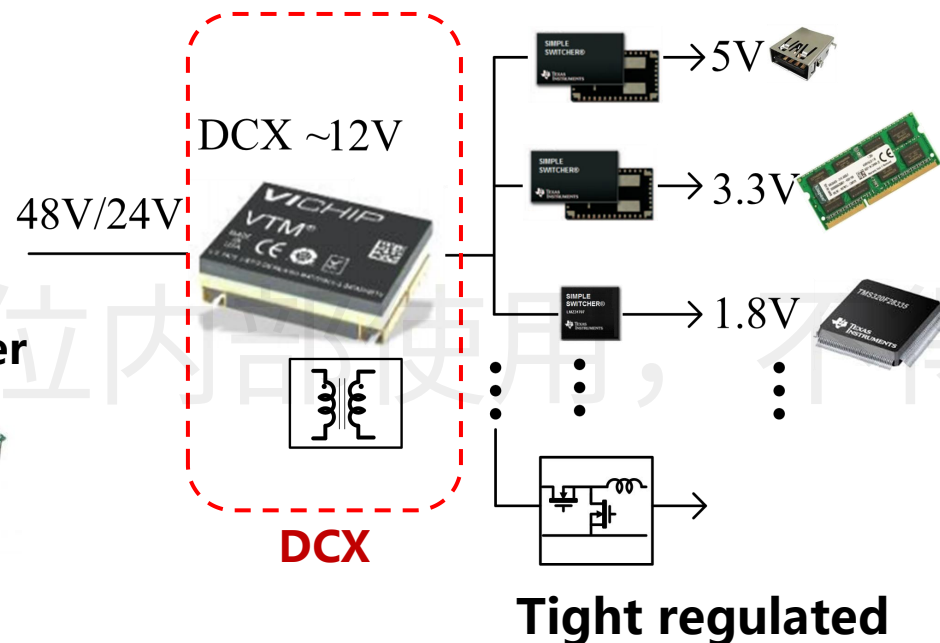
Telecom exchanger



Bias & driver



Portable instruments



- ✓ Easy control
- ✓ Optimized magnetic components
- ✓ High efficiency



1. Introduction of power architectures of internet datacenter
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 - 3.2 EMI design considerations of planar PCB transformer
 - 3.3 Tight regulated 380V-12V conversion

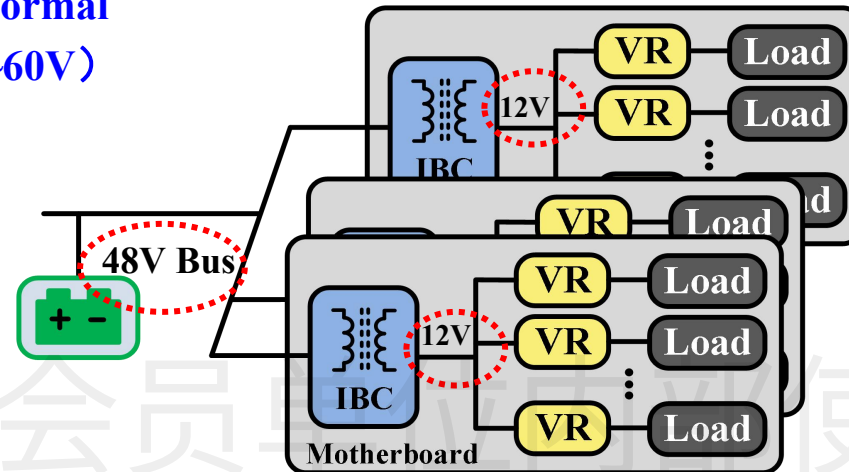
4. Conclusions



2.1 State of the art of DC-DC converter for 48 Bus in server and other applications.



~54V Normal
(42V~60V)



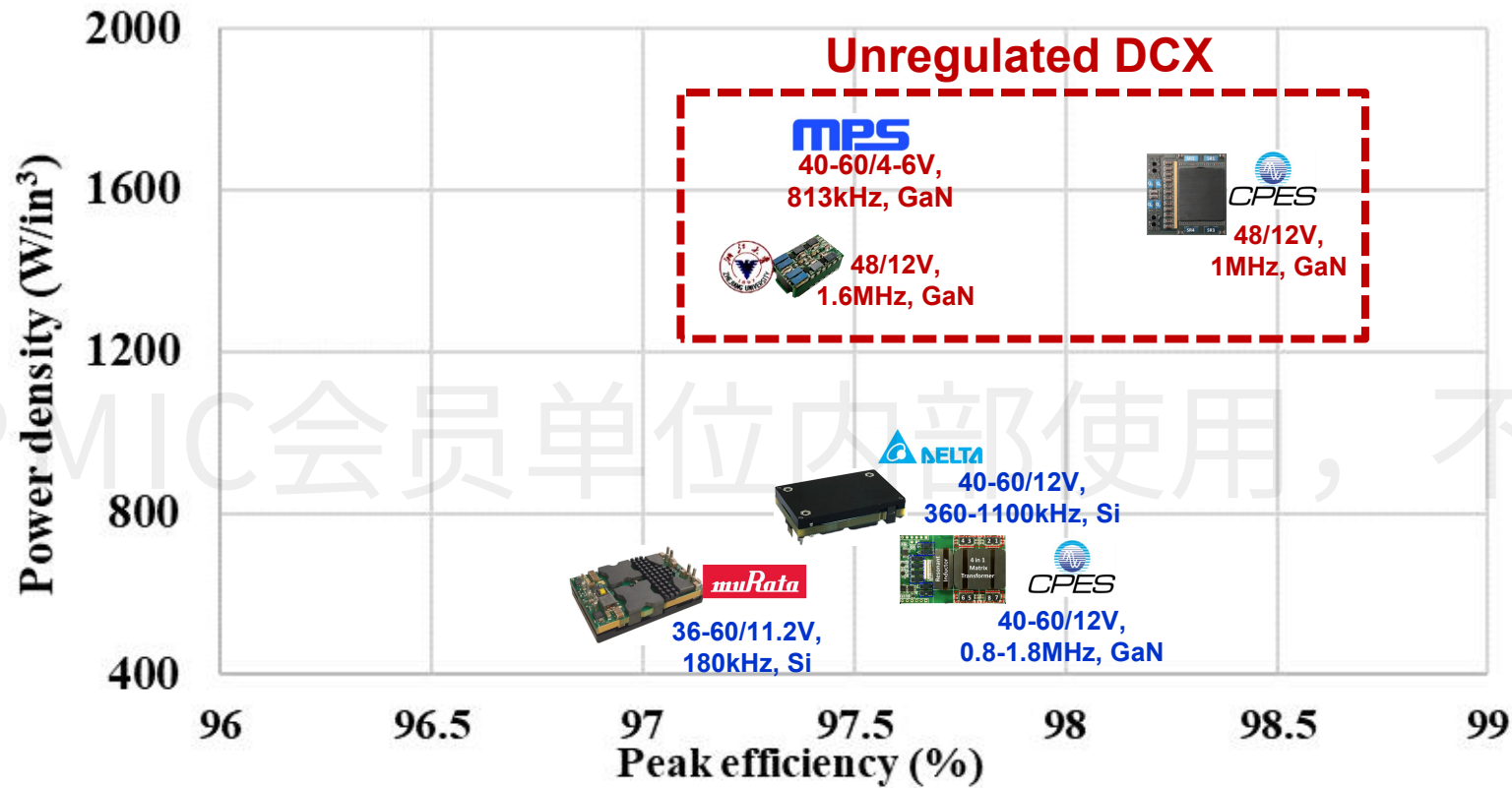
Intermediate Bus Architecture

Requirements:

- ❑ High Efficiency
- ❑ High power density
- ❑ Voltage regulation capability (option)
- ❑ Wide input voltage range

Bus converter with 48V Input

By regulating capability



[1] DRQ-11.4/88-L48NB-C, murata

[2] Q54SJ108A2, Delta

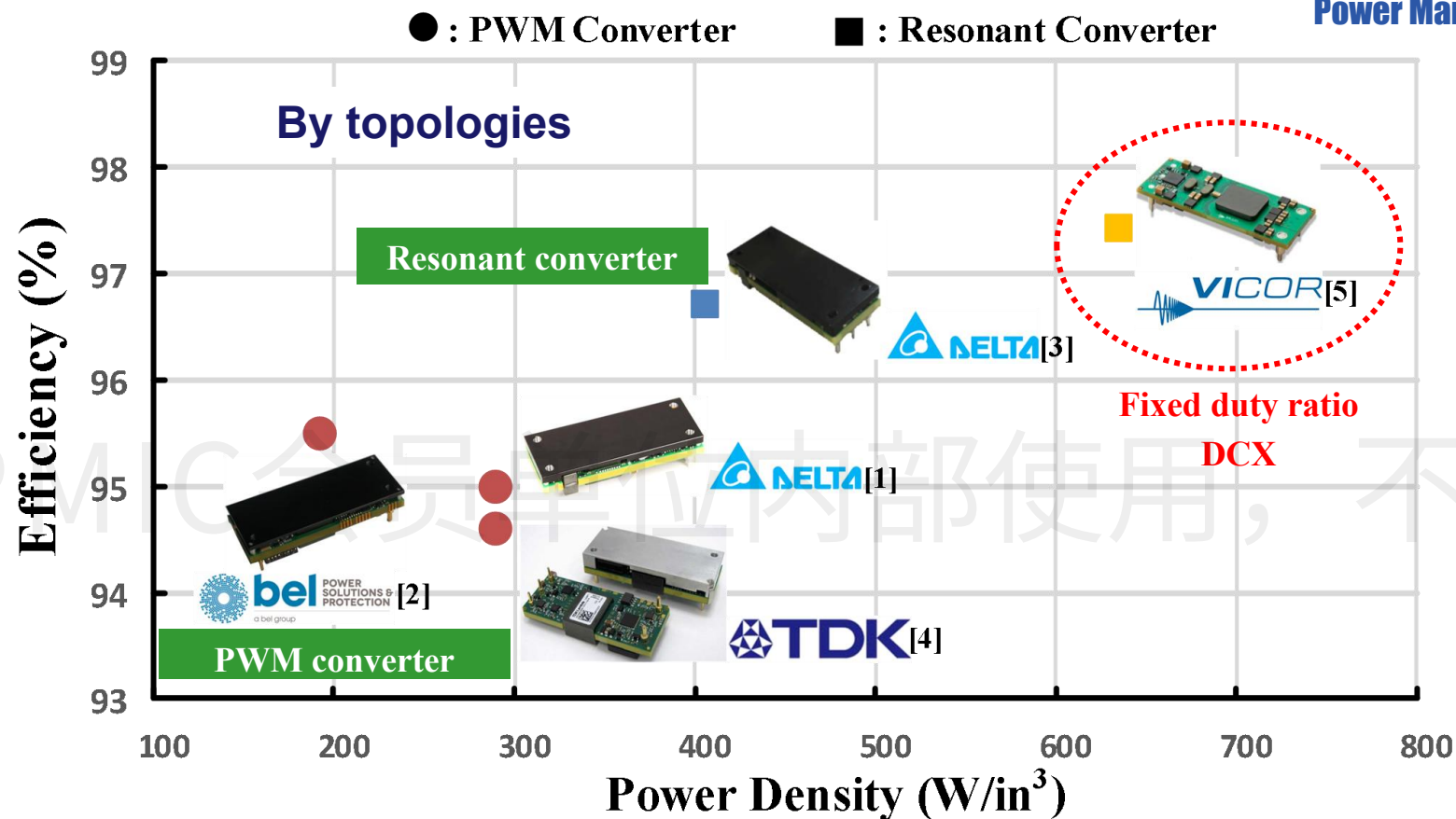
[3] M. H. Ahmed, et al., High-efficiency, High-density Isolated/Regulated 48V Bus Converter with a Novel Planar Magnetic Structure. APEC 2019.

[4] G. Li, et al. High Power Density 48–12 V DCX With 3-D PCB Winding Transformer. IEEE TPE, 2020. 35(2): p. 1189-1193.

[5] M. H. Ahmed, et al., Two-Stage 48V VRM With Intermediate Bus Voltage Optimization For Data Centers. IEEE JESTPE, 2020, Early Access



Open frame 48V dc-dc Converters



Single-stage Converter with regulation capability:



- Limited power density
- Limited efficiency (<97%)

- [1] E48SC12025, 2017, Delta
- [2] ORCY-D4T12x, 2017, Belfuse
- [3] E54SJ12040, 2017, Delta
- [4] IEH48025A120V, 2013, Lambda-TDK
- [5] IB0E120T400xx-xx, 2016, VICOR

2.2 Unregulated DCX for applications with 48V Bus

仅限PMIC会员单位内部使用，不得外传



Conventional Resonant DCX Topology for 48V Applications

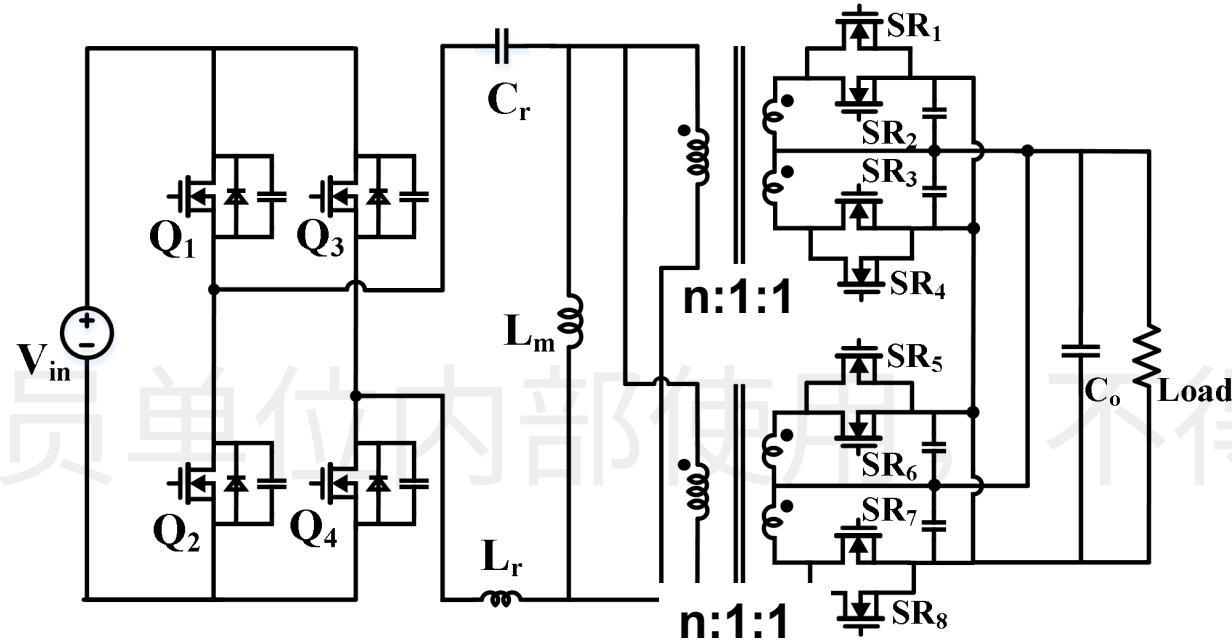
Resonant topology working at resonant frequency



DCX, GaN
48V/12V, 1.6MHz



DCX, GaN
48V/12V, 1MHz

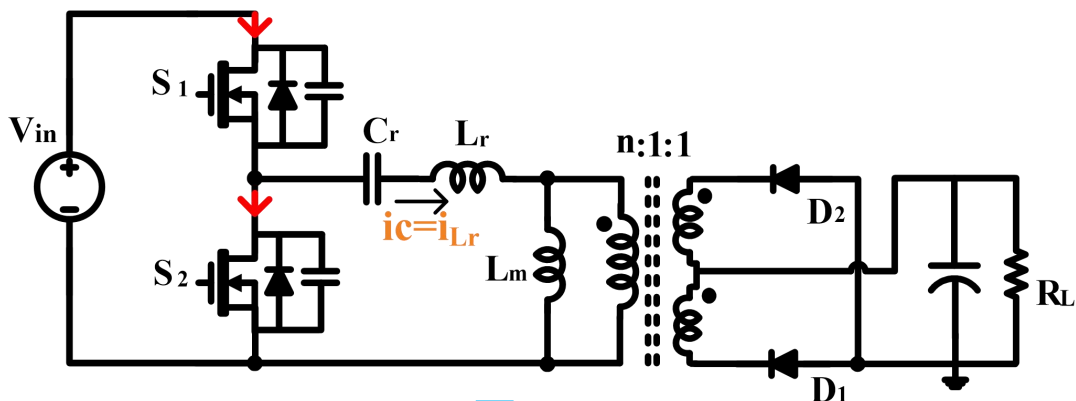


Features:

1. ZVS-on;
2. ZCS-off;
3. Only one magnetic device;
4. Optimized at fixed frequency.

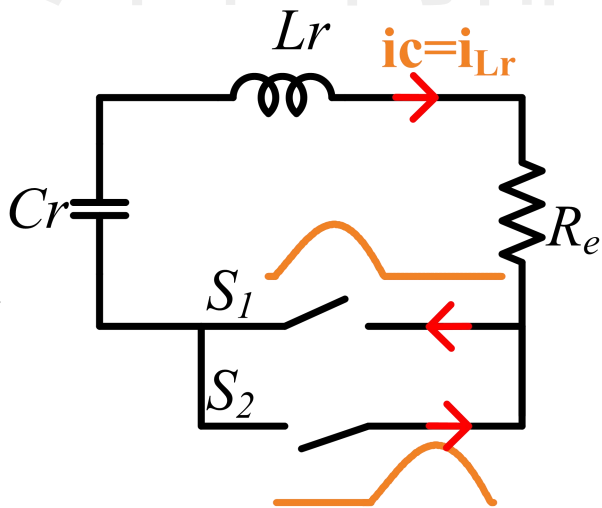
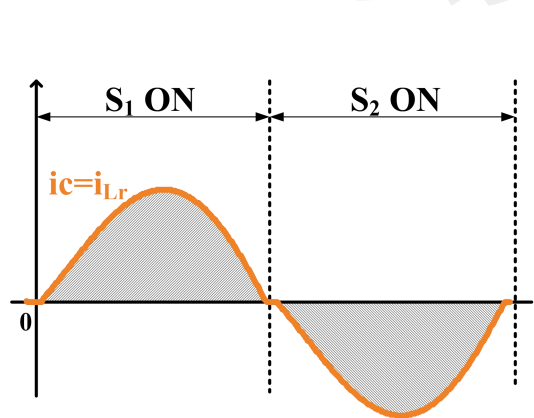
- High efficiency
- High density
- **Complex control and driving**

Equivalent LC Resonant Tank



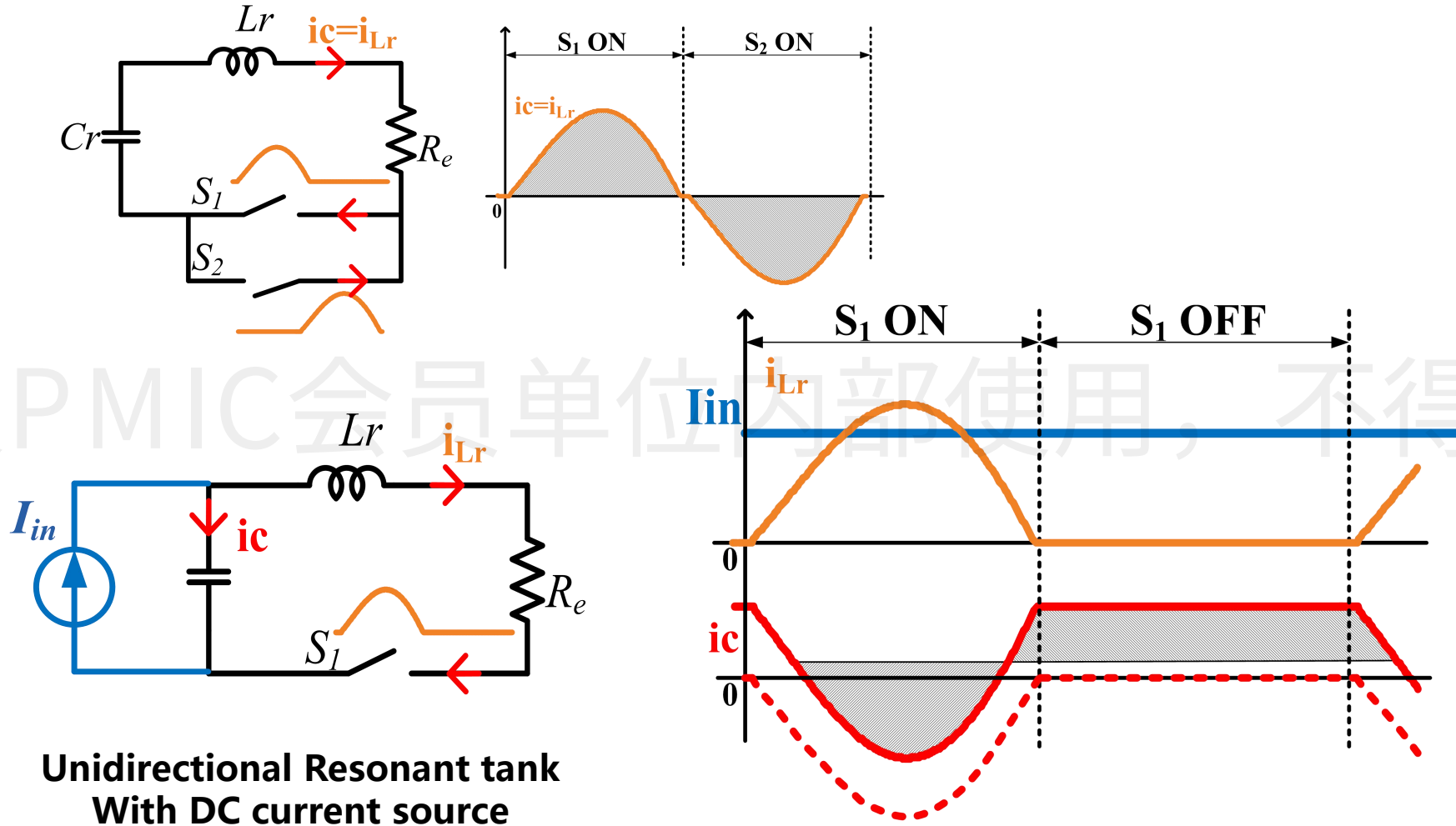
Center tap rectifier
for LLC half bridge

仅限PMIC会员单位内部使用，不得外传



Equivalent resonant tank

Unidirectional Resonant Tank

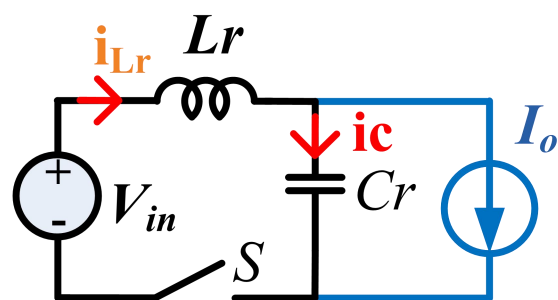
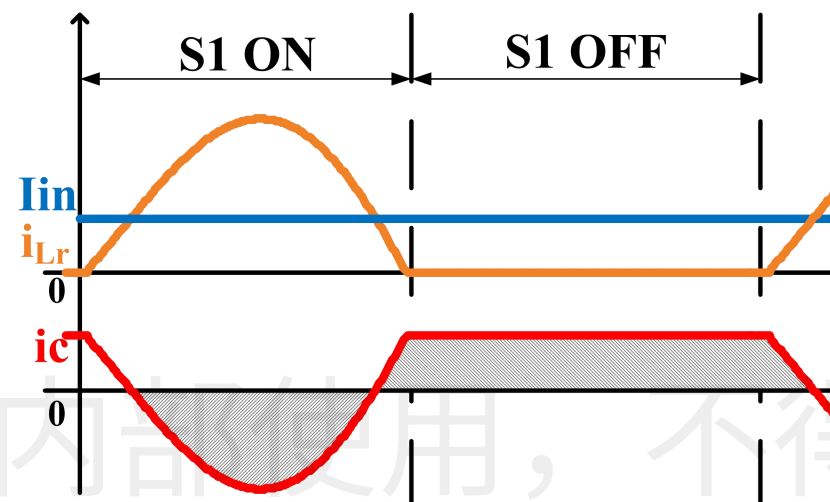
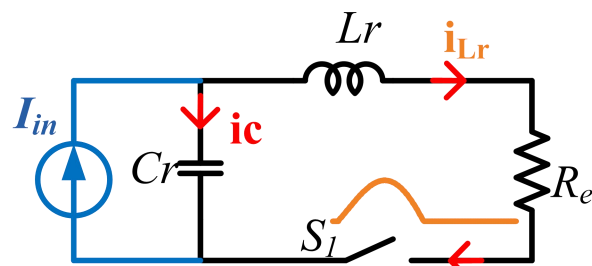


Unidirectional Resonant tank
With DC current source

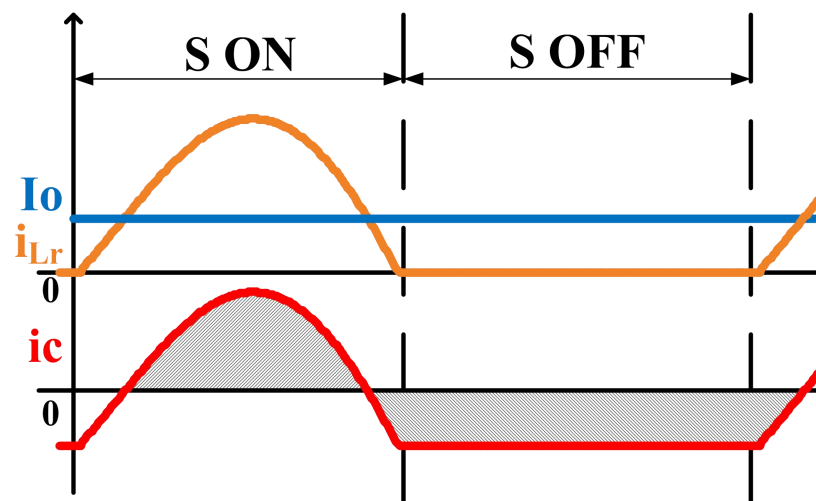
W. Qin, X.K Wu, et_al "A Family of DC Transformer (DCX) Topologies Based on" IEEE T.P.E. 2016

Extension of Unidirectional Resonant Tank

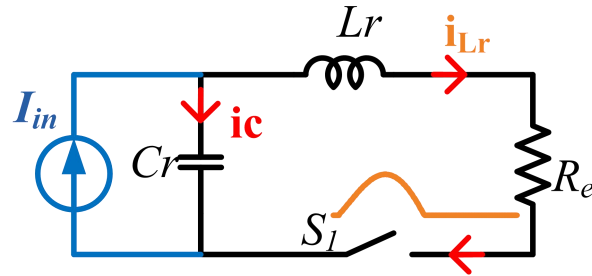
Type I
Input current source



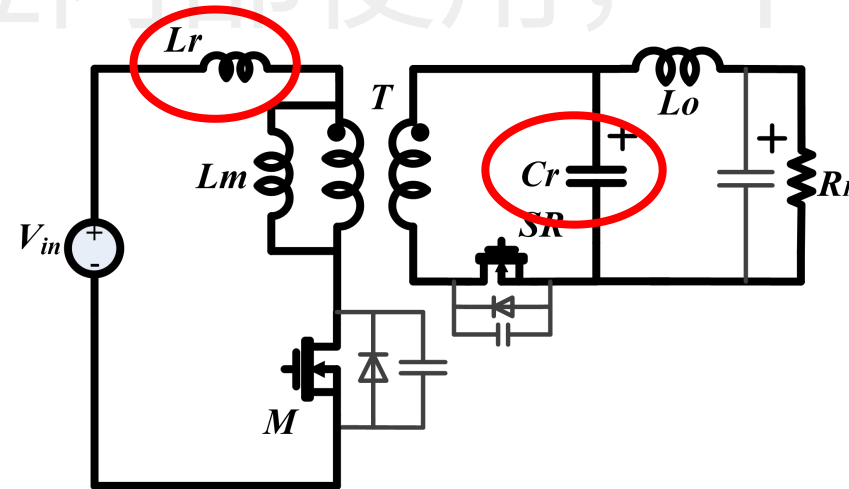
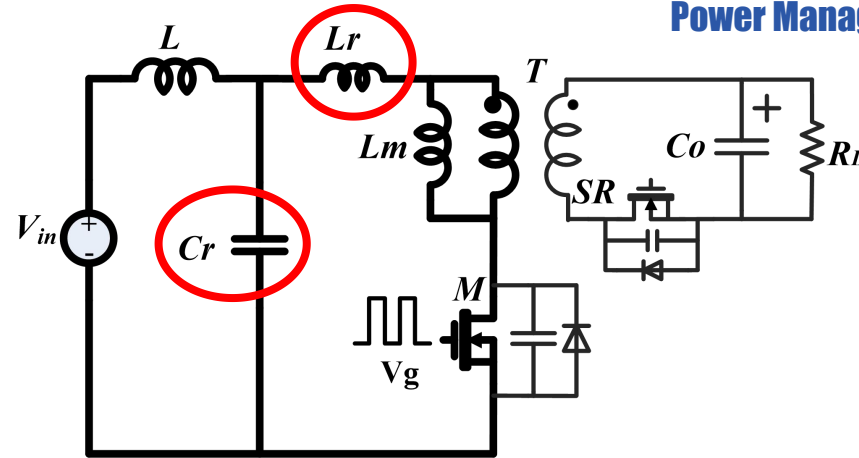
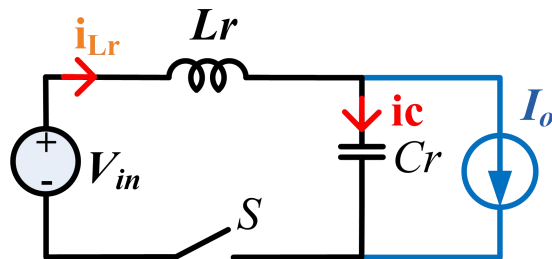
Type II
Output current source



Derivation of single switch DCX topology with Unidirectional Resonant Tank

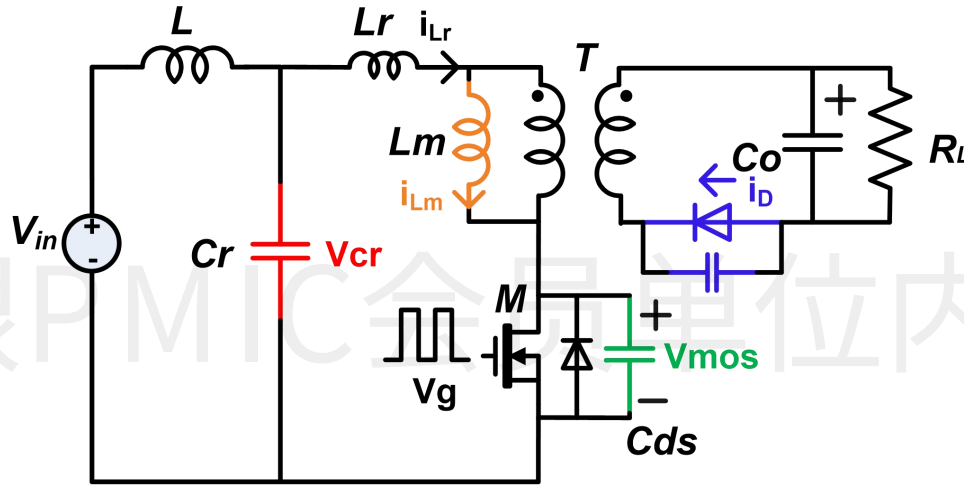


Single Switch Forward Resonant **DCX**

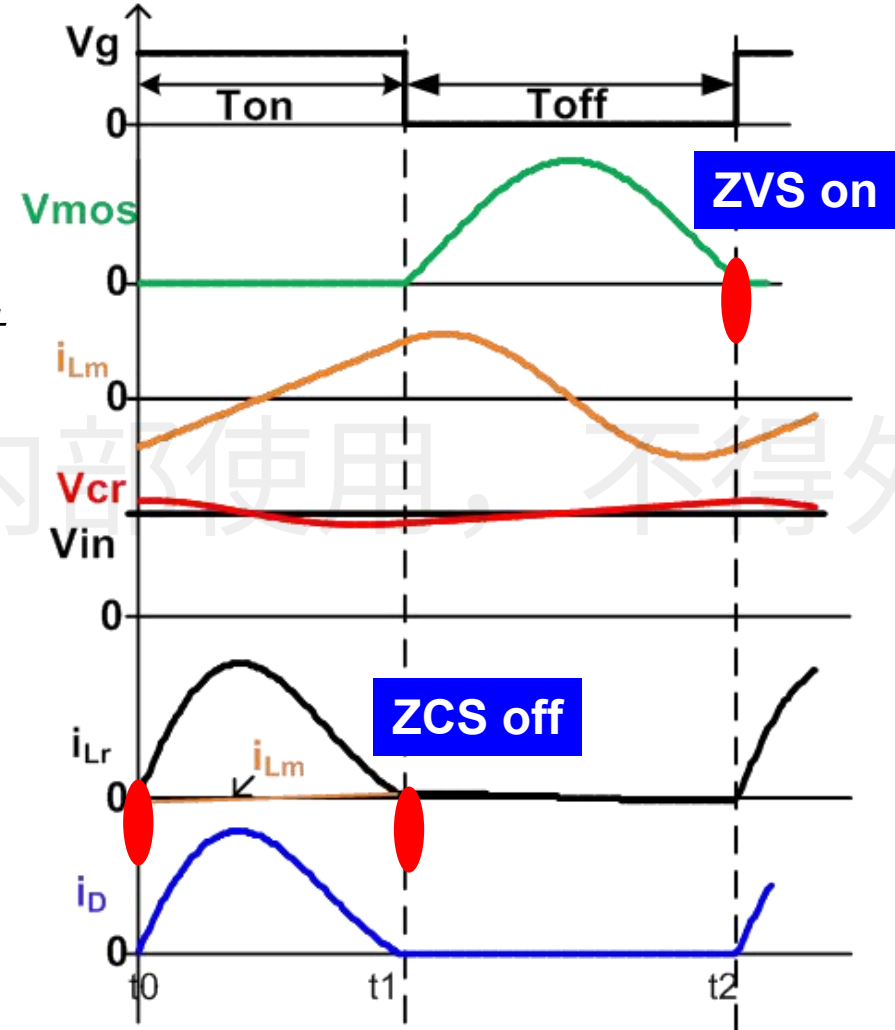


W. Qin, X.K Wu, et_al "A Family of DC Transformer (DCX) Topologies Based on" IEEE TPEL. 2016

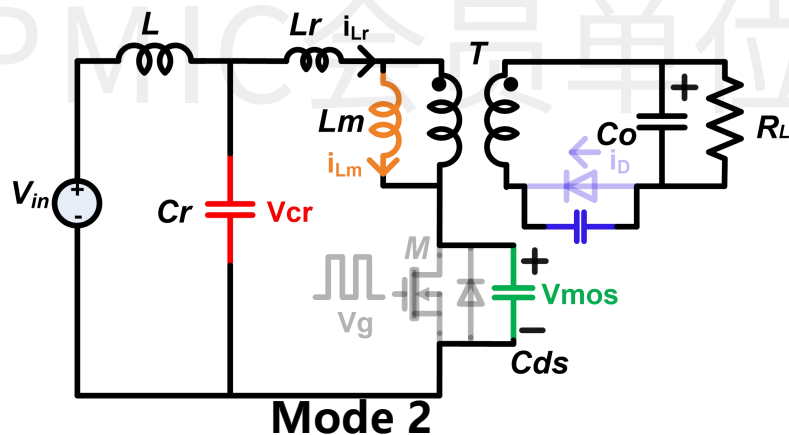
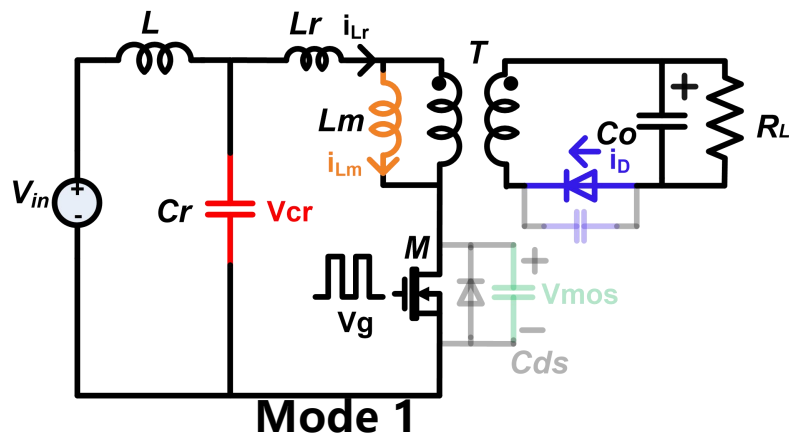
Operation of ZVZCS Forward DCX



- 😊 Very simple.
- 😊 Very good ZVZCS.
- 😊 High frequency operation

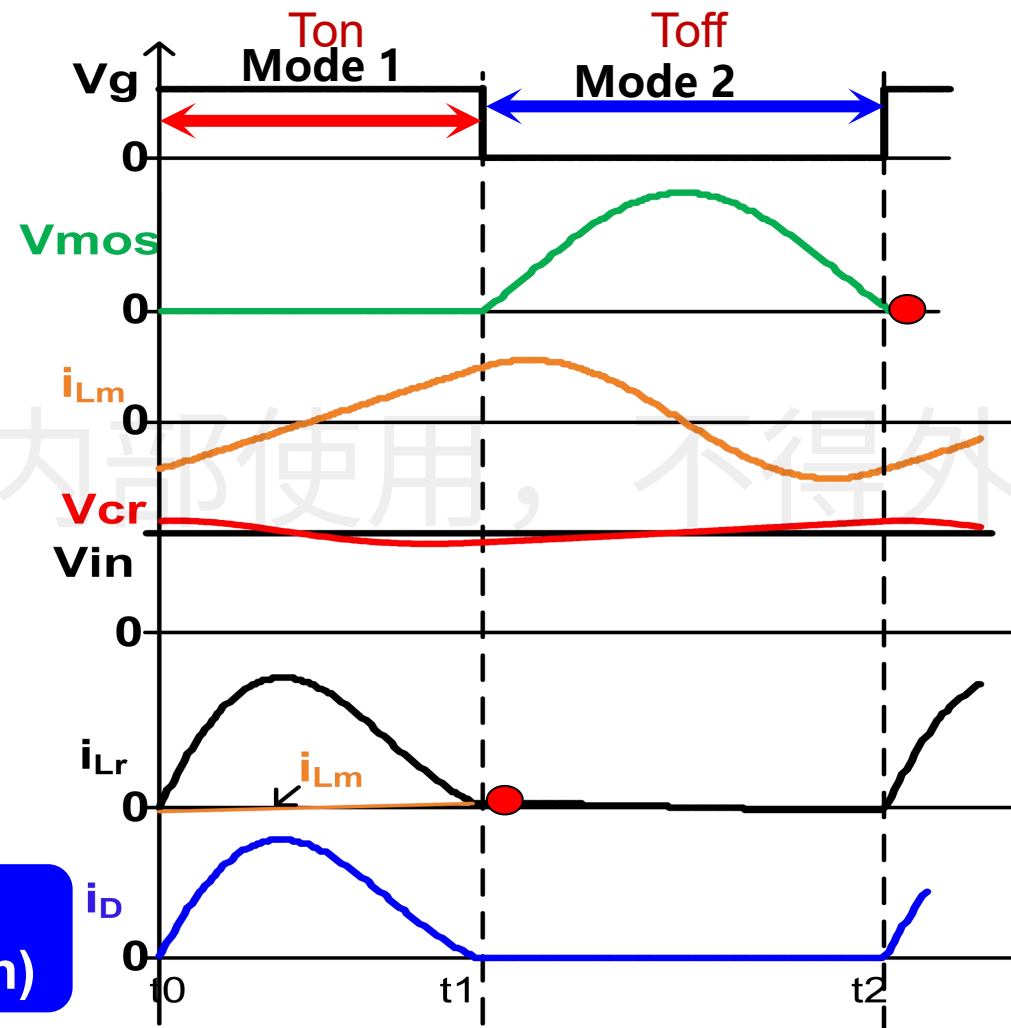


Design examples for the Forward DCX



☺ ZVZCS operation

☹ High voltage stress (at least $3 \cdot V_{in}$)



How to determine the T_{on} and T_{off} ?

Relationship between Ton and Toff

ZCS condition

$$i(T_{on}) = 0 \quad \frac{1}{T_s} \int_0^{T_{on}} i dt = I$$

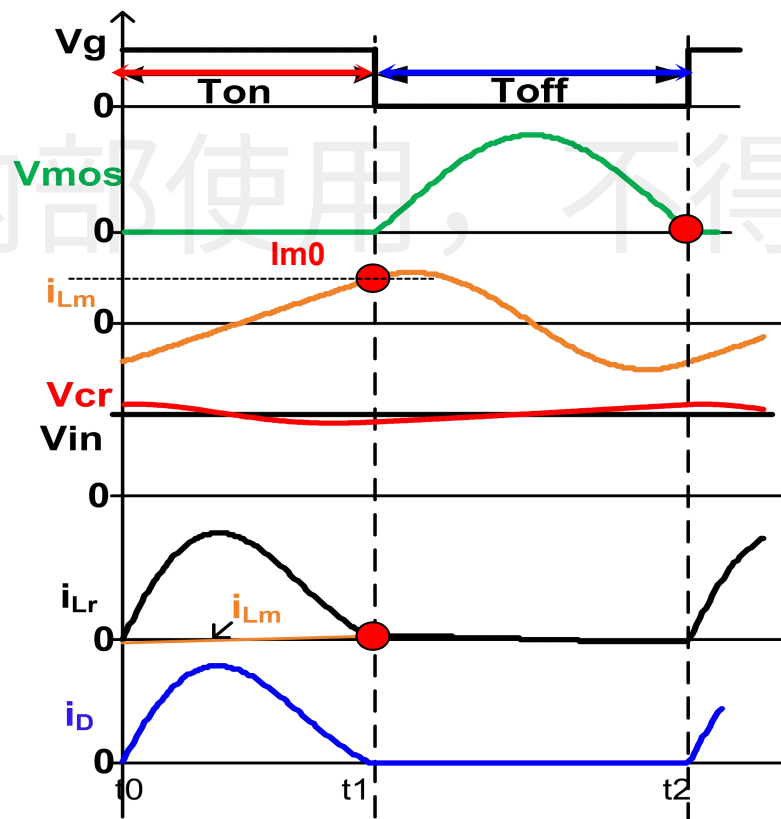
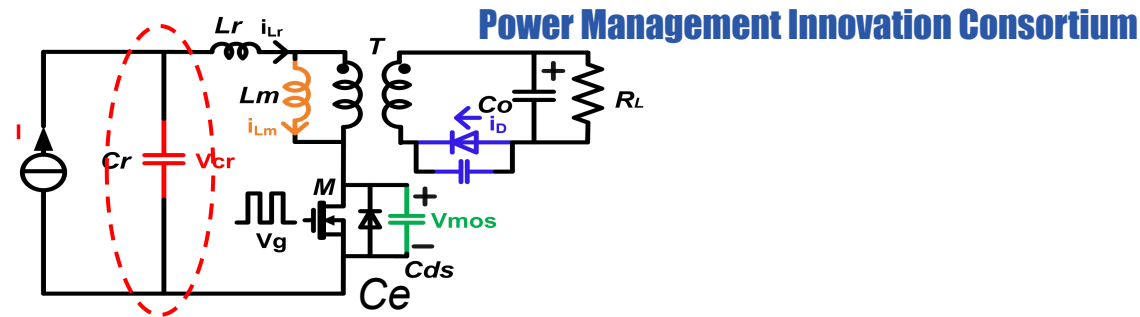
Neglecting the magnetizing current

$$v_{mos}(T_{off}) = 0 \quad I_{m0} = V_{in} \cdot T_{on} / 2$$

$$T_{off} = -\frac{\sin \omega T_{on}}{\omega} - \frac{(\cos \omega T_{on} - 1)^2}{\omega \sin \omega T_{on}}$$

$$\omega = 1/\sqrt{L_r C_r}$$

W. Qin, X.K Wu, et_al "A Family of DC Transformer (DCX) Topologies Based on"
IEEE T.P.E. 2016



Determine Duty Cycle & Frequency

$$T_{off} = -\frac{\sin \omega T_{on}}{\omega} - \frac{(\cos \omega T_{on} - 1)^2}{\omega \sin \omega T_{on}} \quad \text{ZCS condition}$$

$$\omega = 1/\sqrt{L_r C_r}$$

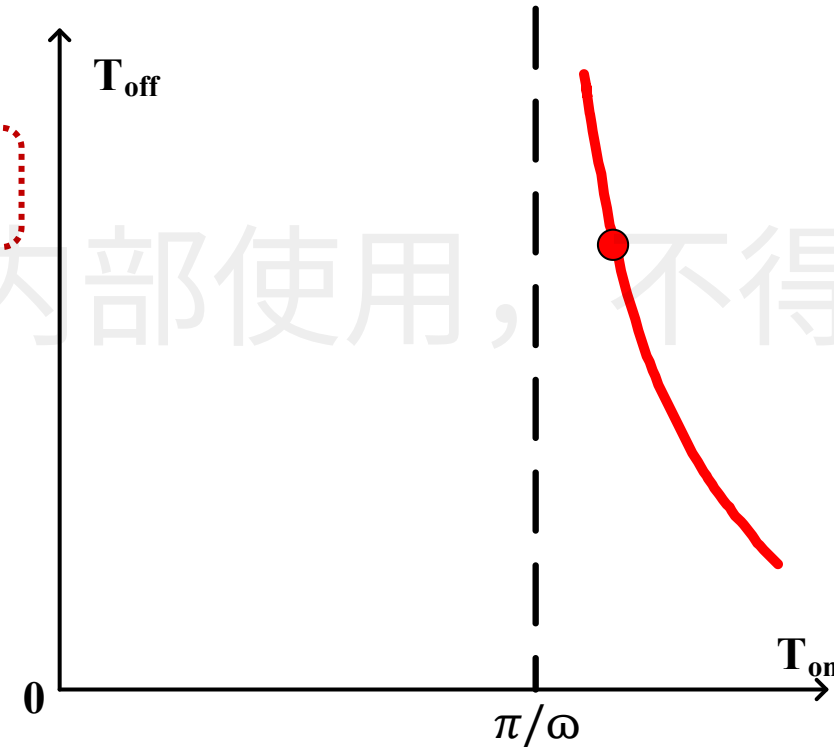
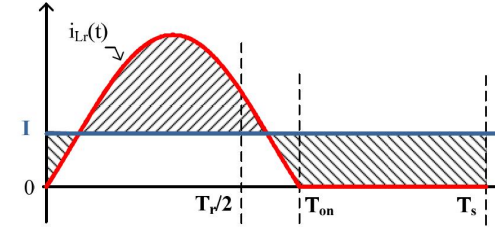
For given C_r , L_r , L_m , C_e and V_{in}

$$T_{on} = \frac{2(\cos \omega_1 T_{off} - 1)}{\omega_1 \sin \omega_1 T_{off}} \quad \text{ZVS condition}$$

$$\omega_1 = 1/\sqrt{(L_r + L_m)C_e}$$

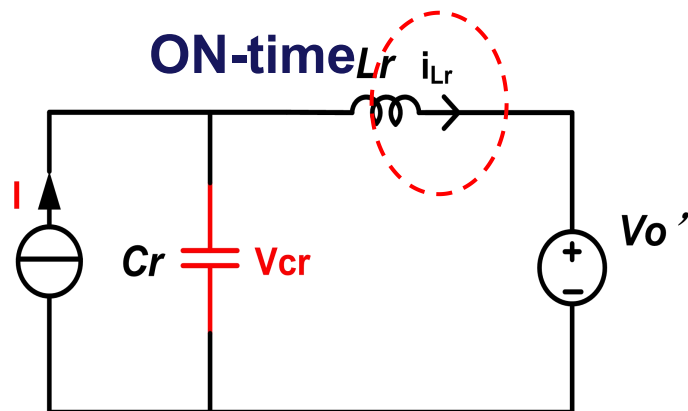
$$D = T_{on} / (T_{on} + T_{off})$$

$$f_s = 1/(T_{on} + T_{off})$$

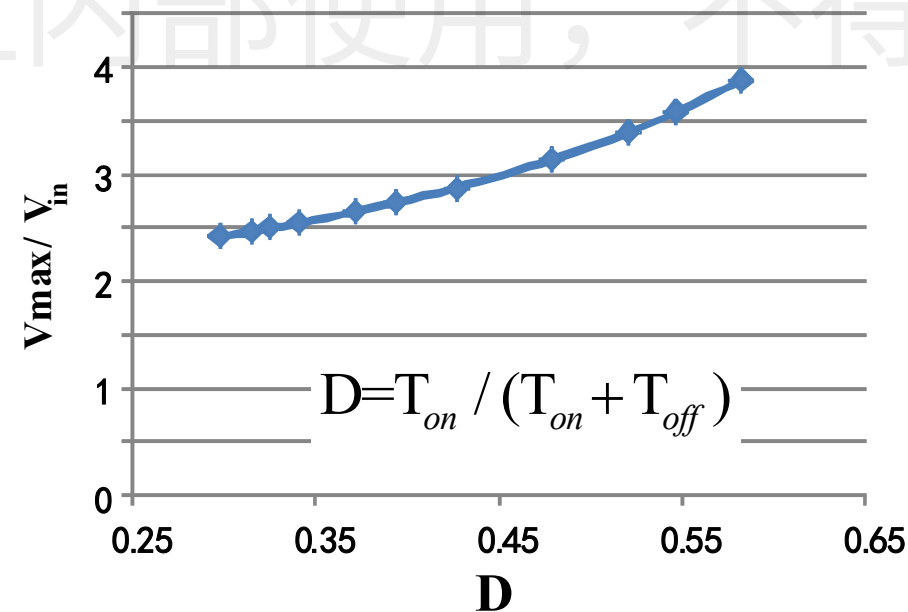
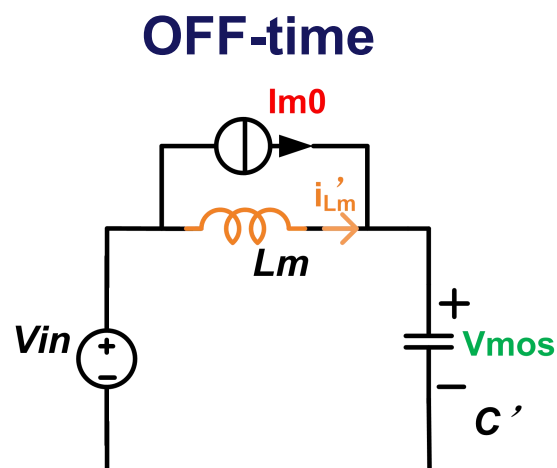


$$T_{on_min} = T_r/2$$

Voltage Stress vs. Duty Cycle (Frequency)

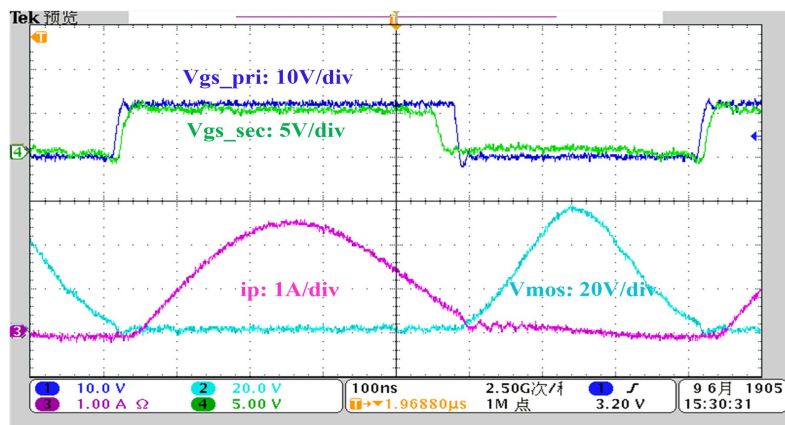


$$V_{\text{mos_Max}} = V_{\text{in}} + V_{\text{in}} \cdot \sqrt{\left(\frac{T_{\text{on}}}{2}\right)^2 / L_m / C' + 1}$$

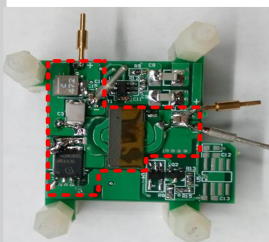


Calculated Voltage Stress

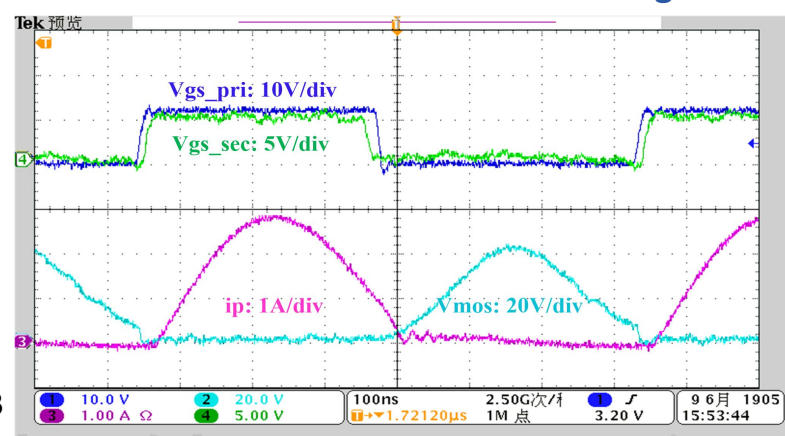
Measured Waveforms at Different D



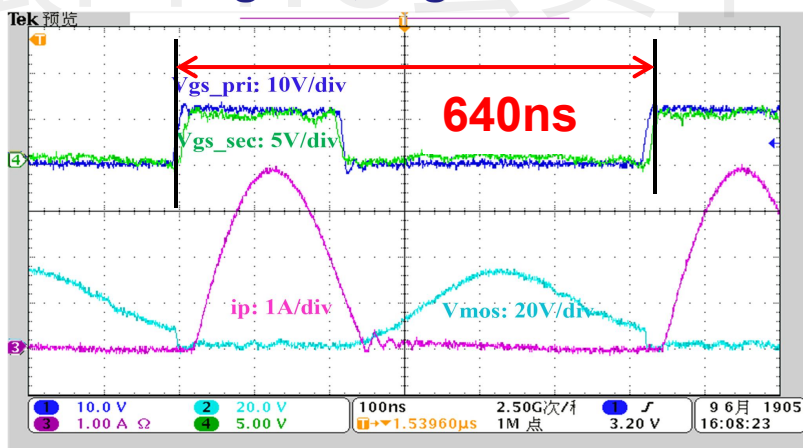
Cr=99nF, fs=1.25MHz
high D, high Vmos



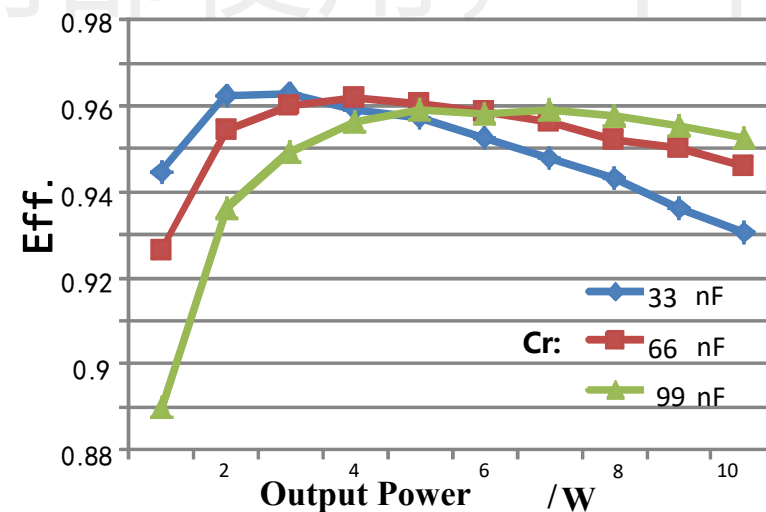
@ 1.6MHz
~150 W/in³
Up to 96%



Cr=66nF, fs=1.45MHz



Cr=33nF, fs=1.6MHz
low D, low Vmos, high Irms

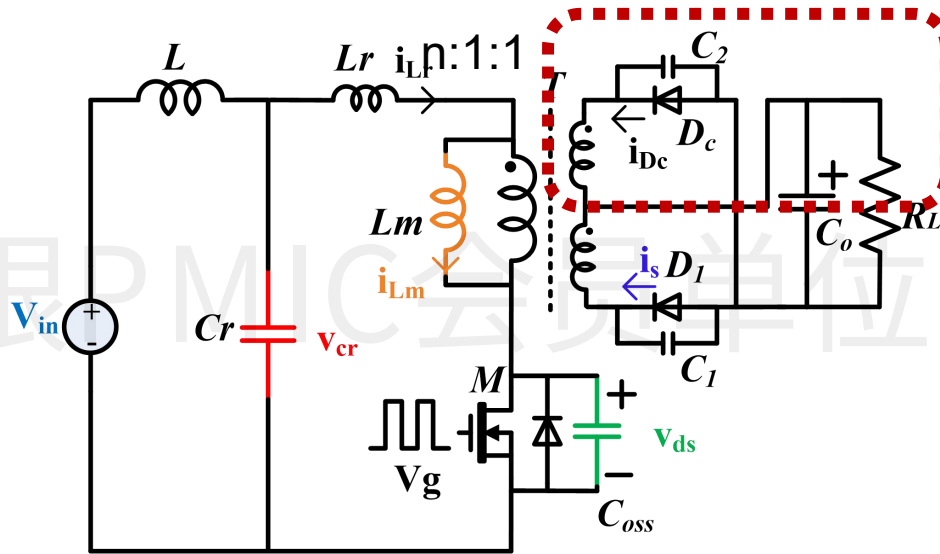


29

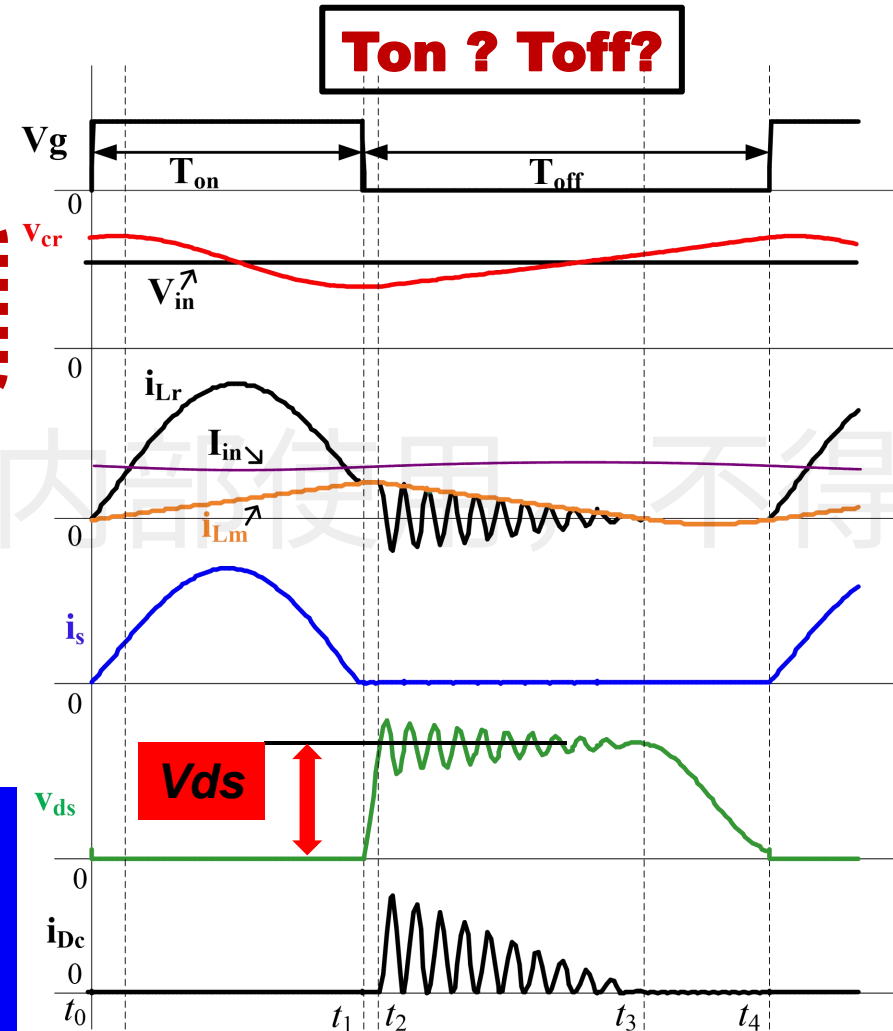
Unidirectional Resonant Tank

Secondary Clamping of Single Switch DCX

□ Reduce the voltage stress



- ✓ Less Turns
- ✓ Magnetizing energy transfer to load
- ✓ Keep ZVZCS



Frequency (f_s) & Duty Cycle (D)

□ Given : L_r , C_r , L_m , C_e

ZCS off $T_{off}-T_{on}$ conditions

$$T_{off} = -\frac{\sin \omega T_{on}}{\omega} - \frac{(\cos \omega T_{on} - 1)^2}{\omega \sin \omega T_{on}}$$

ZVS on

$$T_{off} = T_{on} + \Delta t_2 + \Delta t_4$$

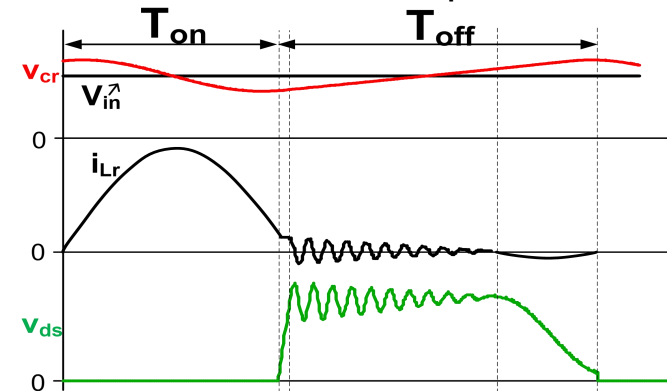
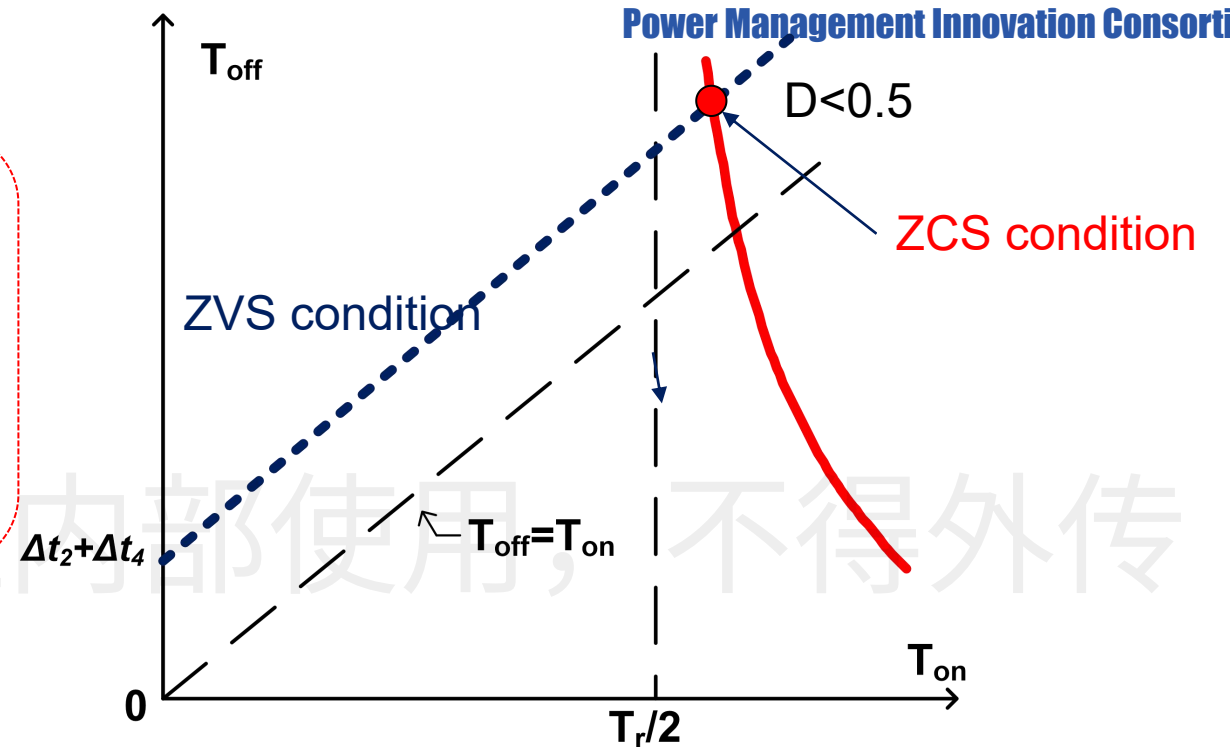
➤ Duty cycle and f_s :

$$D = T_{on} / (T_{on} + T_{off})$$

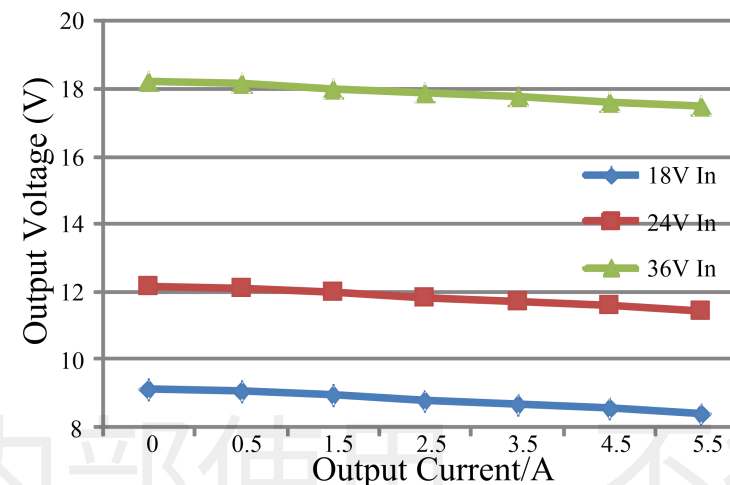
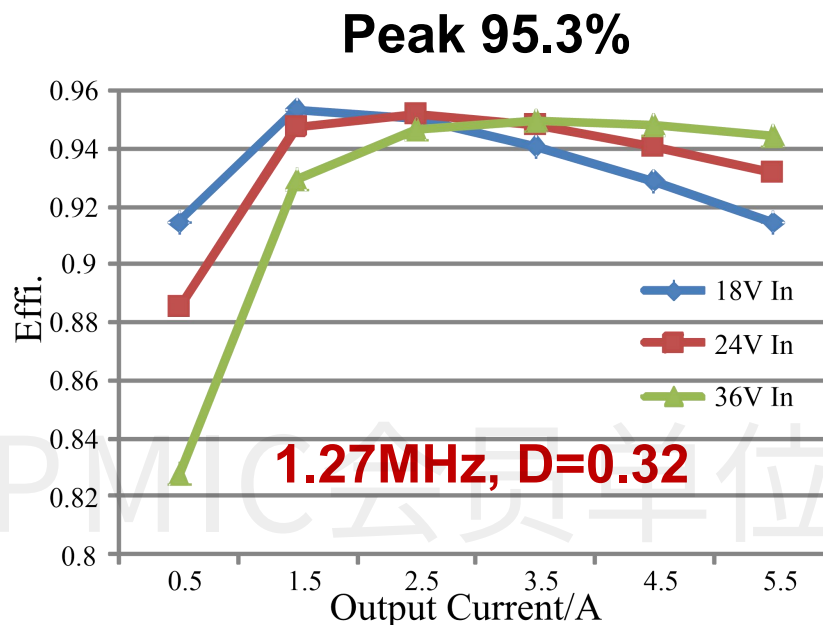
$$f_s = 1 / (T_{on} + T_{off})$$

✓ Simple control and drive

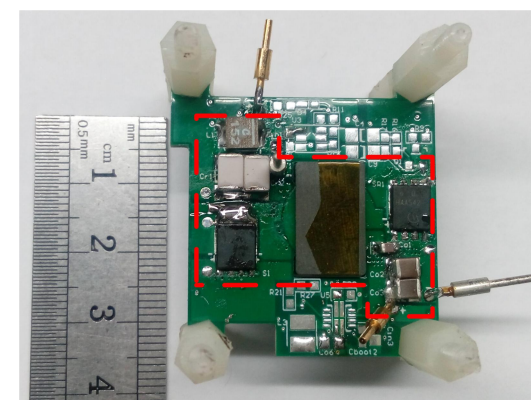
✓ ZVZCS



Measured Efficiencies



Po: 66Watt @24V Vin
fs: ~1.2MHz
Efficiency : 95.3%

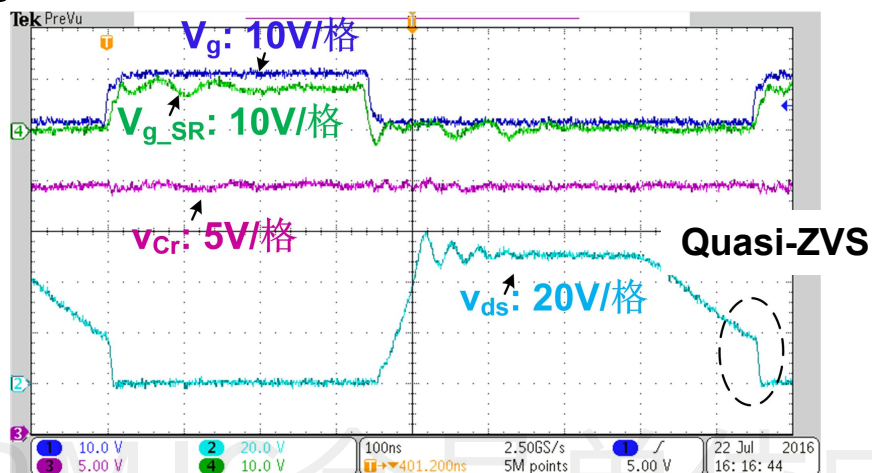


Power density: ~270W/in³

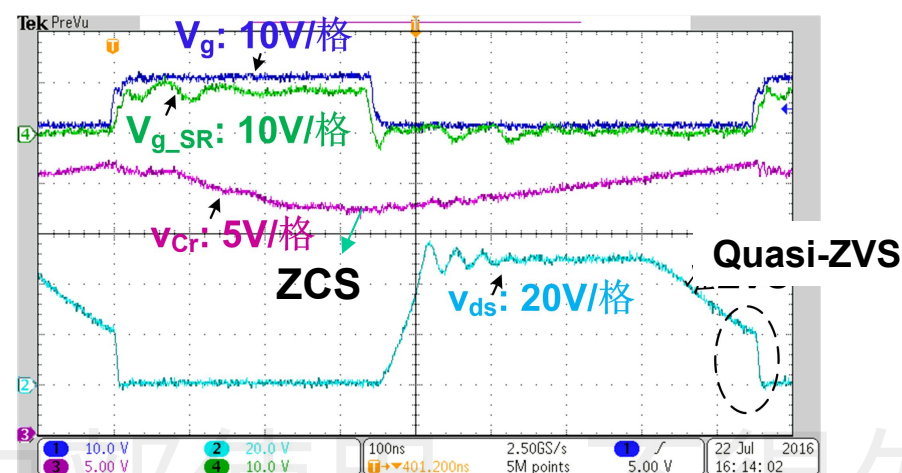
Vin	18~36V
Transformer	2:1:1
Cr	300nF

Experimental verifications

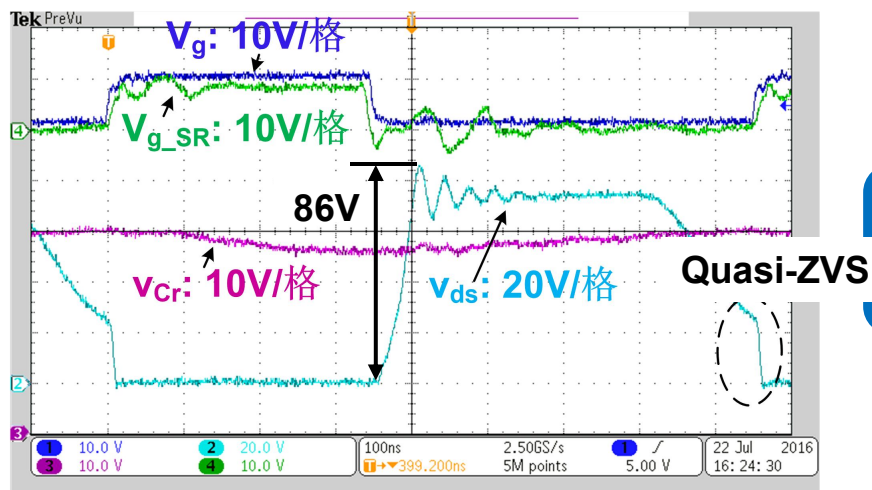
➤ @1.18MHz D=0.4



24V Vin, Null load



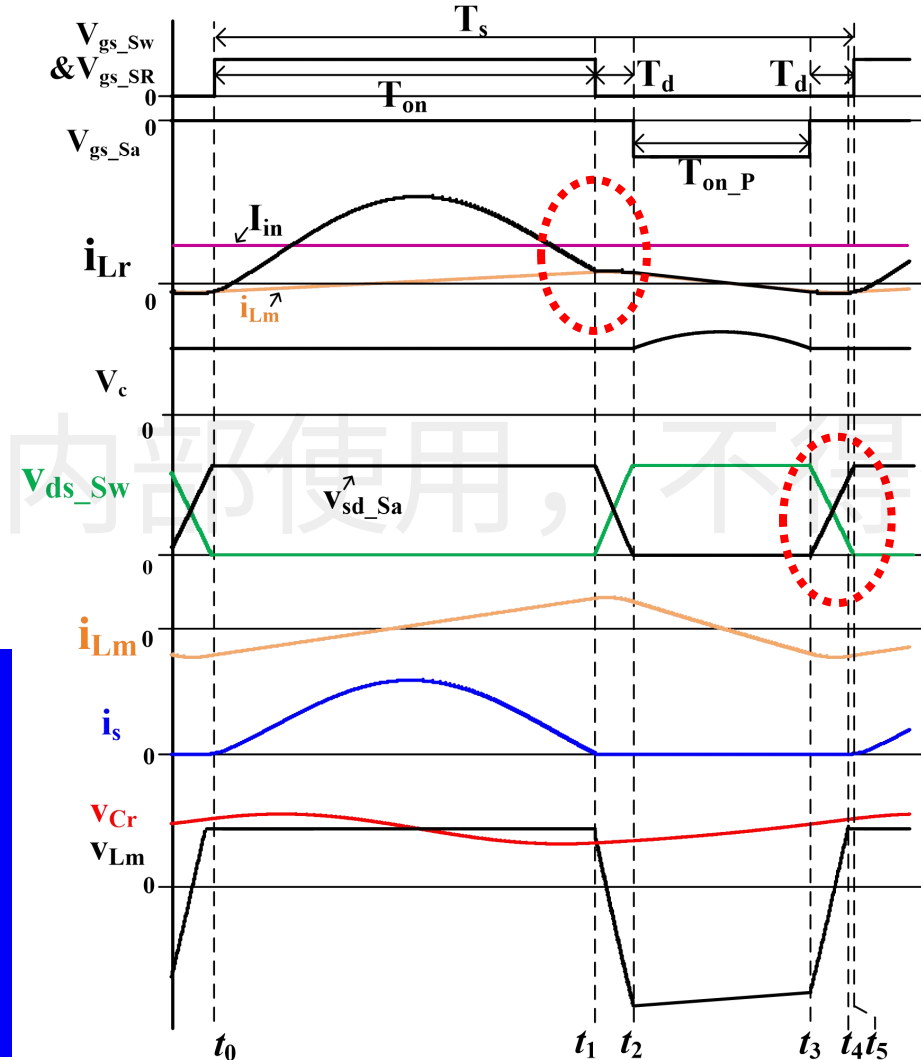
24V Vin, full load, $I_o=5.5A$



36V Vin, $I_o=5.5A$

ZVZCS in full voltage and load ranges

□ Stress: $2.4 \cdot V_{in}$



- ❑ Leakage energy recycling
- ❑ Low side driving
- ❑ Simple transformer structure
- ❑ Large duty cycle ($D > 0.5$)

ON-OFF Relationship (ZVS on)

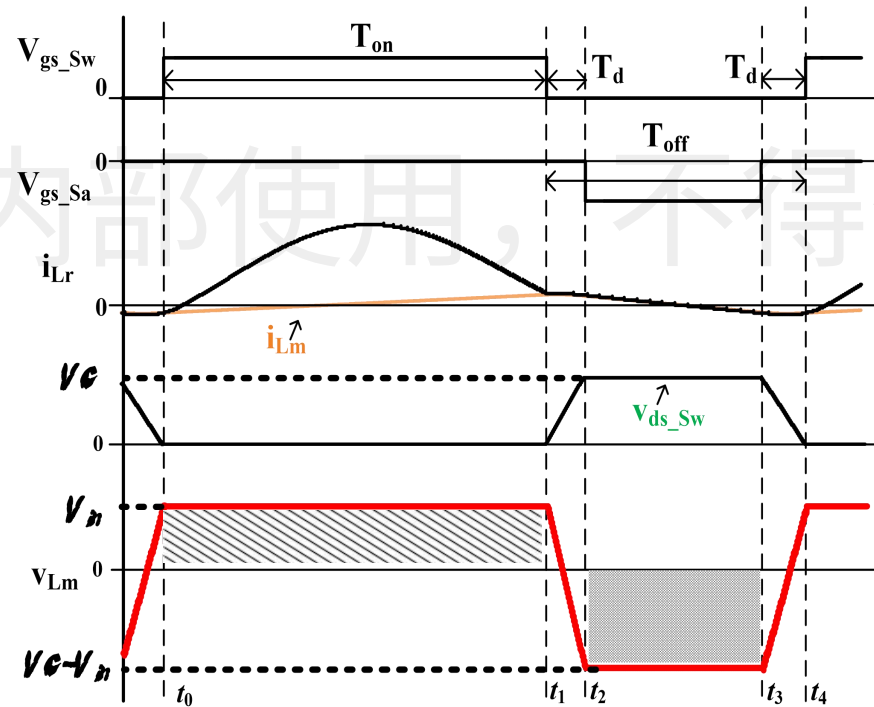
Lm volt-second balance @Vin_max & estimated large D

$$\frac{V_c}{V_{in}} = \frac{T_{on}}{T_{off} - 2T_d} + 1 \approx 1 / (1 - D)$$

Given:
 T_d, V_{c_max}



$$T_{off} = \frac{V_{in_max} \cdot T_{on}}{V_{c_max} - V_{in_max}} + 2T_d$$



*Neglect voltage ripple of Vc

Frequency (f_s) & Duty Cycle (D)

ZCS condition

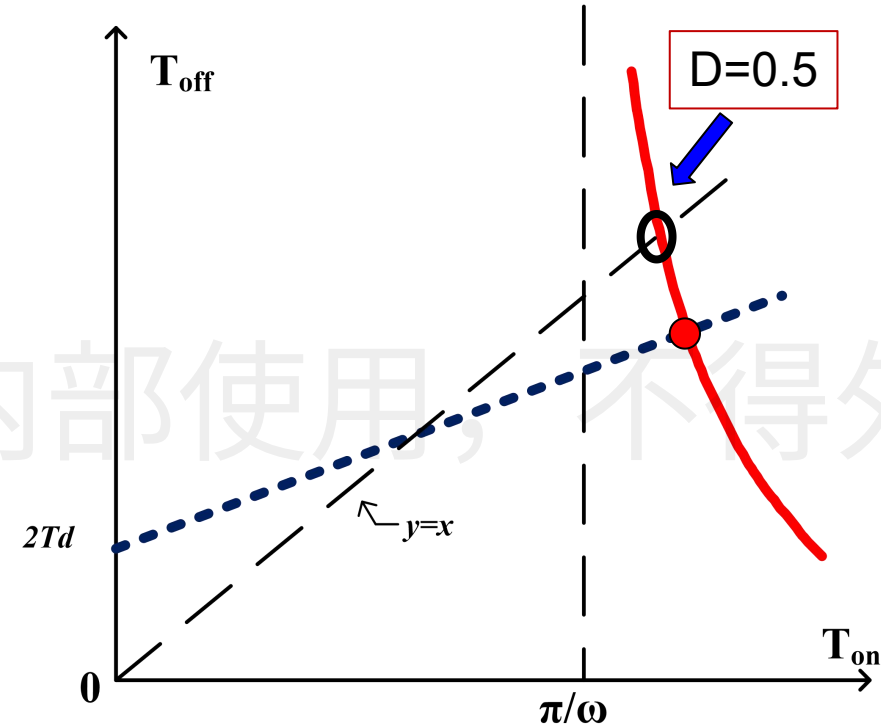
$$T_{off} = -\frac{\sin \omega T_{on}}{\omega} - \frac{(\cos \omega T_{on} - 1)^2}{\omega \sin \omega T_{on}}$$

ZVS condition

$$T_{off} = \frac{V_{in_max} \cdot T_{on}}{V_{c_max} - V_{in_max}} + 2T_d$$

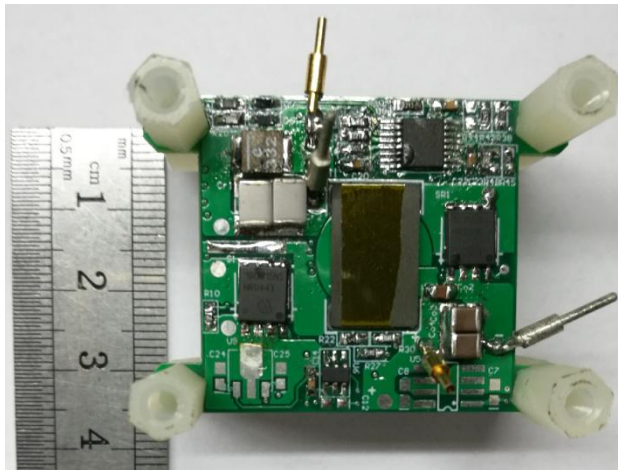
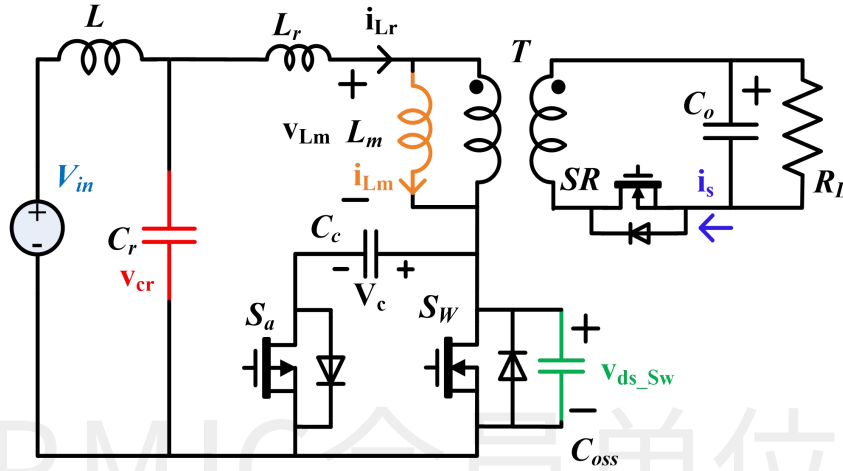
$$D = T_{on} / (T_{on} + T_{off})$$

$$f_s = 1 / (T_{on} + T_{off})$$



□ ZVS is Load independent

Key parameters of ACF Prototype



Prototype parameters

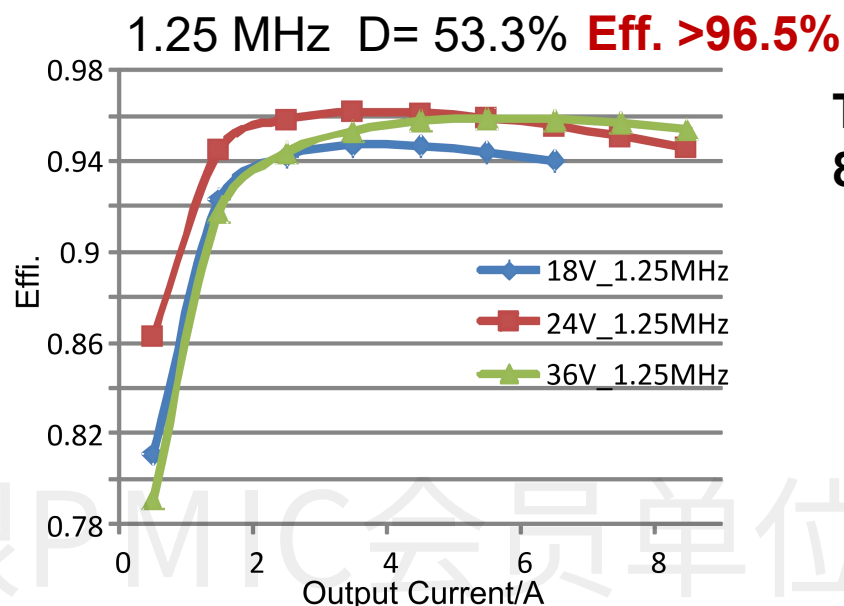
N-channel MOSFET	BSC190N15NS
P-channel MOSFET	FDMC86259P 150V-137m-20nC
Secondary SR	BSC052N08NS
Transformer	EC14.5C/ Turns ratio: 2:1
Resonant Capacitor	141nF

f_s : 1.25MHz

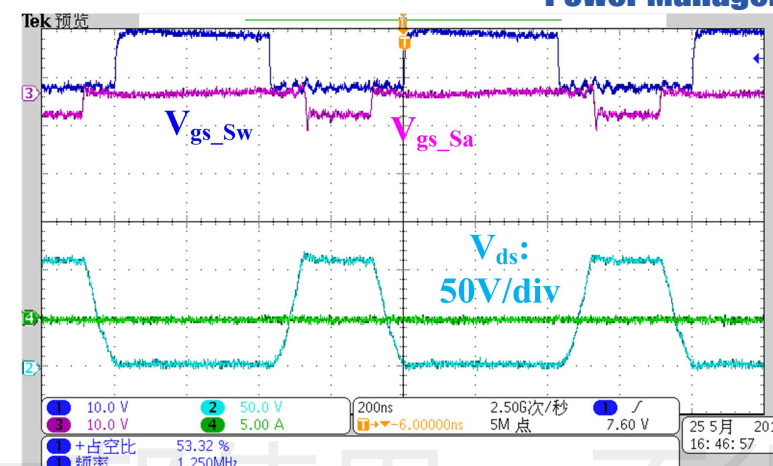
D : 53.3%

Efficiency: >96.5%

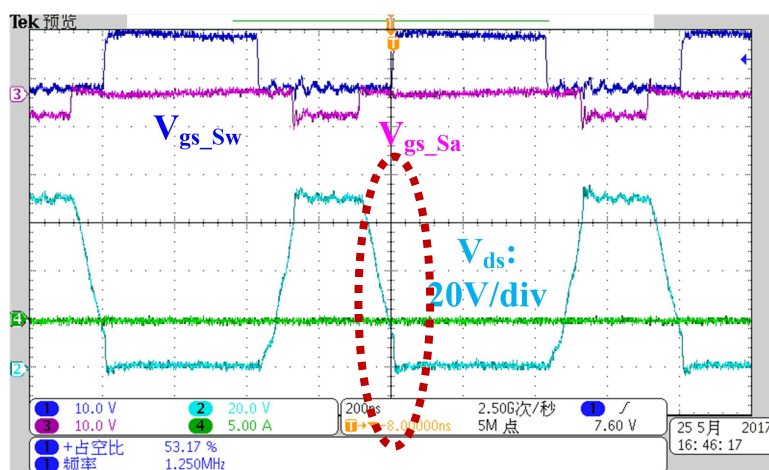
Measured waveforms at Fixed *Ton*, *Toff* and *Td*



Td
86ns

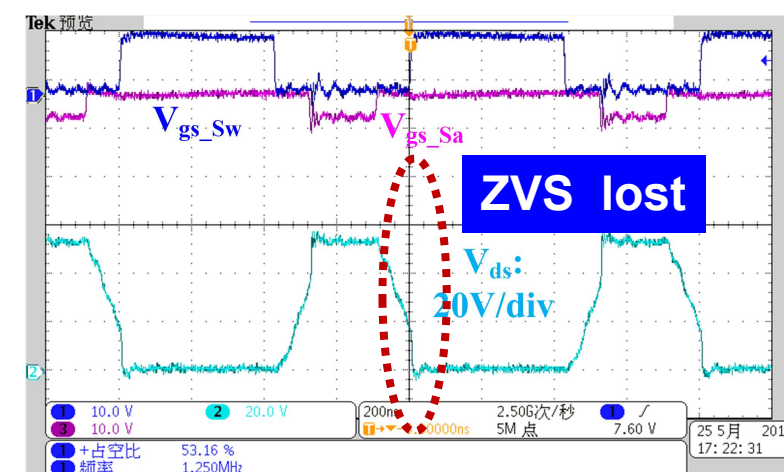


36V In, $I_o=5.5A$



24V In, $I_o=5.5A$

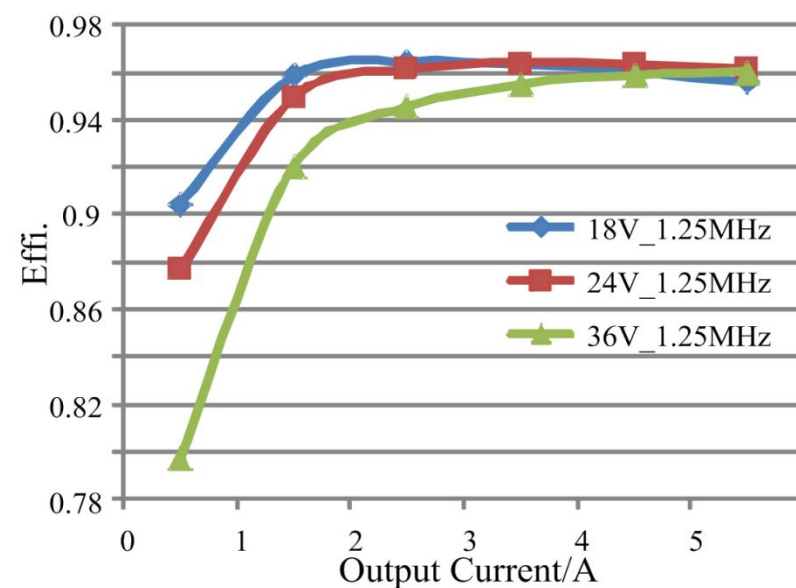
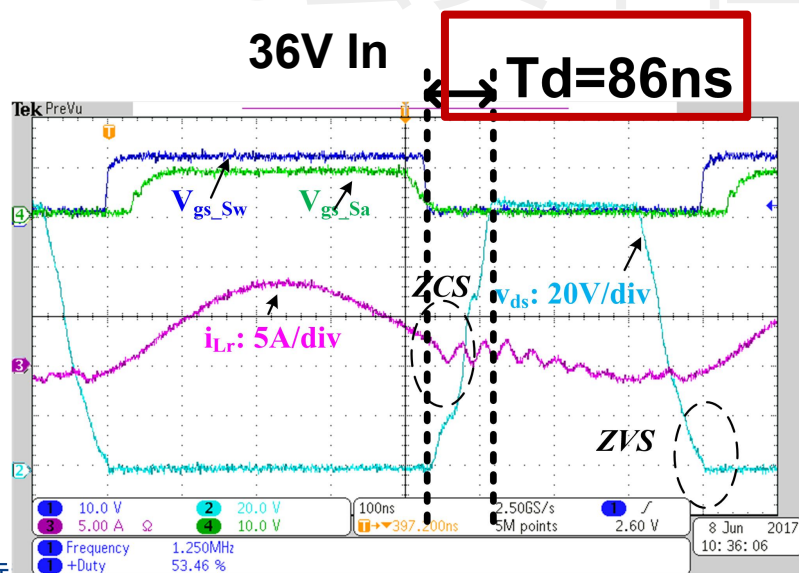
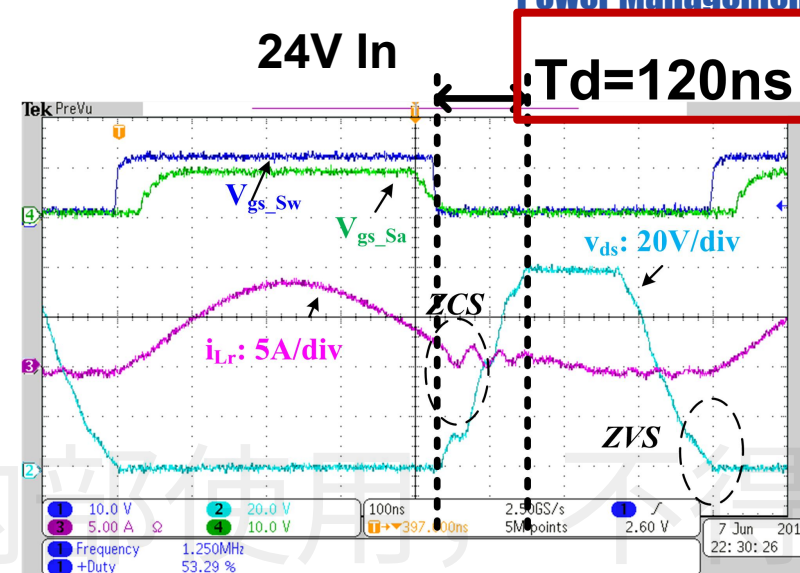
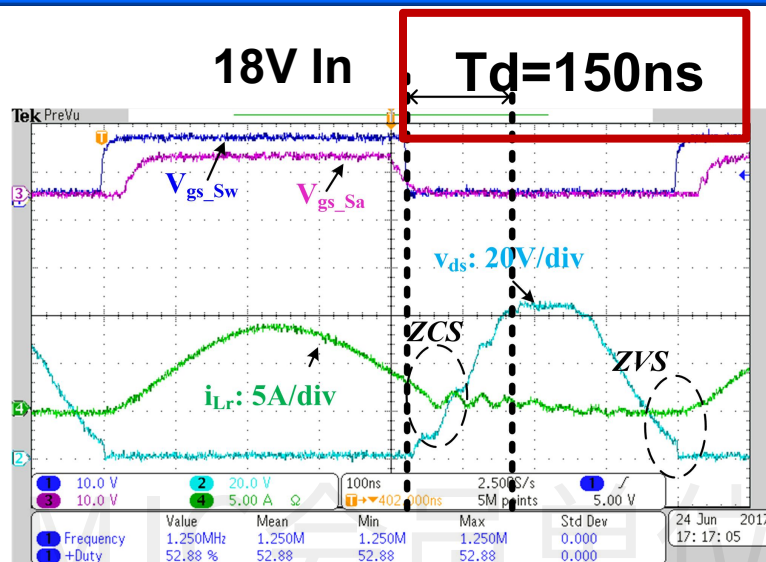
Td
86ns



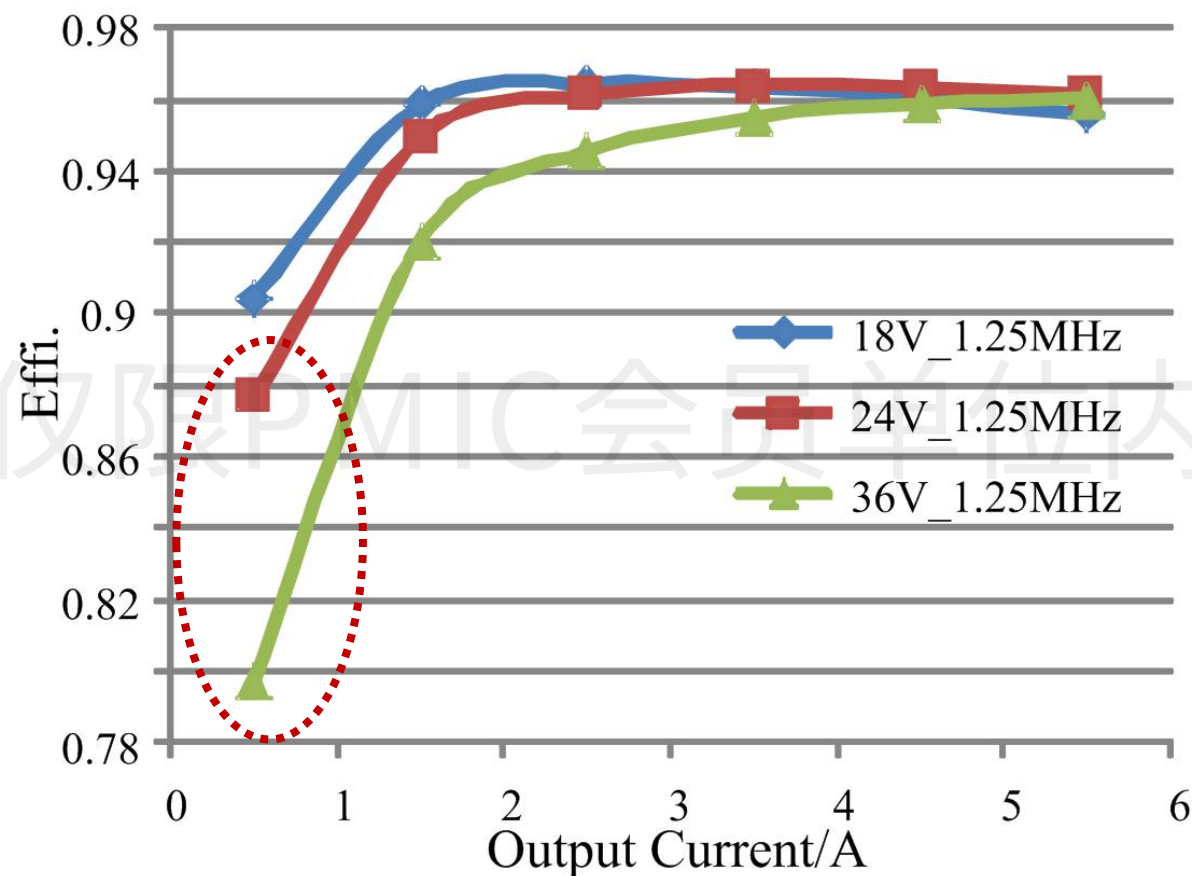
18V In, $I_o=5.5A$



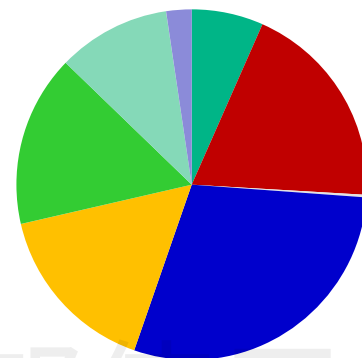
Adaptive dead time (T_d) control



Light load efficiency deteriorate with Fixed Ton

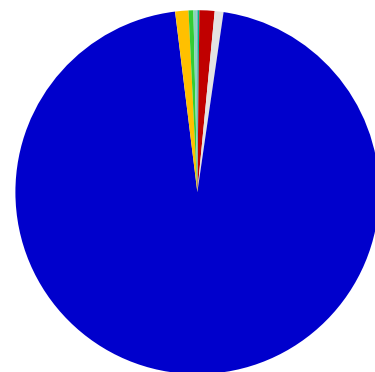


Full Load--5.5A



@24V Input

Light Load--0.5A



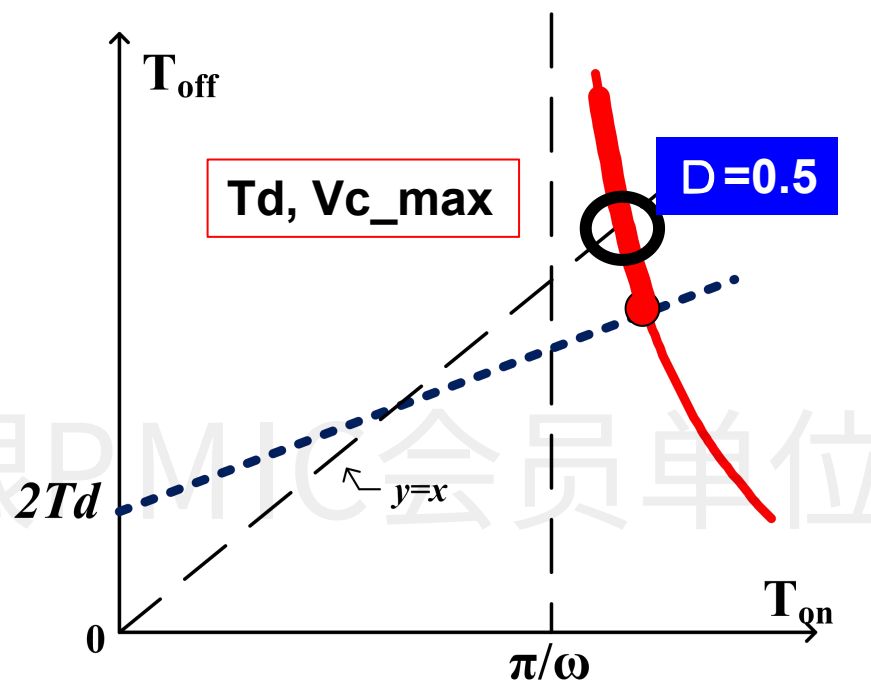
Legend for Full Load and Light Load charts:

- L
- con_N
- con_P
- core
- winding_pri
- winding_sec
- con_sec
- Co

Legend for Full Load and Light Load charts:

- L
- con_N
- con_P
- core**
- winding_pri
- winding_sec
- con_sec
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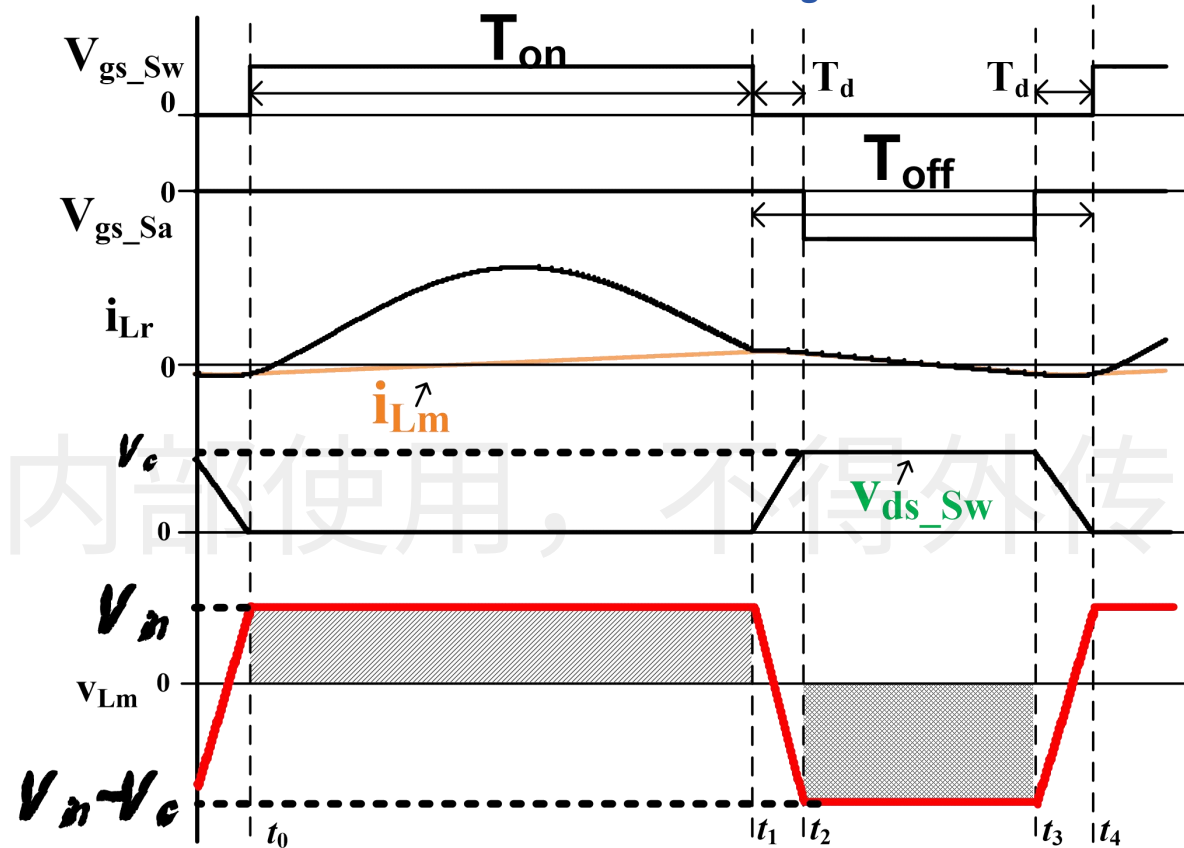
The rated operating point of ACF-DCX



Larger D , less conduction loss

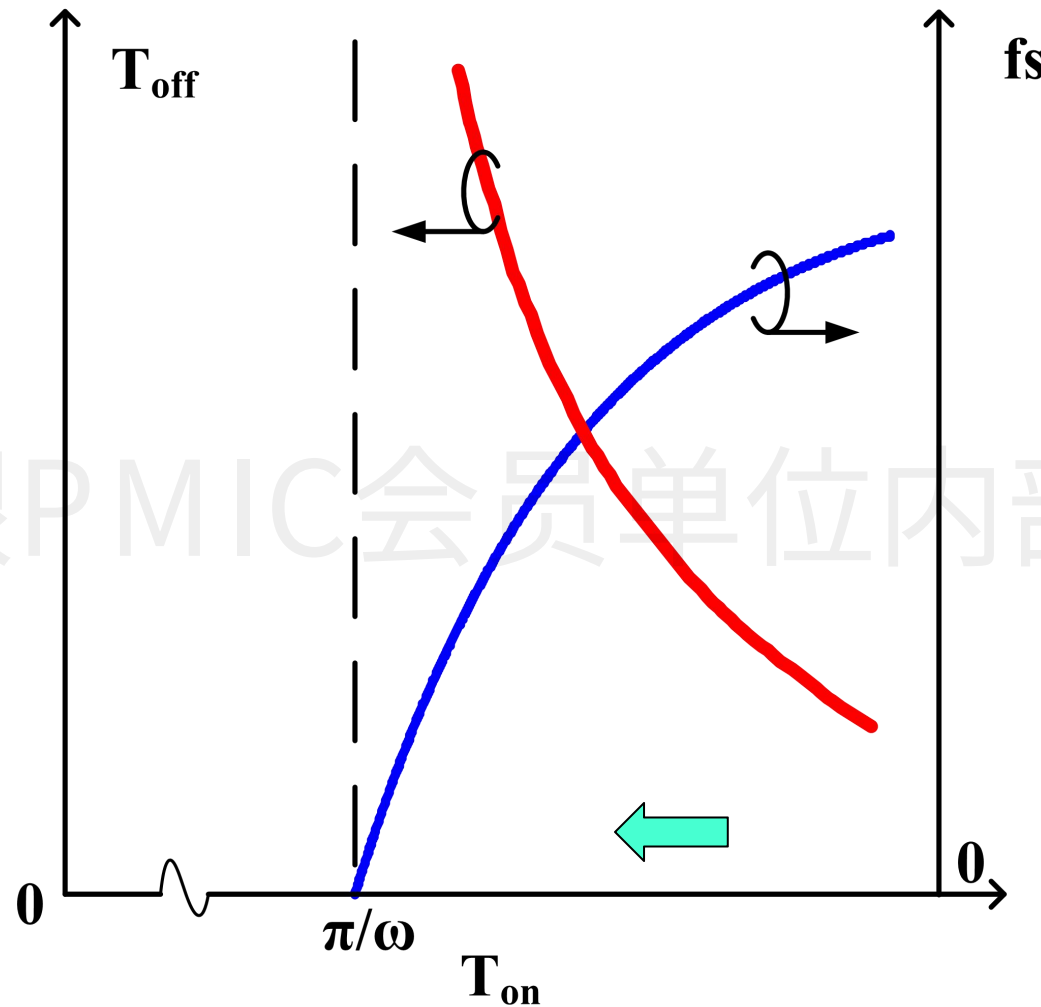
L_m , volt-second balance

$$\frac{V_c}{V_{in}} = \frac{T_{on}}{T_{off} + 2T_d} + 1 \approx 1 / (1 - D)$$

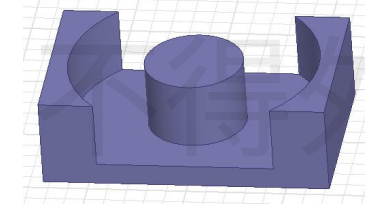


Relationship Between Duty Cycle (D) & Frequency(f_s)

Power Management Innovation Consortium



$$\Delta B = \frac{V_{in} \cdot T_{on}}{NAe}$$



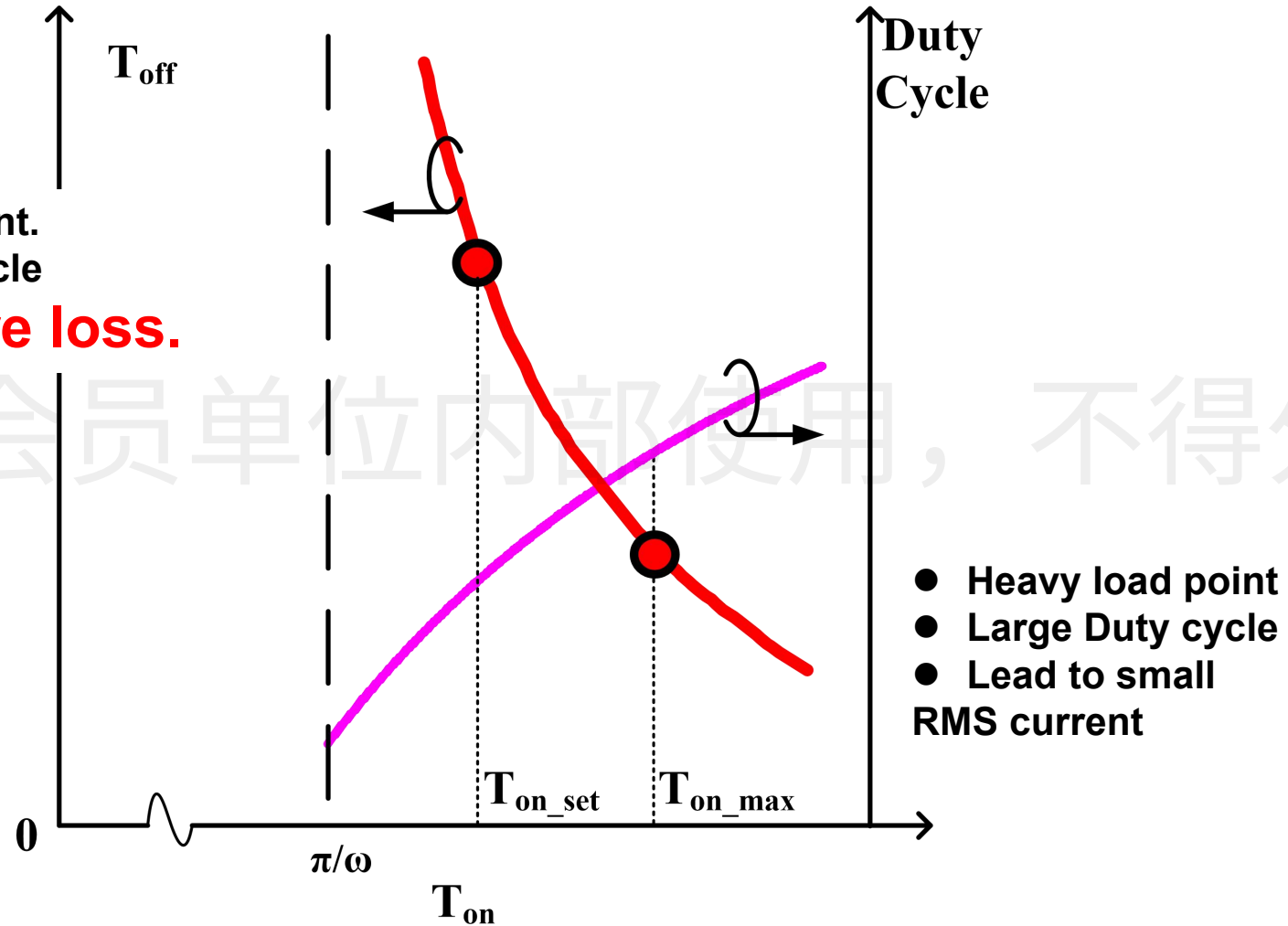
$$p_v = C \cdot \Delta B^\alpha f^\beta$$



- Core loss decreases.

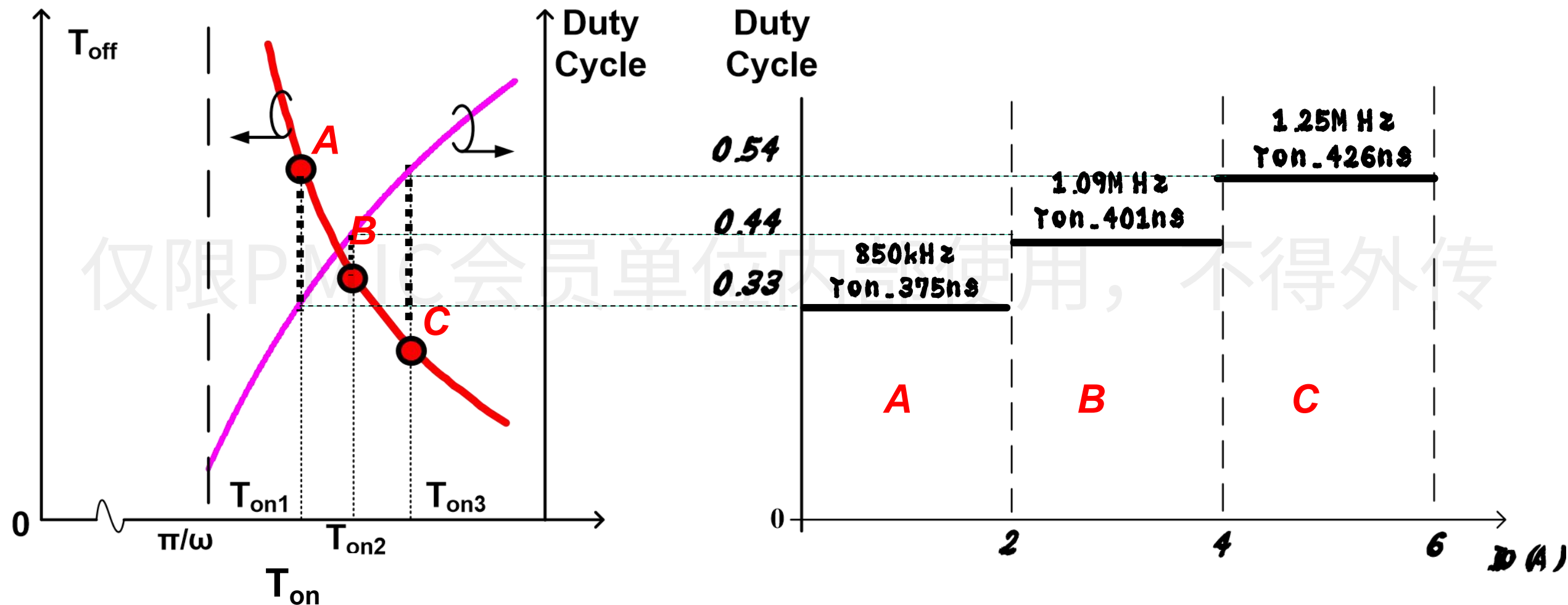


- Light load point.
- Small duty cycle
- **Small core loss.**

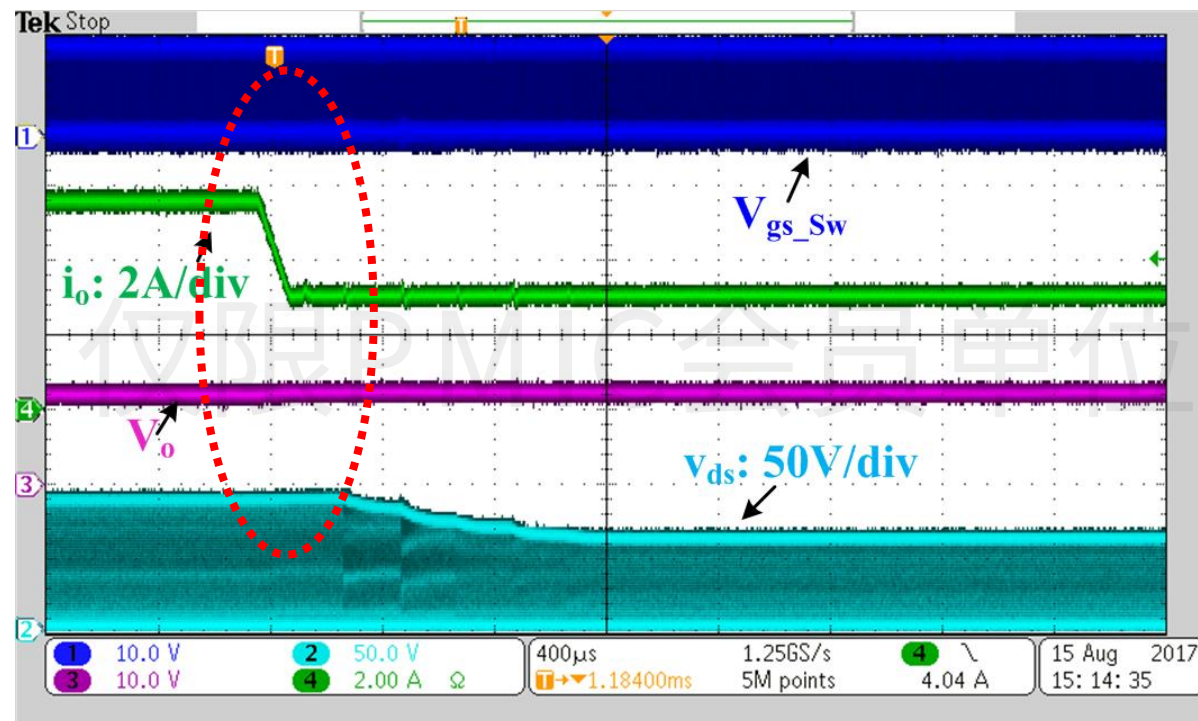


- **Load adaptive Ton control.**

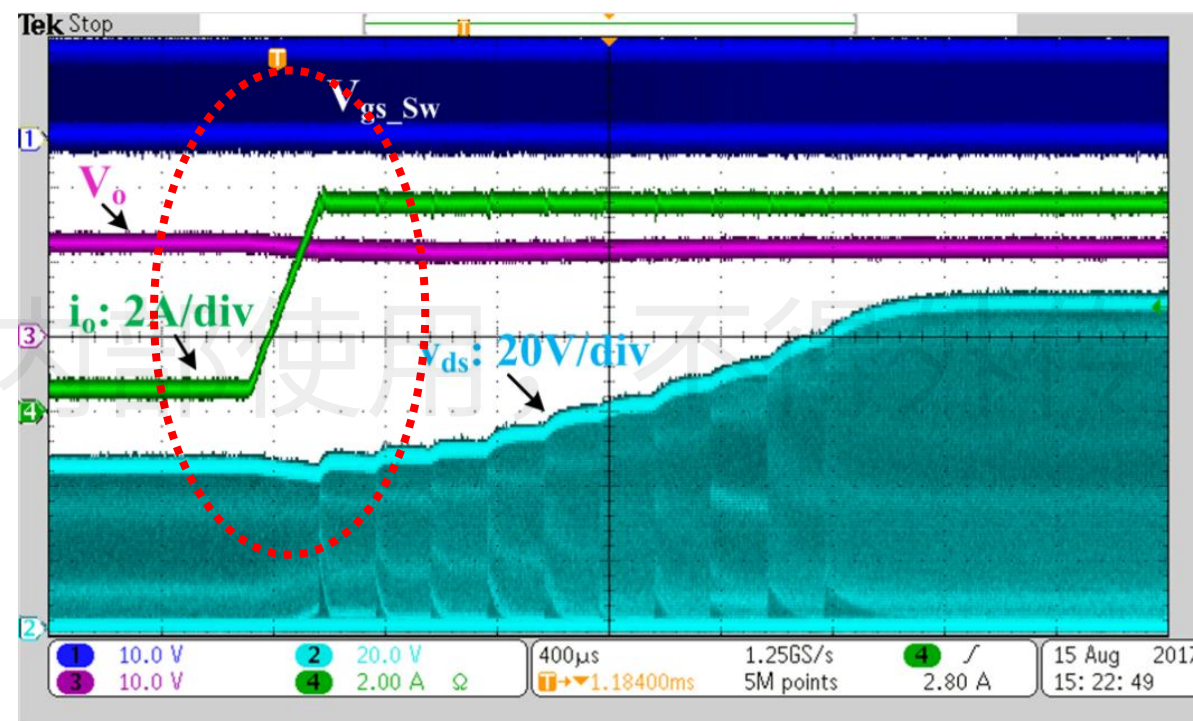
Adaptive **Ton** Control Strategy



Load Transient Process

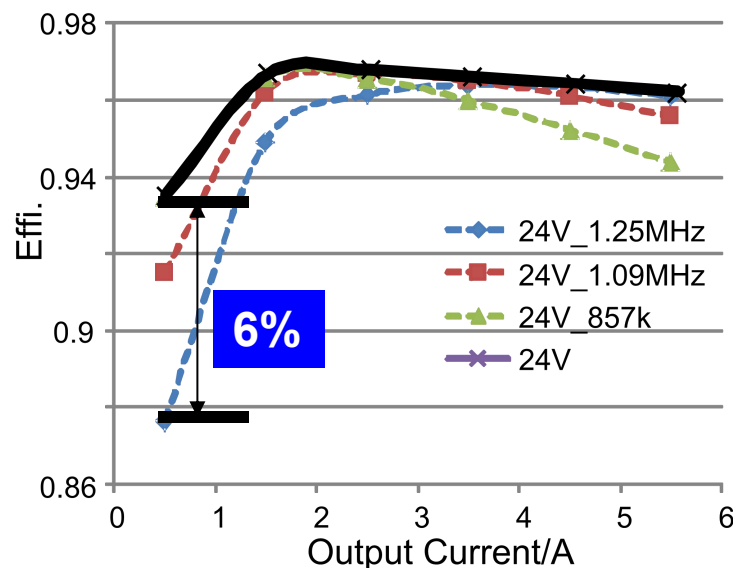
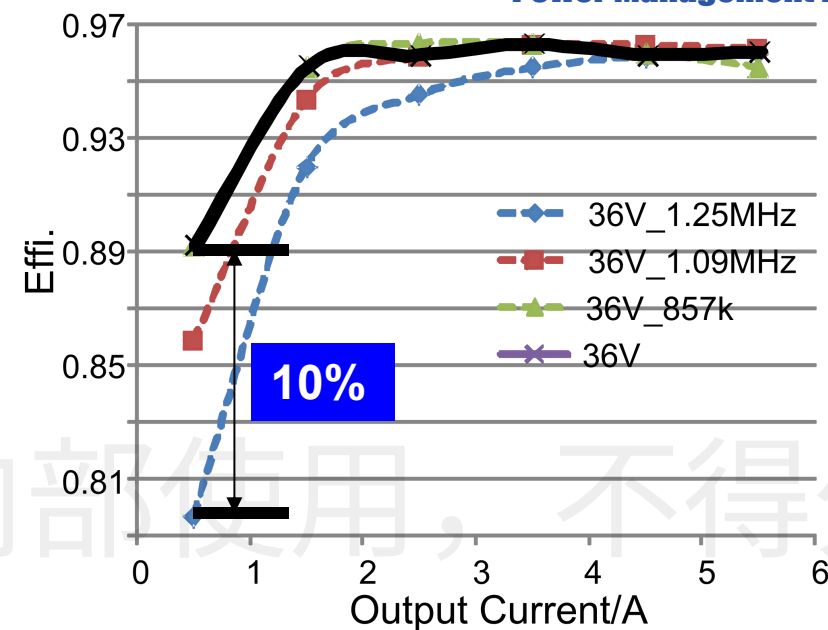
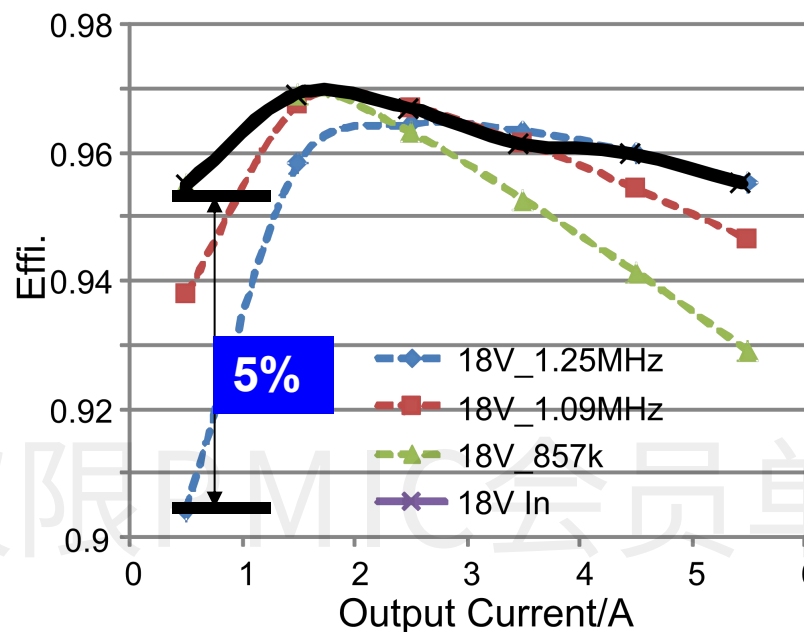


Load Step-down



Load Step-Up

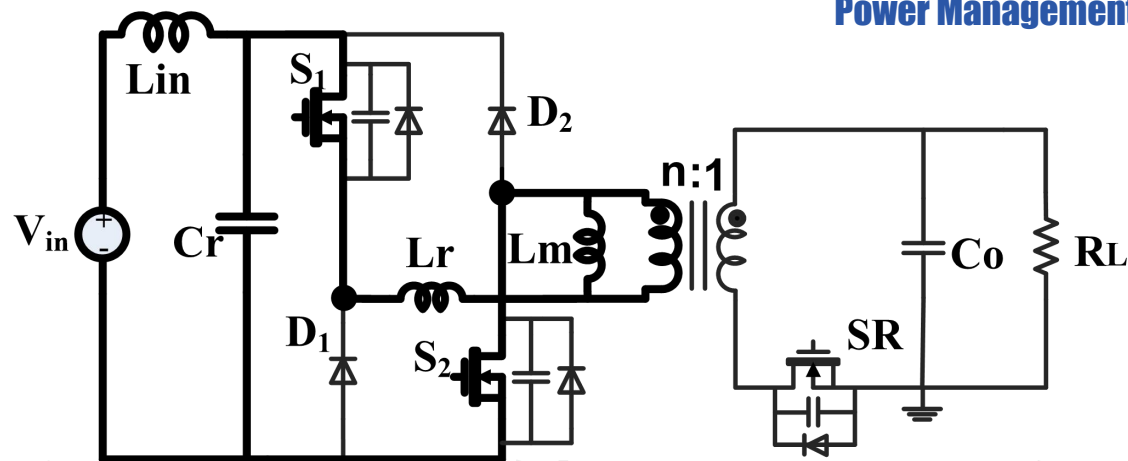
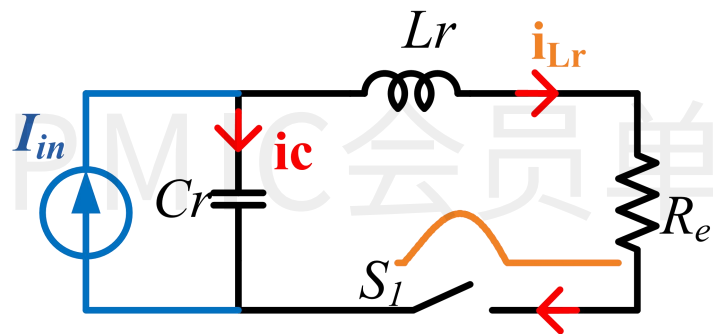
Efficiencies with Adaptive Ton Control



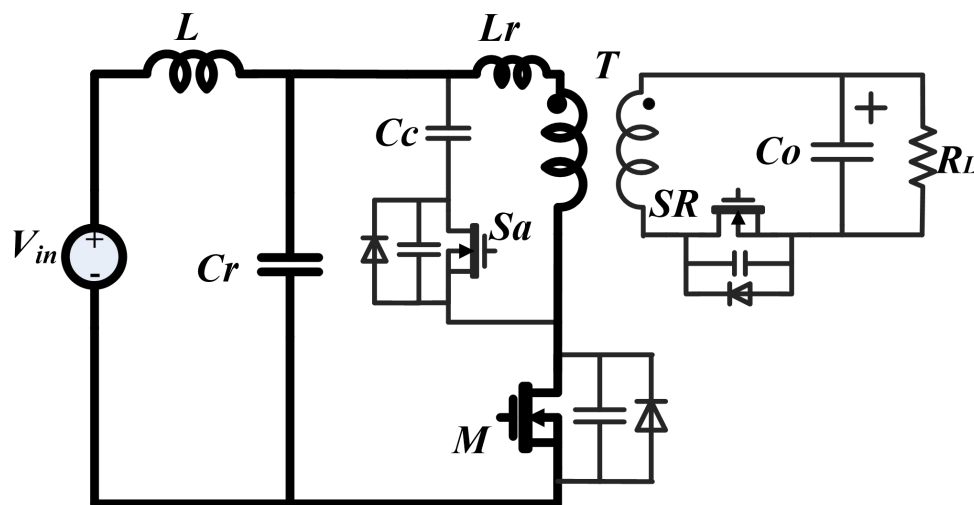
D~0.5

		
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Family of Forward DCX Topologies

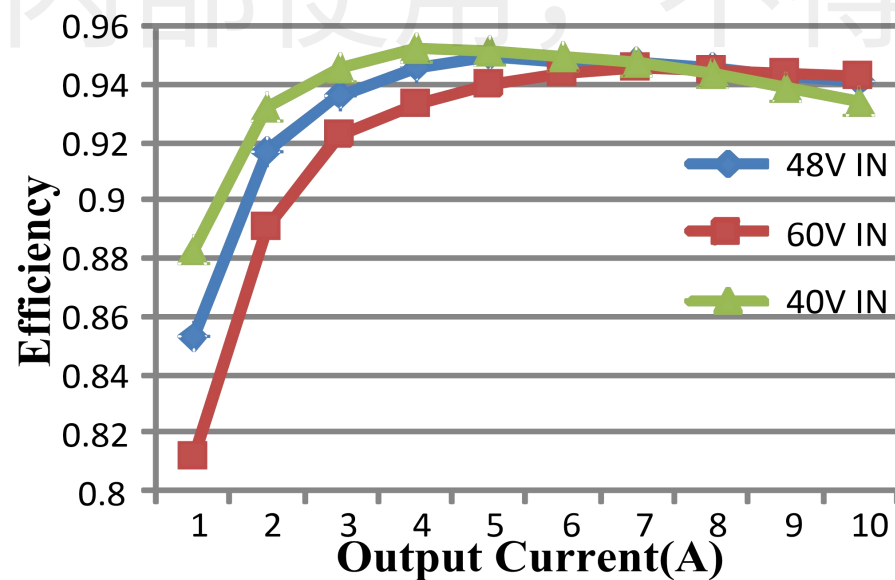
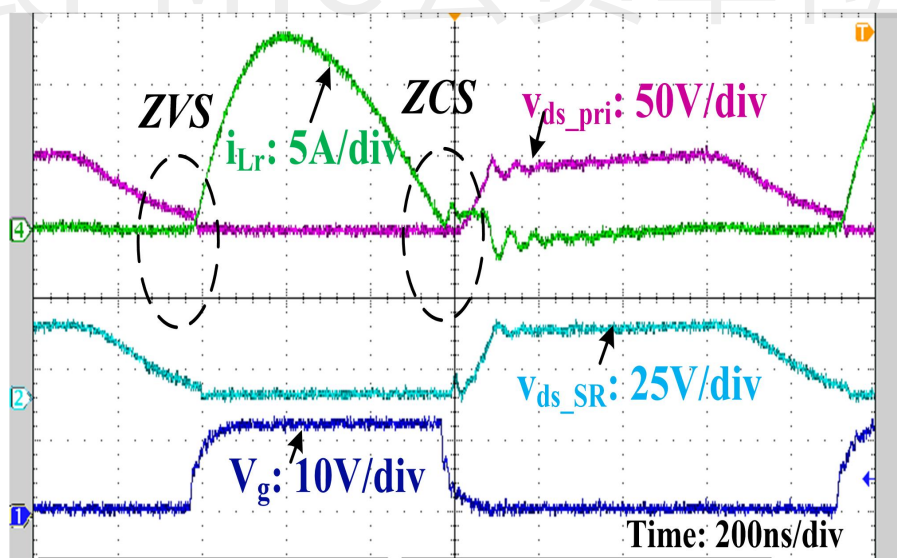
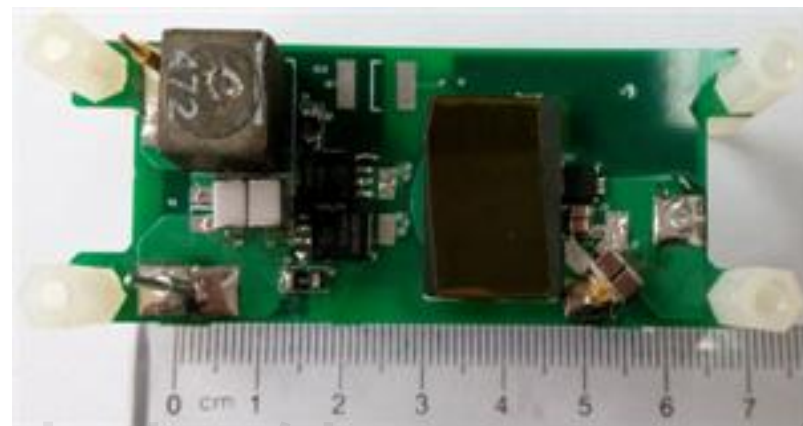
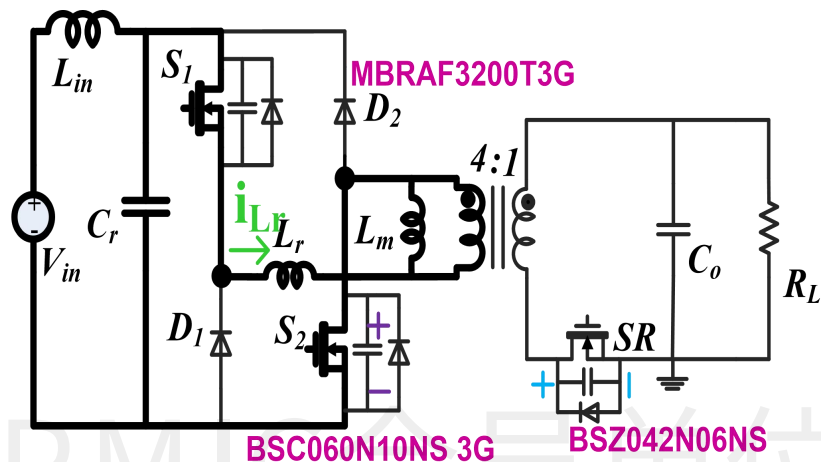


双管正激DCX



有源箝位正激DCX

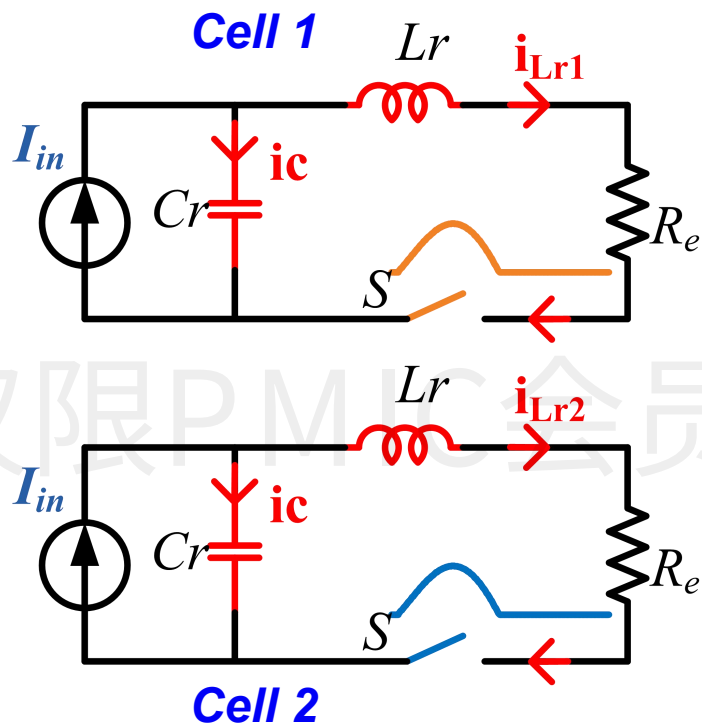
Verifications of Two-switch Forward DCX



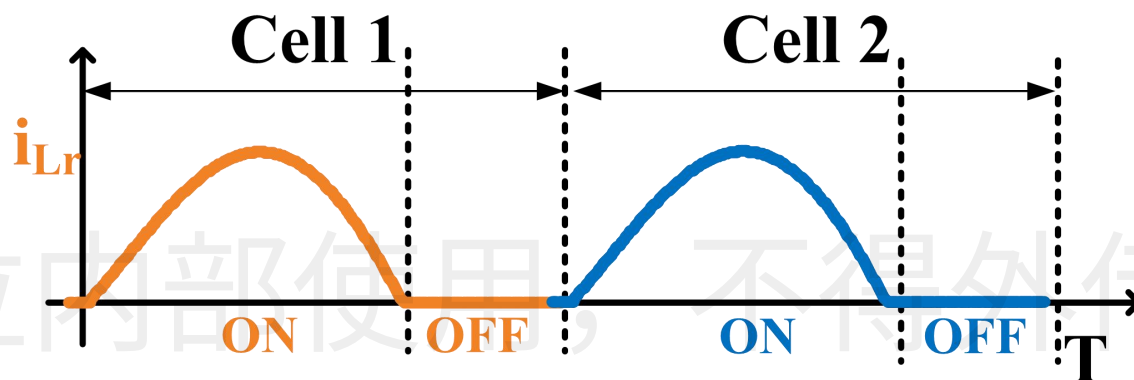
Extension-I of Unidirectional Resonant Tank with DC current Link

Power Management Innovation Consortium

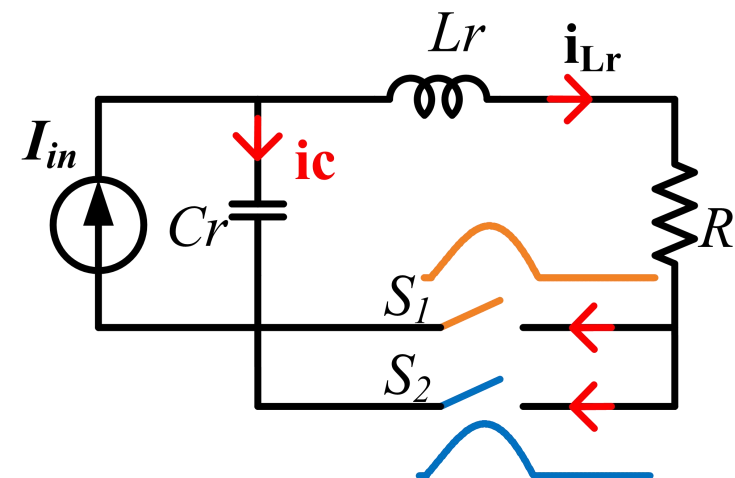
For higher power level



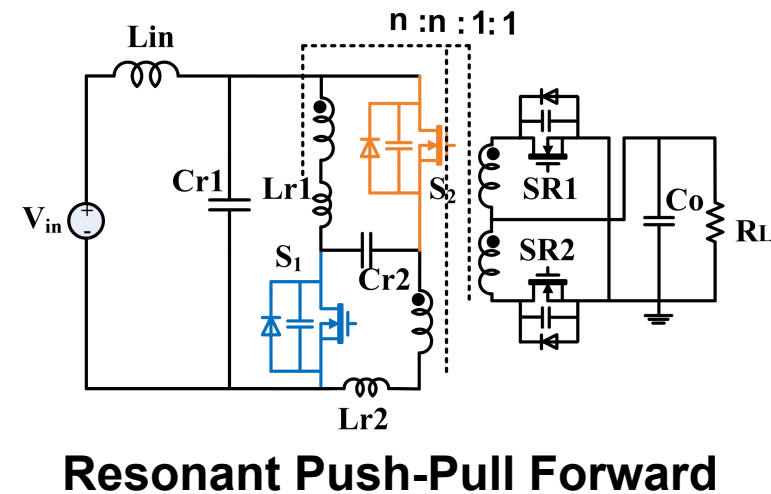
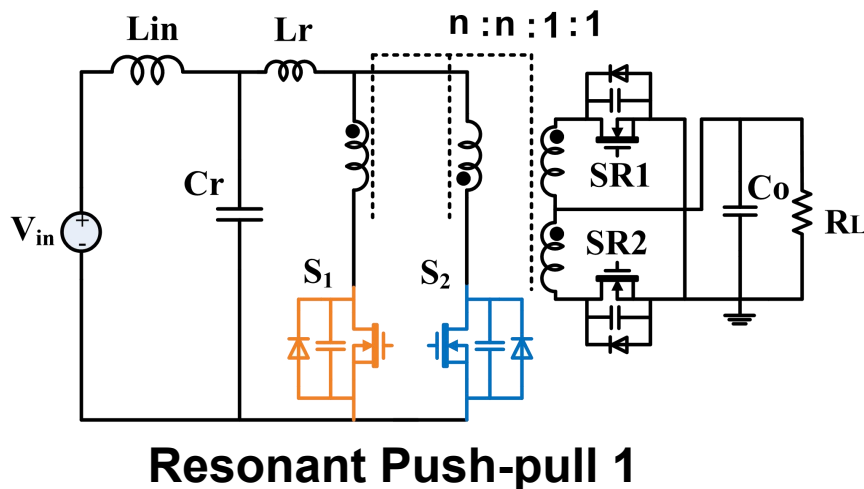
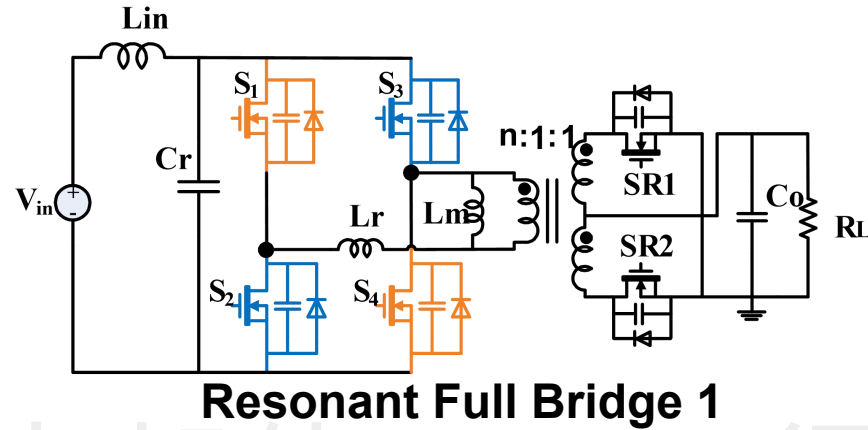
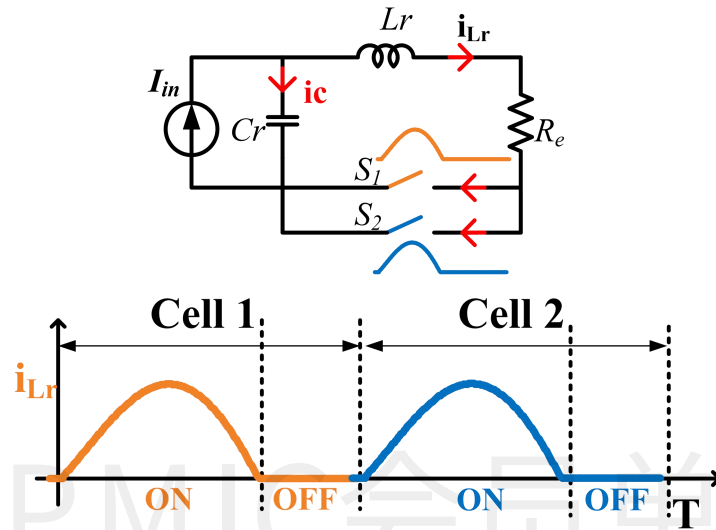
Integration I

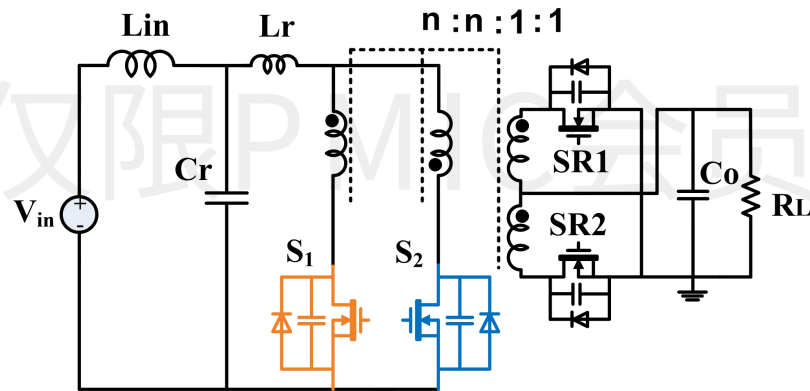


Common Resonant
Cap.

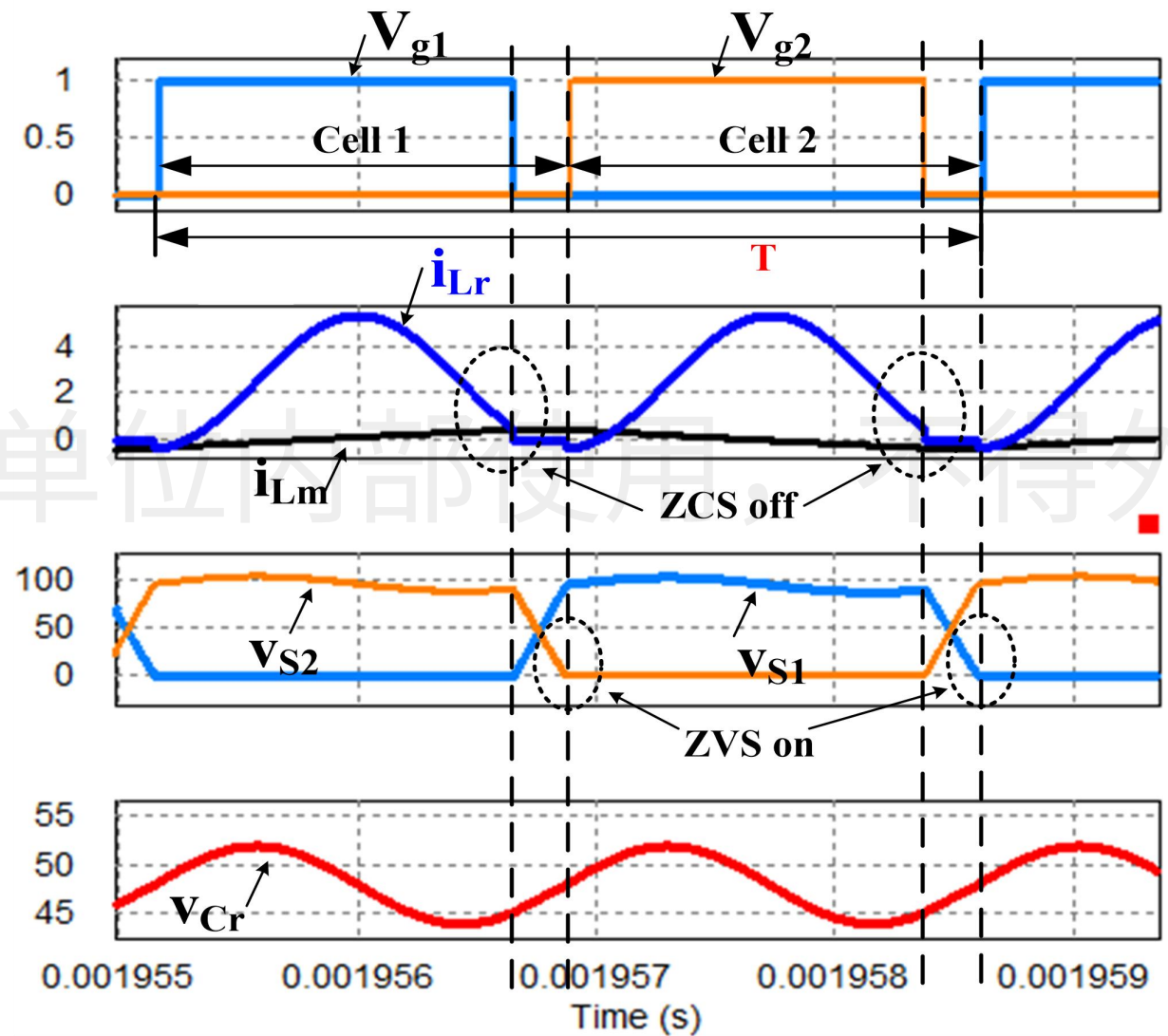


Topologies with Resonant Tank I

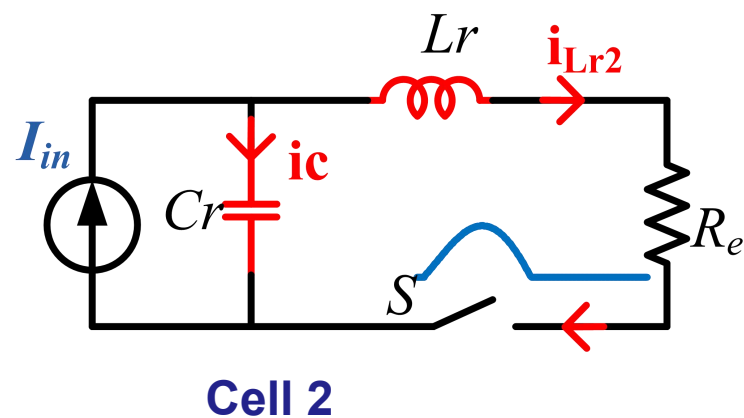
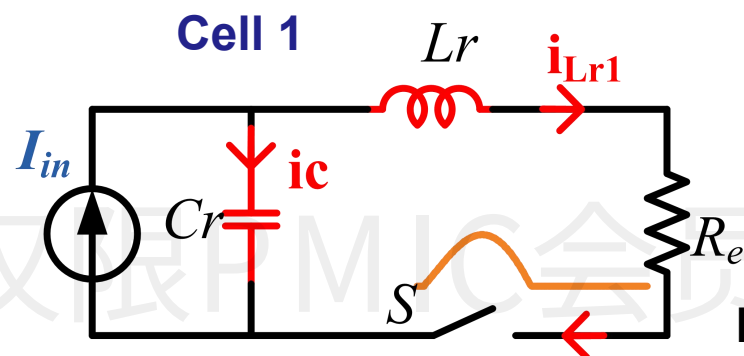




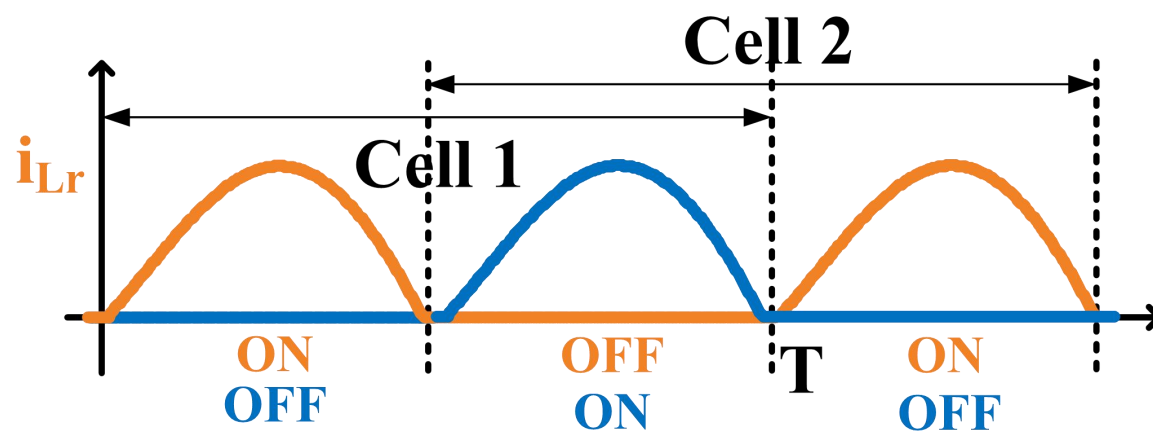
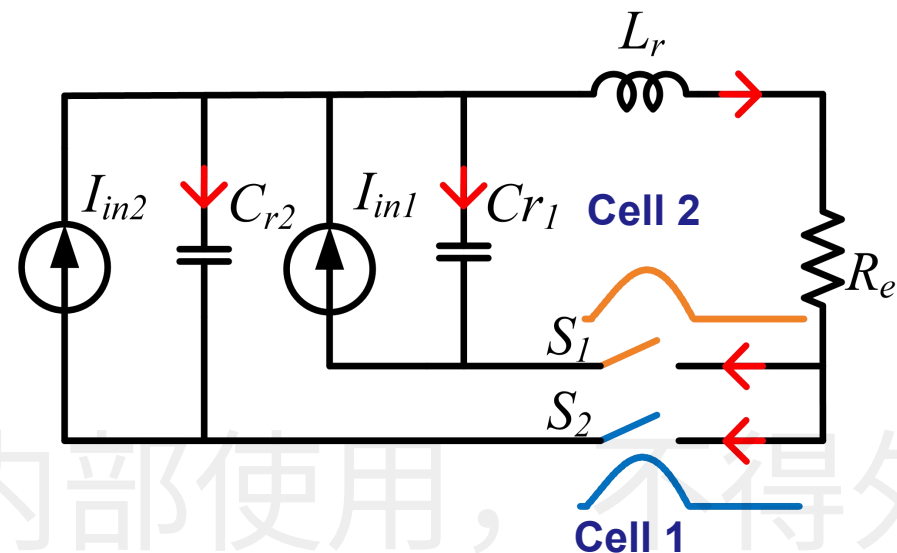
Push-pull DCX



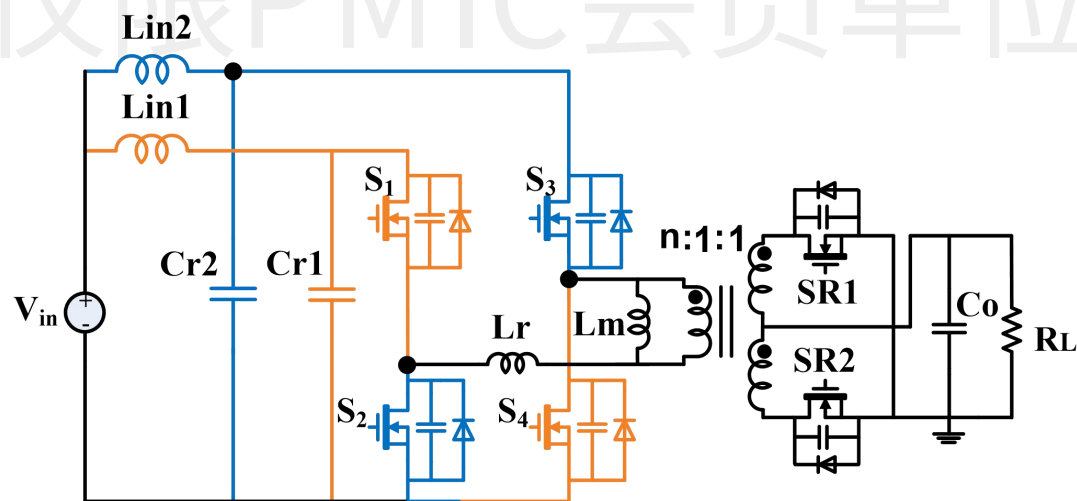
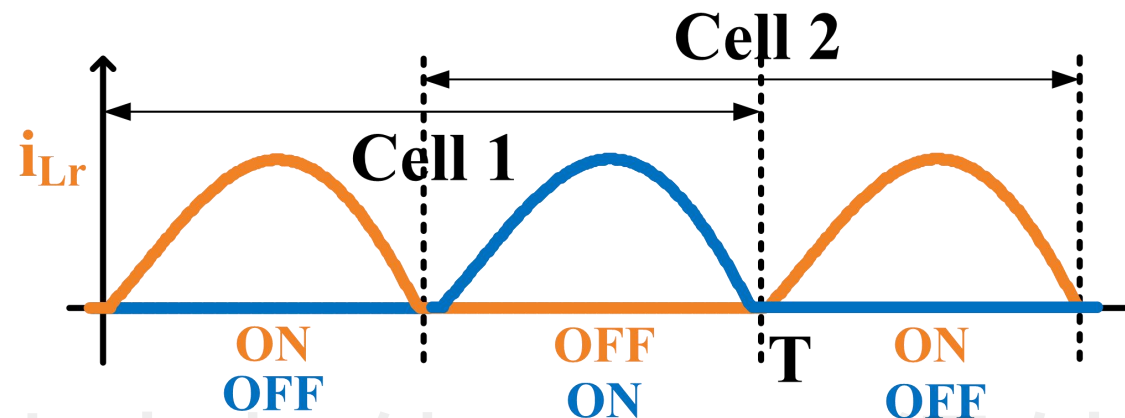
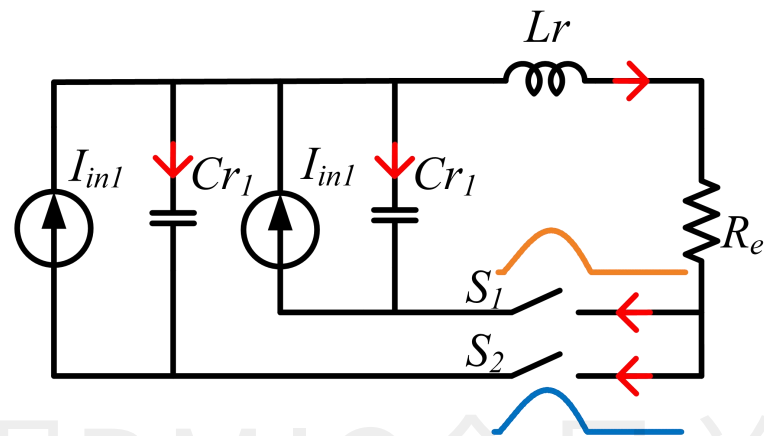
Integrating method--
independent resonant Cap.



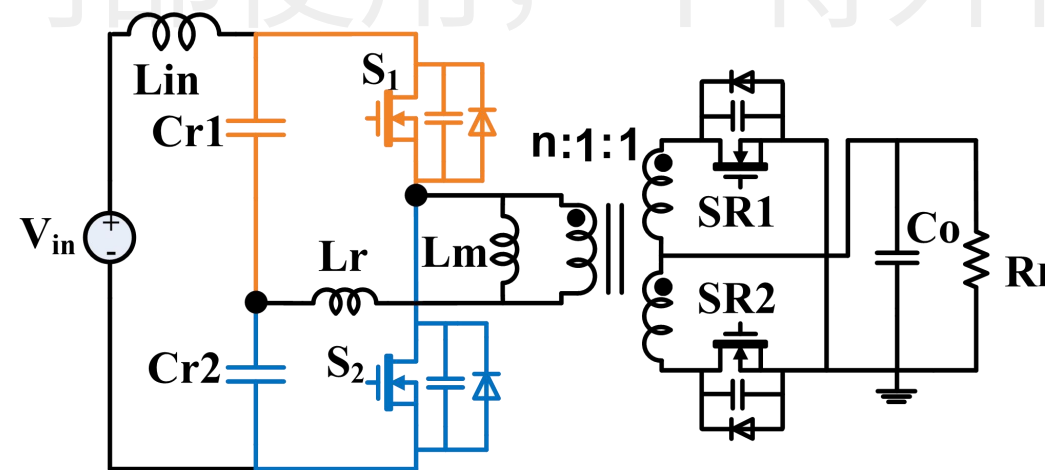
Integration II



Family Topologies of Resonant Tank II

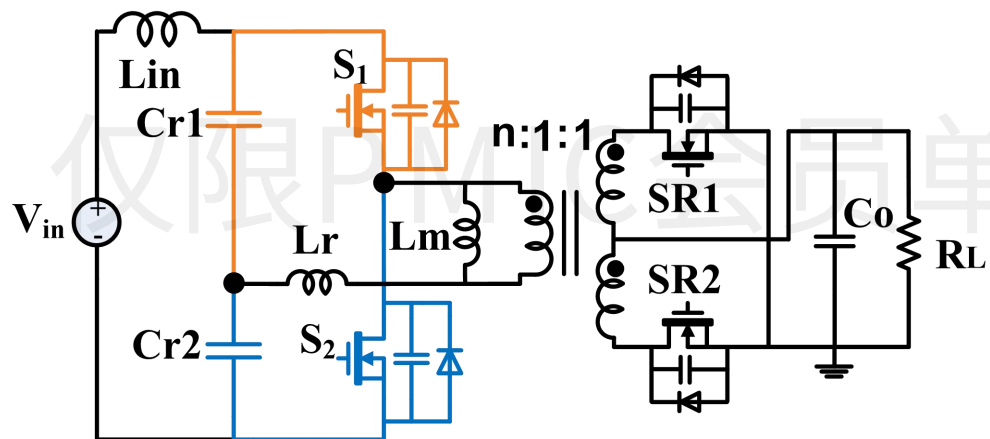


Resonant Full Bridge 2

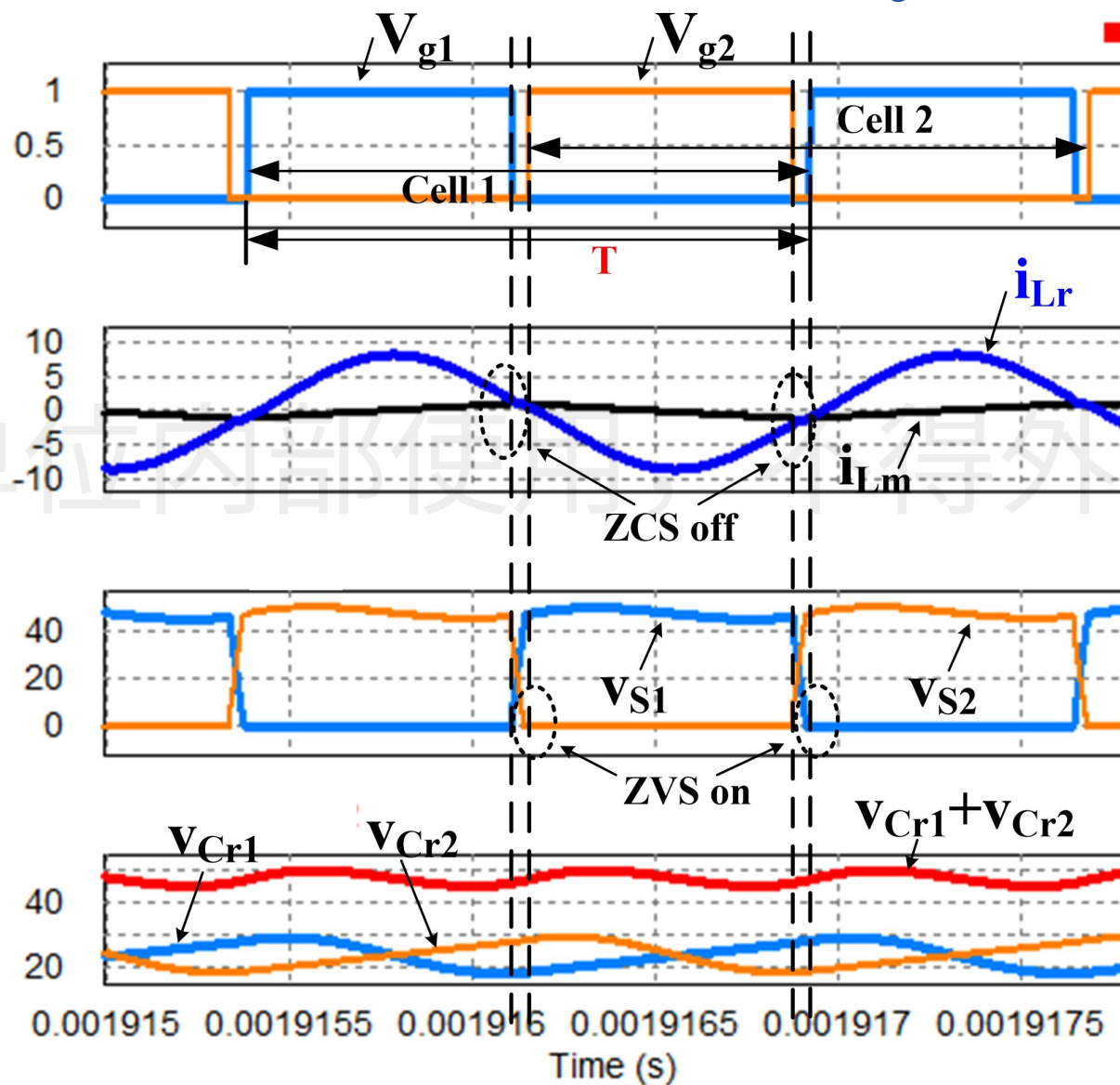


Resonant half-bridge

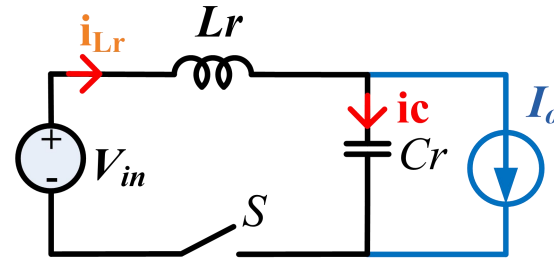
Verification with Simulation



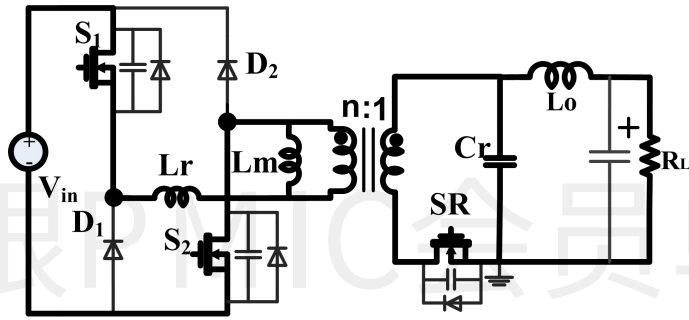
Half Bridge DCX



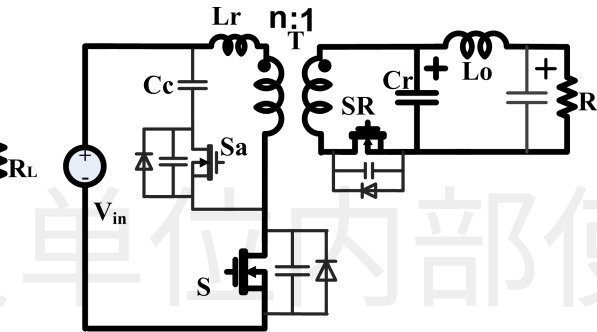
Topologies of Resonant DCX with output DC current source



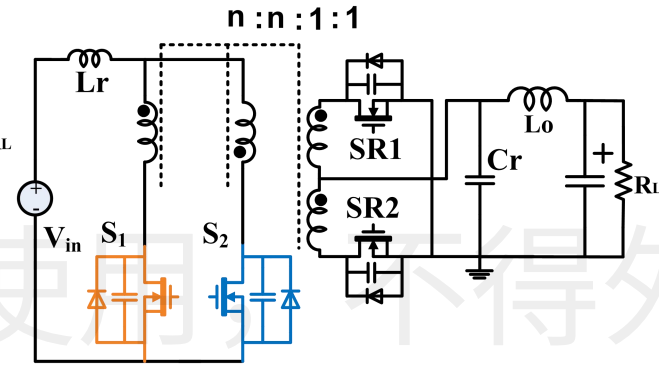
Resonant cell with output current feed



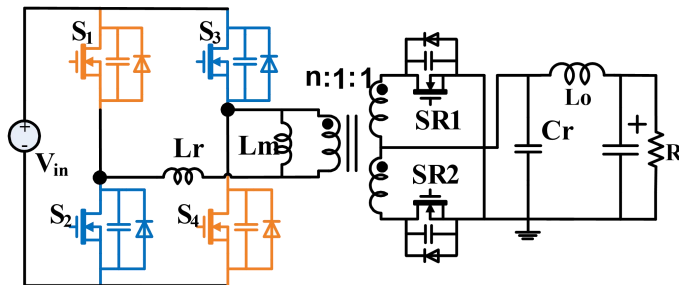
Two-switch forward



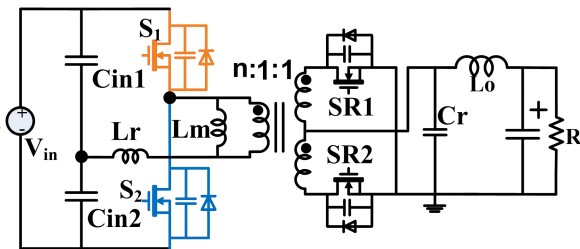
Active clamping forward



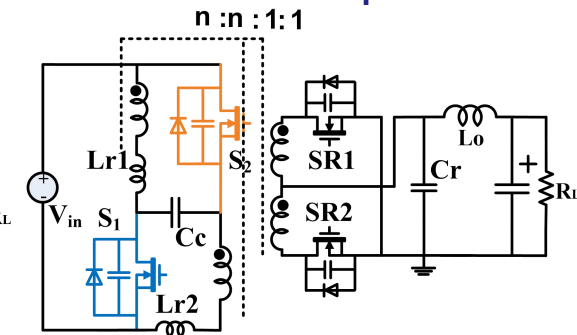
Push-pull



Full bridge



Half bridge



Push-pull forward

Y.C, Ren., et_al., "A family of high power density unregulated bus converters". Trans. on, Power Electron., 2005.pp. 1045-1054.

- The unidirectional resonant tank with DC current source has following features:
 - The single switch forward DCX achieves ZVSZCS for low power low voltage applications. MHz frequency is easily implemented with high efficiency.
 - The active clamping forward DCX can reduce the voltage stress and improve the light load efficiency with adaptive on time control at MHz frequency.
 - Based on the proposed unidirectional resonant tank and tank integrating method, more resonant topologies are derived for high power applications, which are also competitive with conventional LC resonant DCXs.



2.3 Tight regulated DC-DC converter for 48V in server



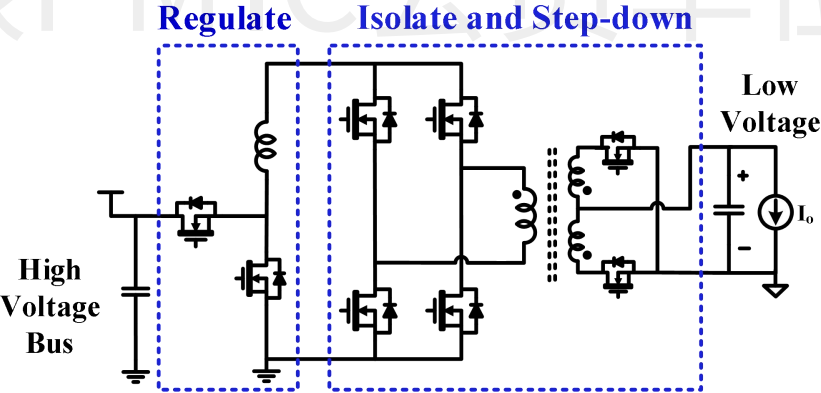
Two-stage Converter

48V/12V:



SynQor

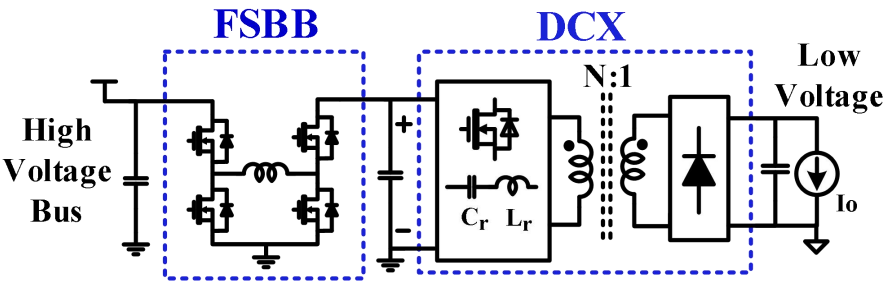
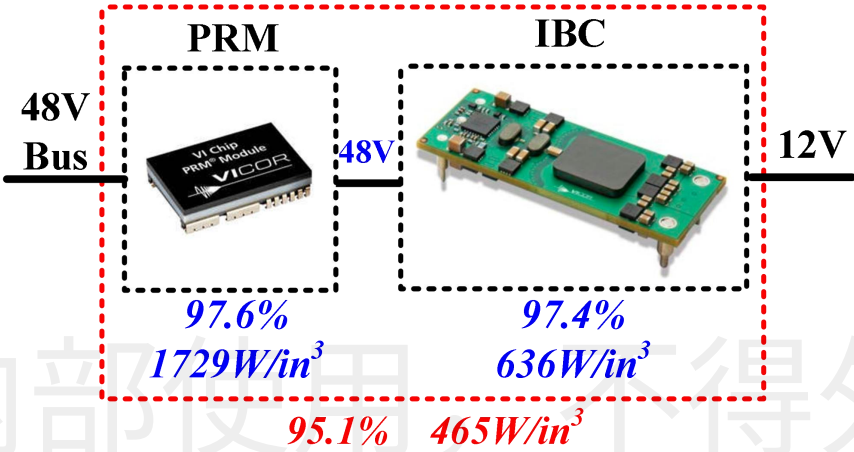
96% 242W/in³



PRM: PRM48by480x500A00
IBC: IB0xE120T40xx-xx
SynQor: PQ6012QZB33



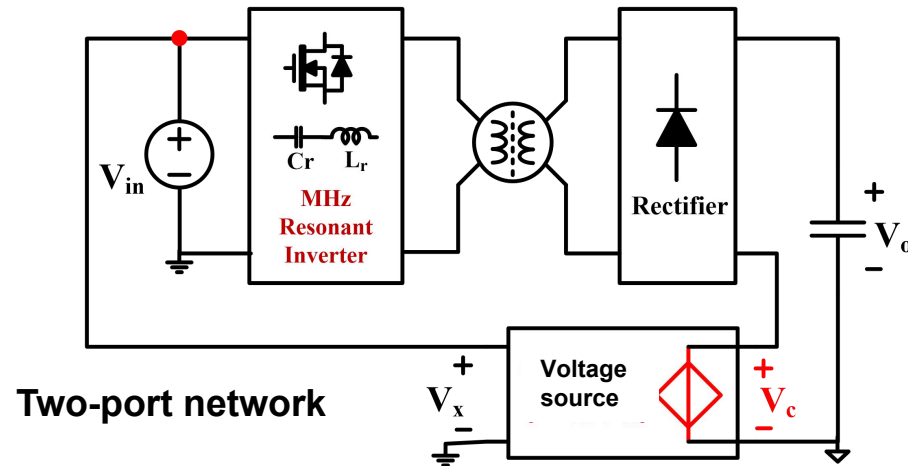
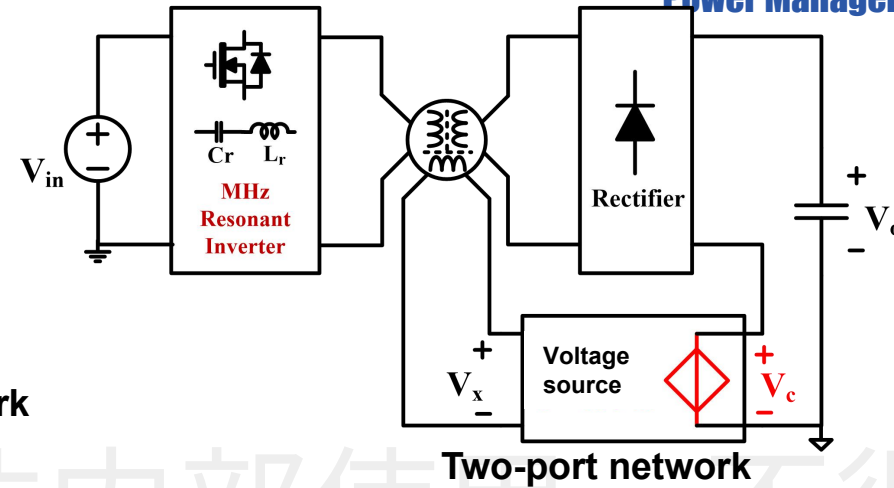
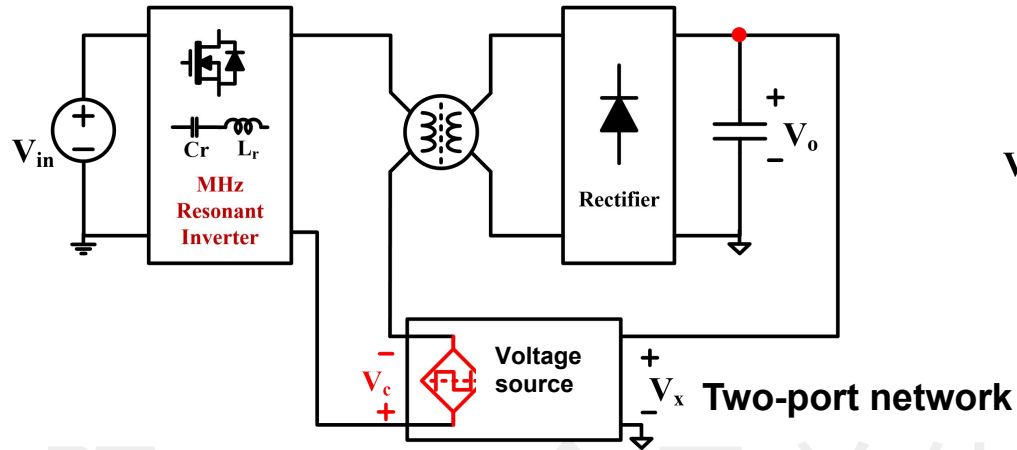
VICOR



- System efficiency sacrifice
- Power density decrease

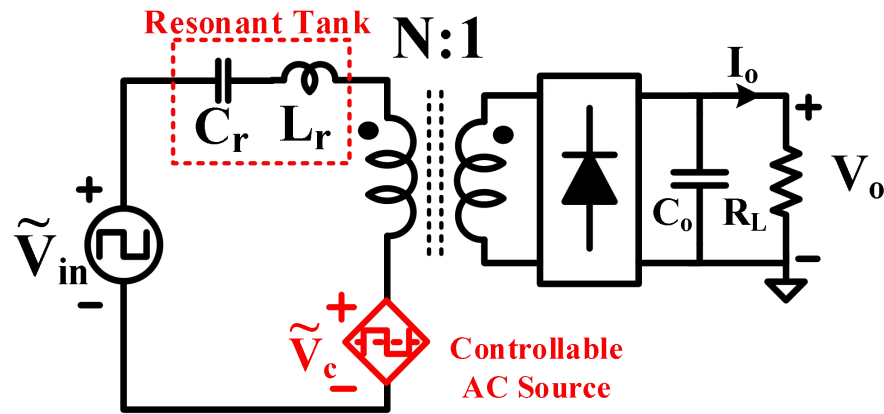


Tight Regulated DCX (RDCX)

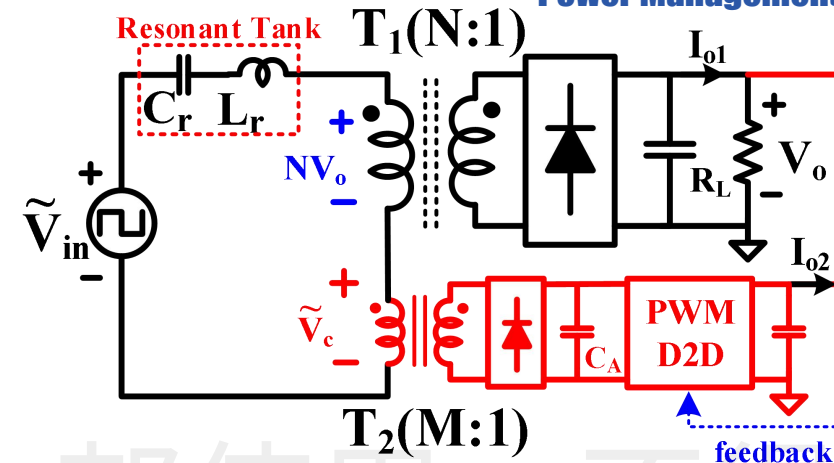


(Sigma Converter from CPES)

RDCX- ac in series/dc parallel



Concept block



Implementation block

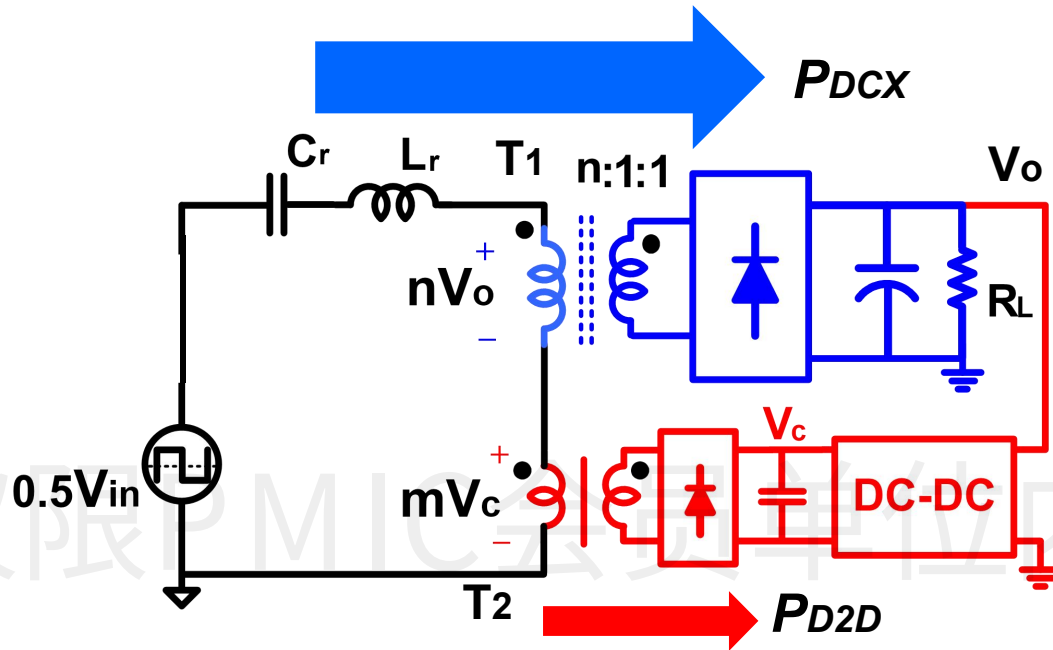


- Regulated V_o
- Partial power regulation
- Simple control
- Most power transferred to load by DCX

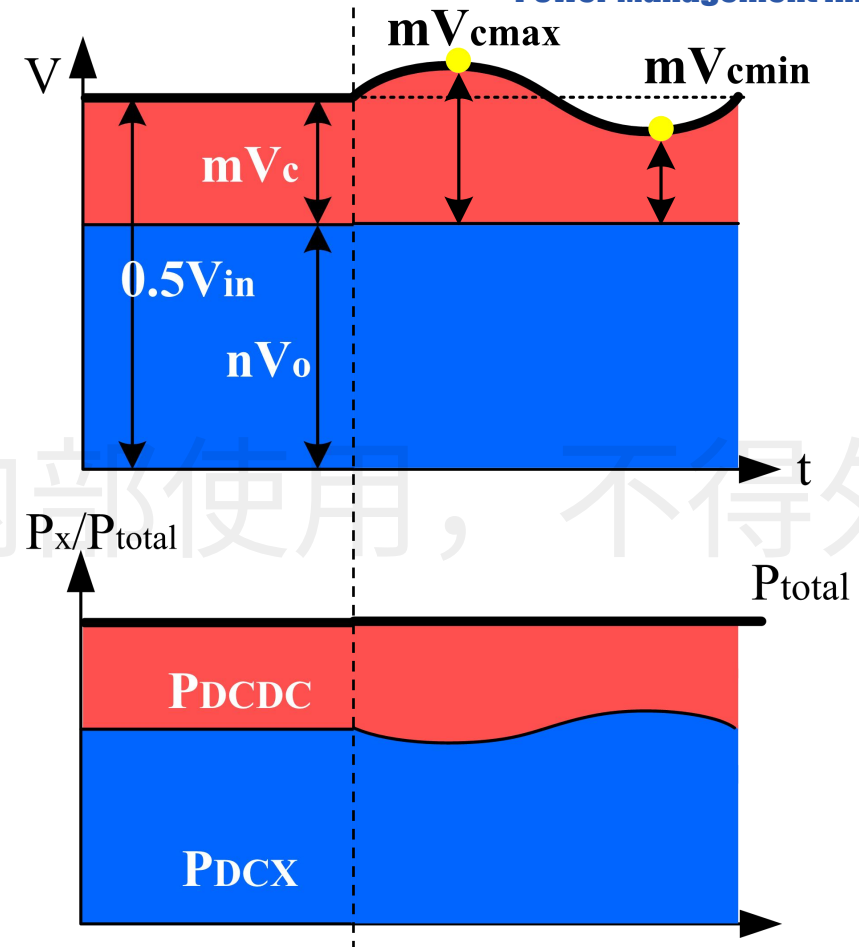
[1] X. Wu, H. Chen and Z. Qian, 1-MHz LLC Resonant DC Transformer (DCX) With Regulating Capability. IEEE Transactions on Industrial Electronics, 2016. 63(5): p. 2904-2912.



RDCX Operating Principle

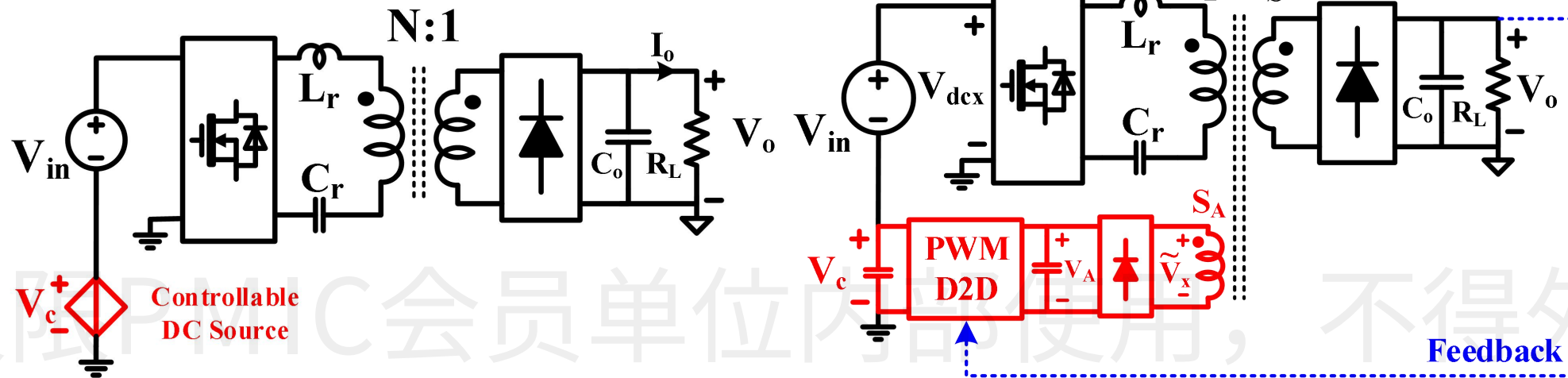


$$k = \frac{P_{dcdc}}{P_{total}} = \frac{mV_c}{mV_c + nV_o}$$



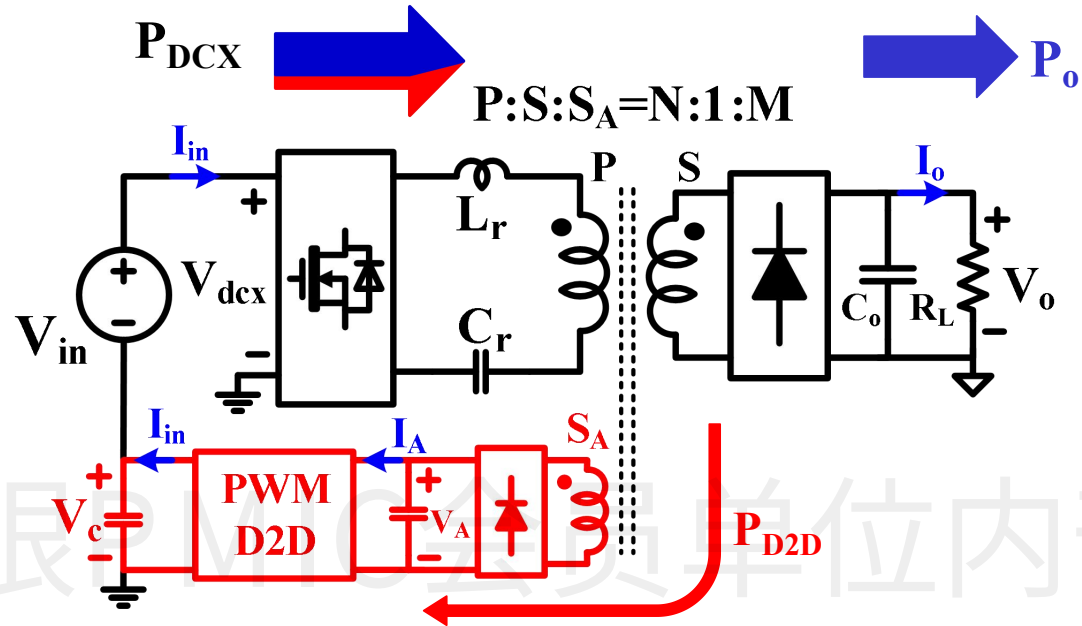
⊗ two independent magnetic components

RDCX --- DC in series/ac parallel



- Regulated V_o
- Part power regulation
- Without additional transformer
- Suitable for high normal input voltage

Regulation Principle



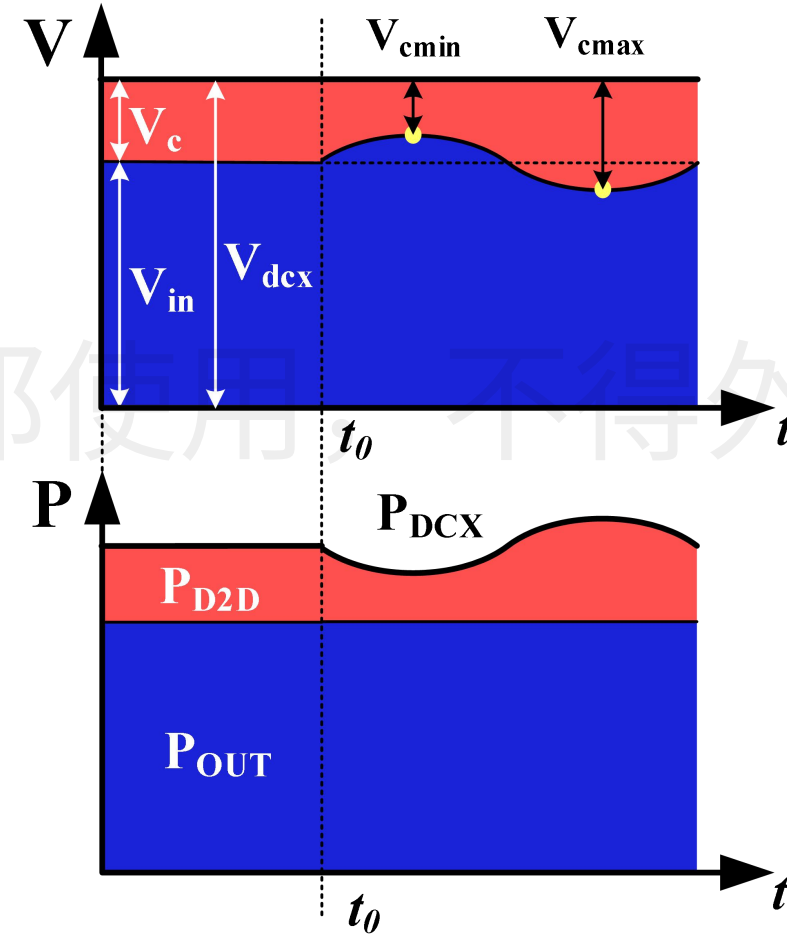
Voltage relationship:

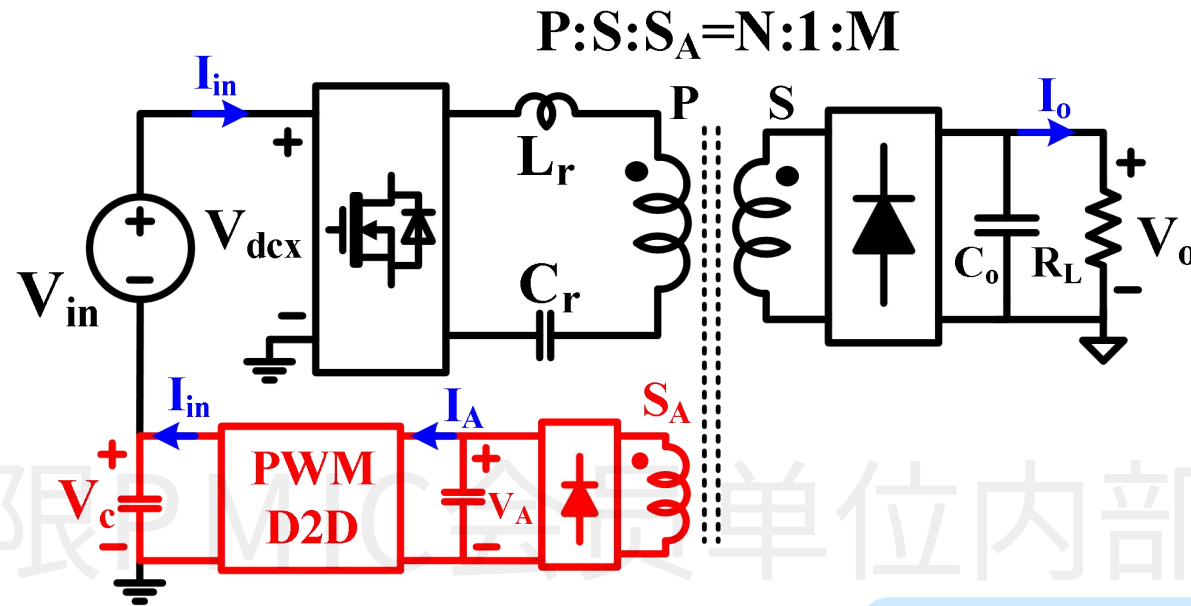
$$V_o = \frac{V_{dcx}}{N} = \frac{1}{N} \cdot (V_{in} + V_c) \quad V_A = M \cdot V_o$$

Power relationship:

$$P_{D2D} = \frac{V_c}{V_{in}} \cdot P_{in}$$

$$P_{DCX} = \frac{V_c + V_{in}}{V_{in}} \cdot P_{in}$$





Voltage Relationship:

$$V_o = \frac{V_{in} + V_C}{N}$$

$$V_A = M \cdot V_o$$

Define Voltage Gain of D2D:

$$G = \frac{V_C}{V_A} = \frac{N \cdot V_o - V_{in}}{M \cdot V_o} = f(D)$$

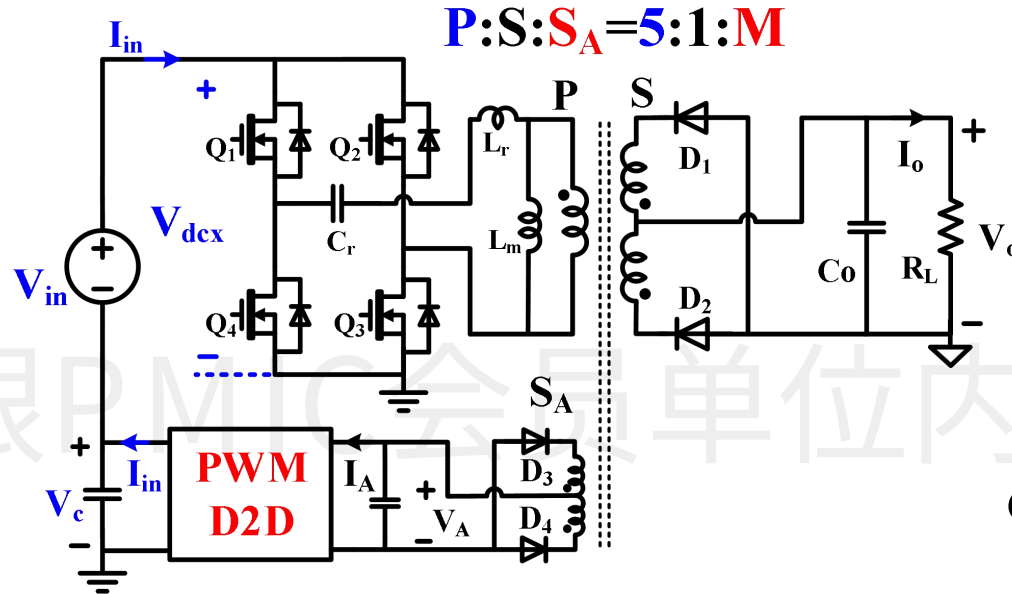
RDCX Voltage Gain:

$$\frac{V_o}{V_{in}} = \frac{1}{N - f(D) \cdot M}$$

Transformer Design: N, M

Auxiliary D2D Design: $f(D)$

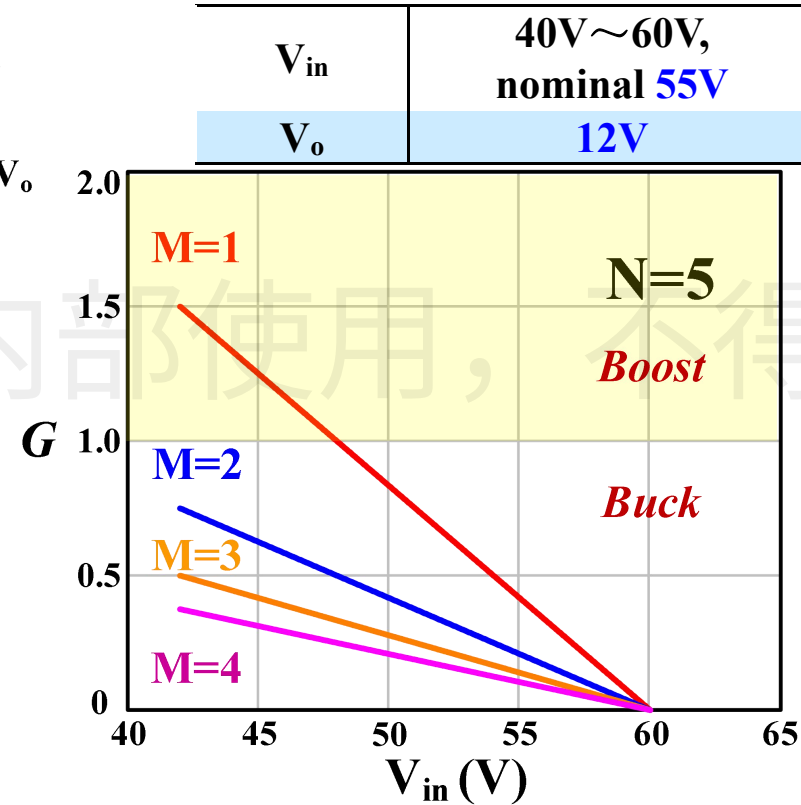
Relationship between M and D2D



Voltage Gain of the D2D:

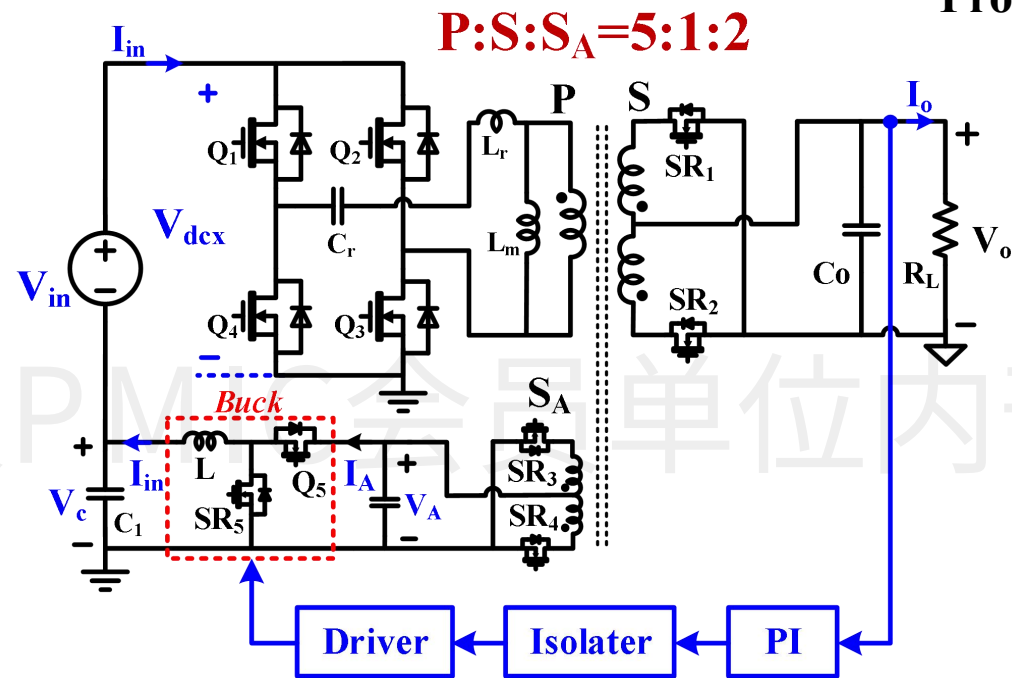
$$G = \frac{V_c}{V_A} = \frac{N \cdot V_o - V_{in}}{M \cdot V_o} = f(D)$$

Application:



48V/12V-30A RDCX Prototype

Prototype:



$450\text{W}/\text{in}^3$

Size: $45.0 \times 34.5 \times 8.5\text{mm}^3$

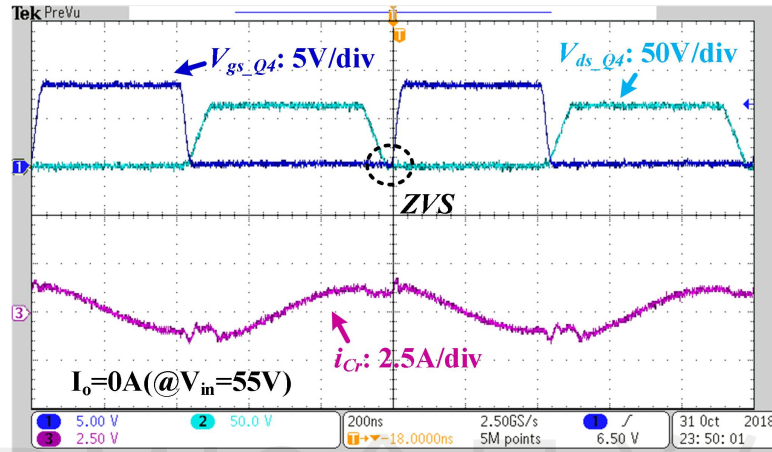
Based on $5 \times 6\text{mm}^2$ Si MOSFETs

Parameters:

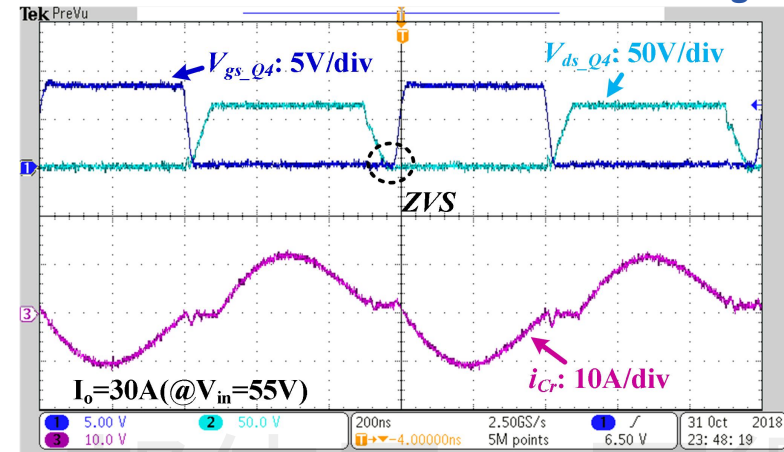
V_{in}	$42\text{V} \sim 60\text{V}$, 55V
V_o	12V
P_{out}	360W
f_s	1MHz



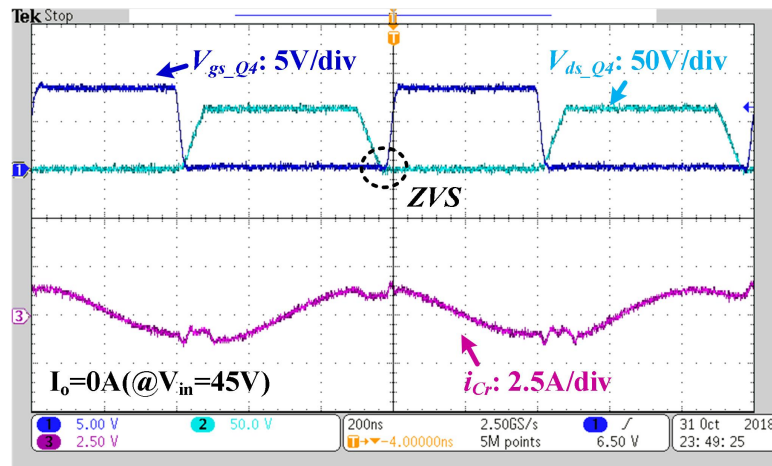
ZVS Waveforms at Different V_{in} or Load



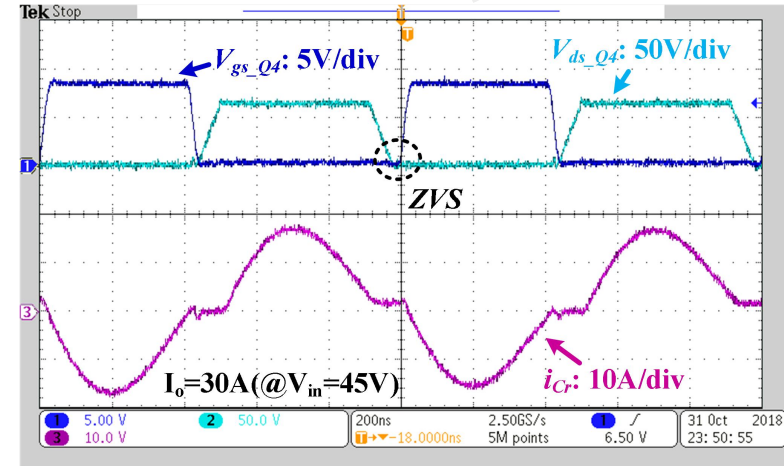
Waveforms @ $V_{in}=55V$ and $I_o=0A$



Waveforms @ $V_{in}=55V$ and $I_o=30A$

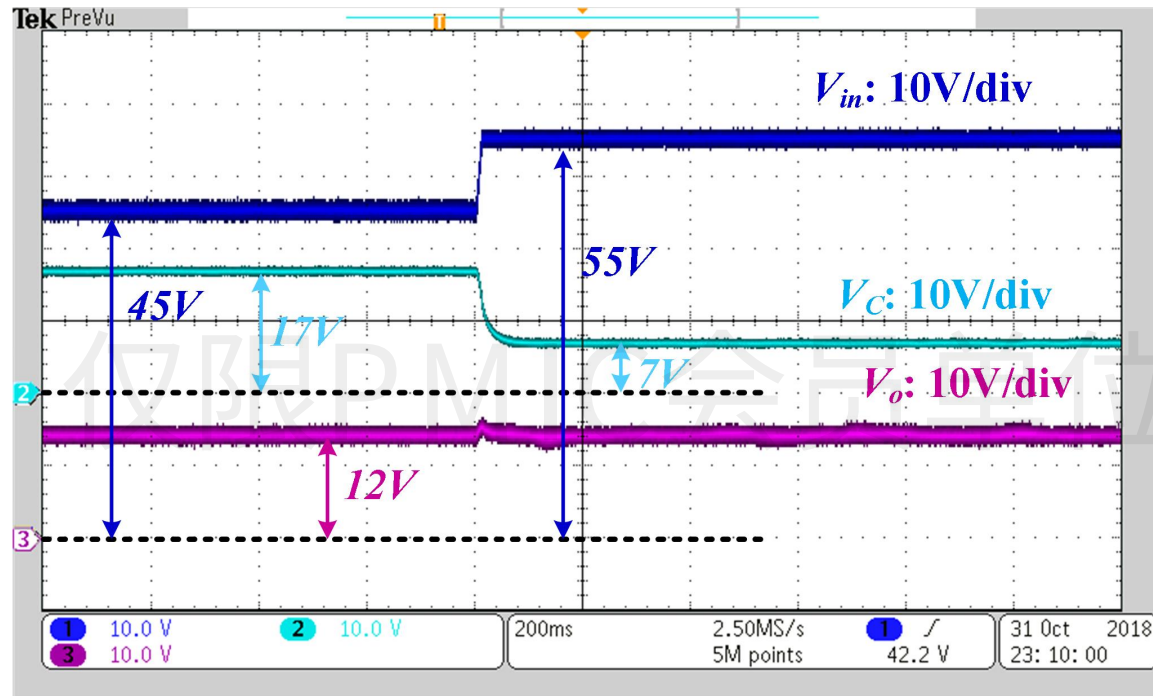


Waveforms @ $V_{in}=45V$ and $I_o=0A$

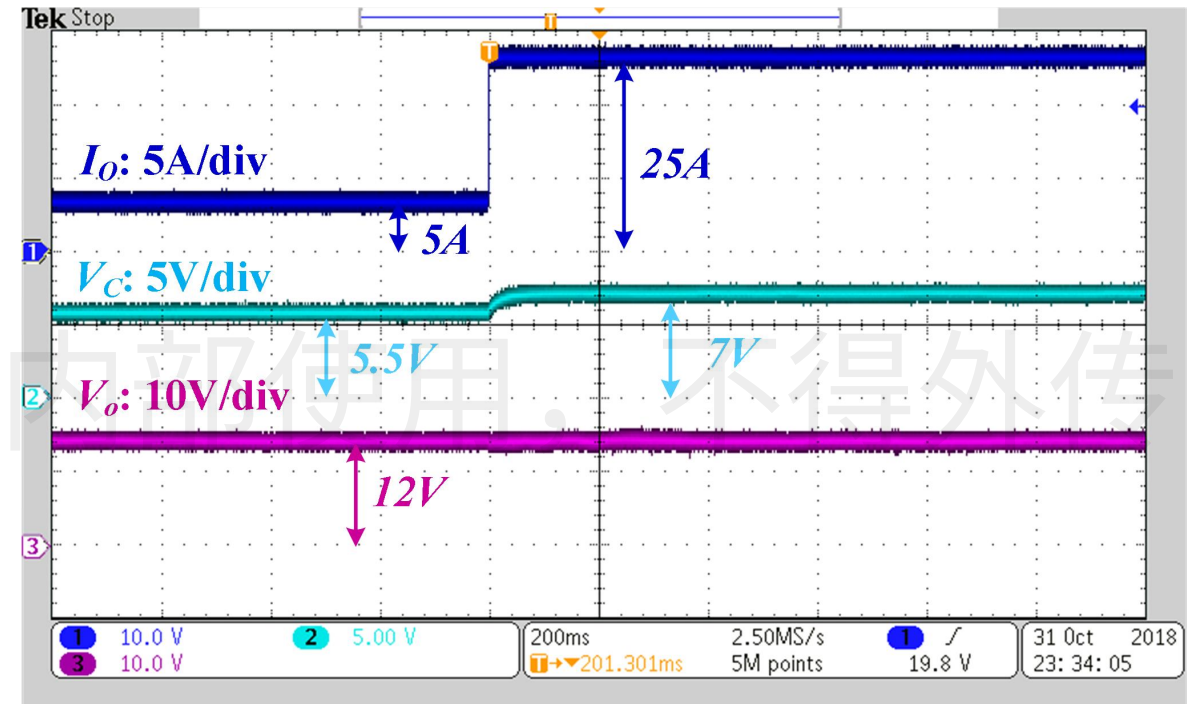


Waveforms @ $V_{in}=45V$ and $I_o=30A$

Dynamic Performance

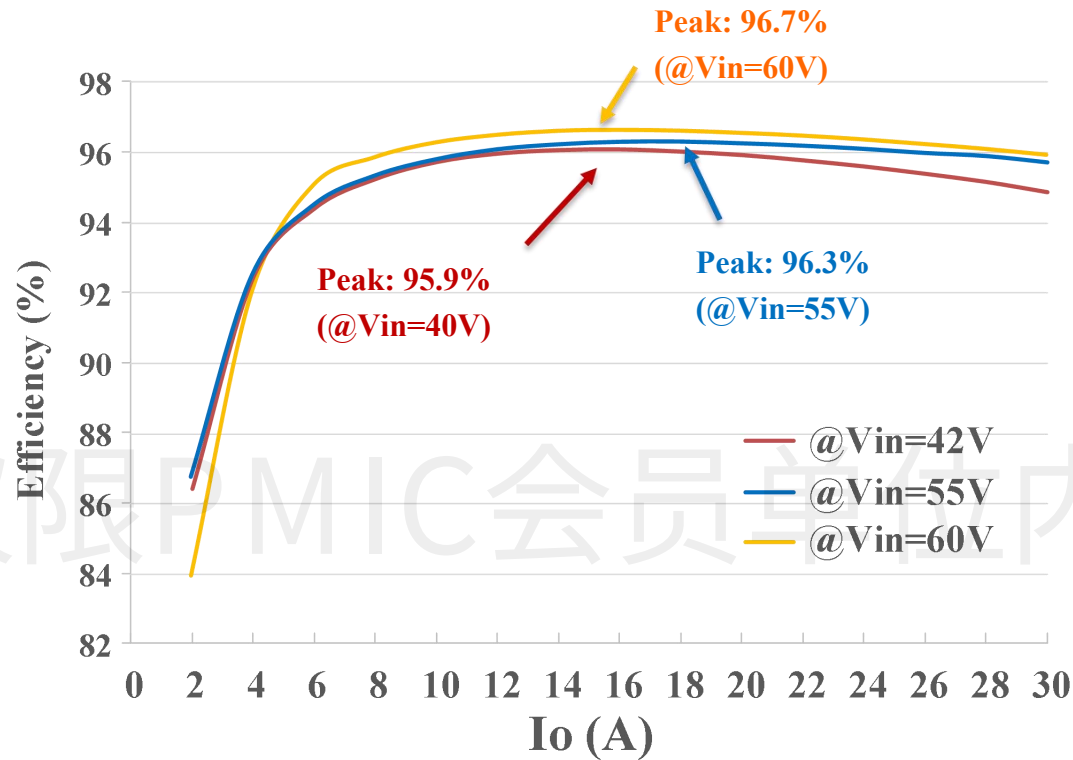


Dynamic response with step change in V_{in}
@ $I_o=25A$

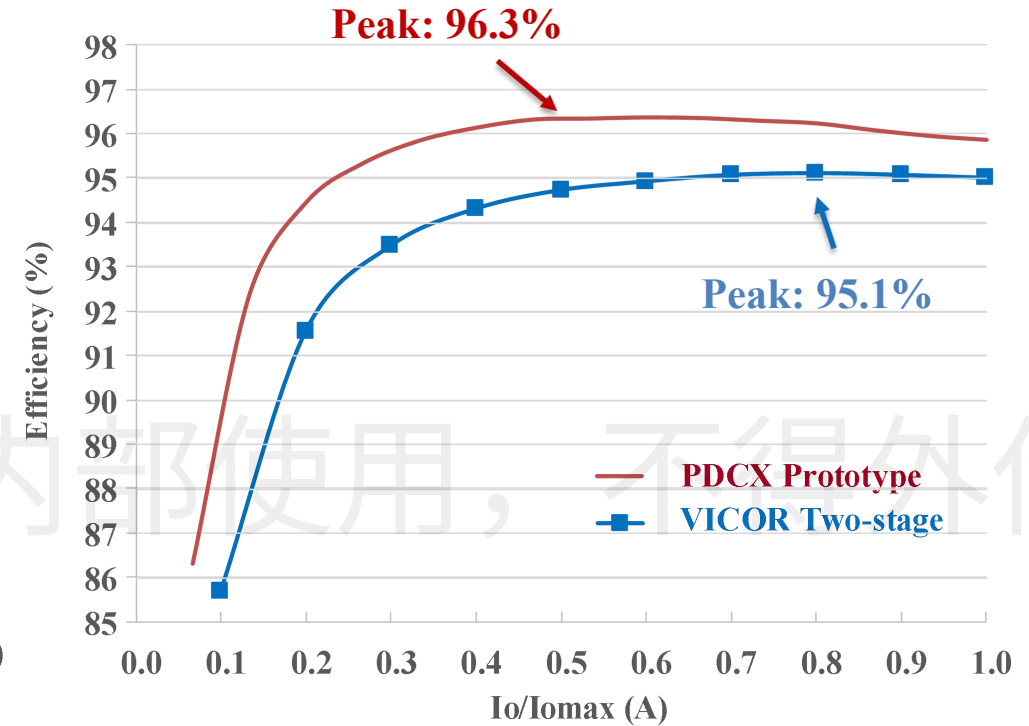


Dynamic response with step change in I_o
@ $V_{in}=55V$

Measured Efficiency— RDCX



Measured efficiency of RDCX at different input voltages



Measured efficiency of RDCX and calculated efficiency of two stage @ $V_{in}=55V$

PRM: PRM48by480x500A00, VICOR, 2015

IBC: IB0xE120T40xx-xx, VICOR, 2017

- A family of MHz RDCX converters with voltage regulation capability is proposed.
- High frequency, high power density and high efficiency are achieved in RDCX with tight regulating capability.
- The auxiliary transformer is not necessary to implement partial power regulation
- Different RDCXs have different sweet operating point.



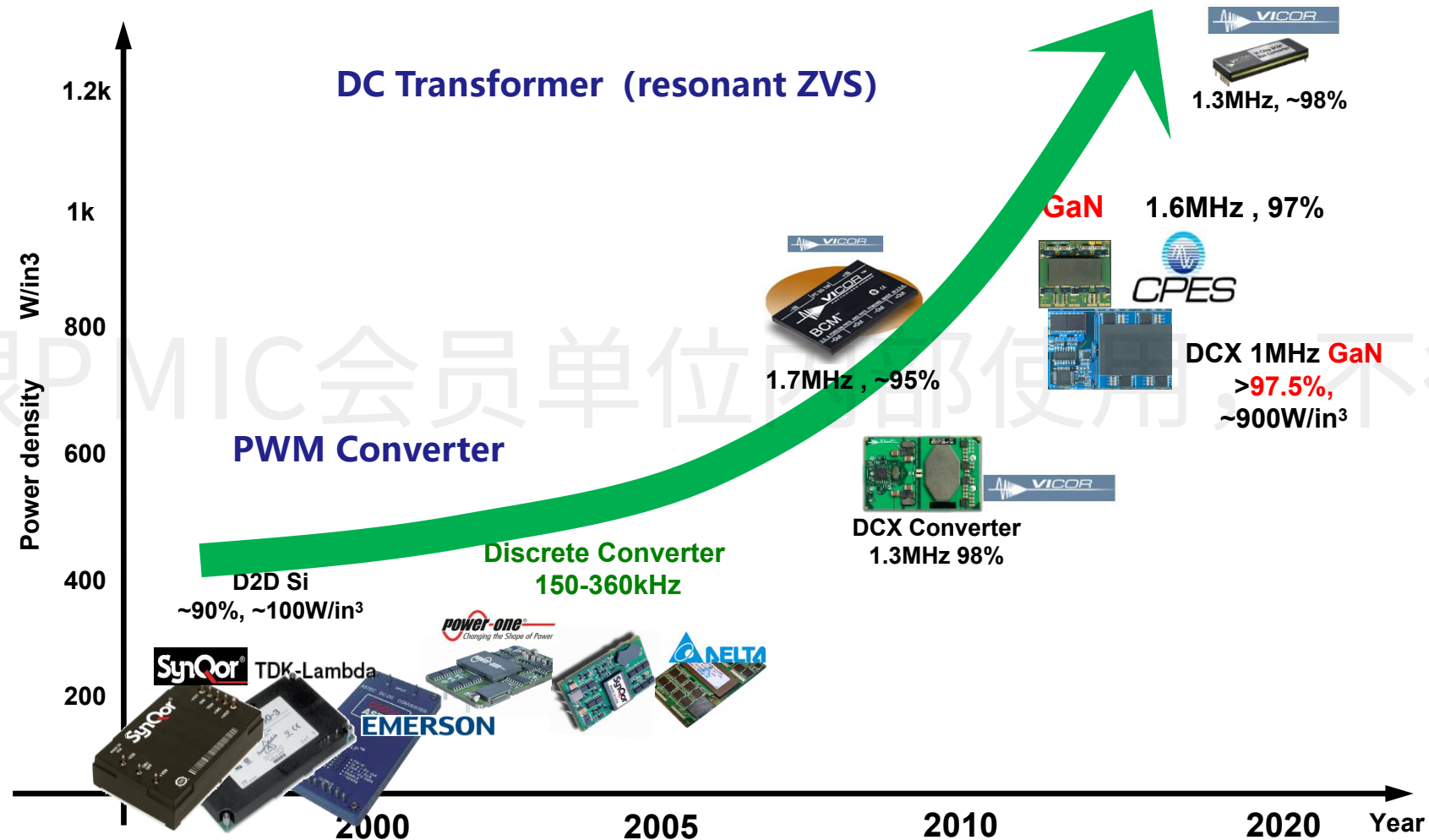
- 1. Introduction of power architectures of internet datacenter**
- 2. MHz high efficiency 48V-12V/6V power converters for 48V bus**
 - 2.1 State of the art of DC-DC converter for 48 Bus in server and other applications.
 - 2.2 Unregulated DCX for applications with low Bus voltage
 - 2.3 Tight regulated DC-DC converter (RDCX) for 48V-12V in server
- 3. MHz high efficiency 380V-48/12V power converters**
 - 3.1 Unregulated DC-DC techniques
 - 3.2 EMI design considerations of planar PCB transformer
 - 3.3 Tight regulated 380V-12V conversion
- 4. Conclusions**



3.1 State of the art of 380V DC-DC converters



Trends of Isolated 380V DC-DC Power Modules



3.2 Unregulated DCX techniques for 380V systems



ZVS Resonant DCX Topologies



Si
~ 1 MHz,
~98%

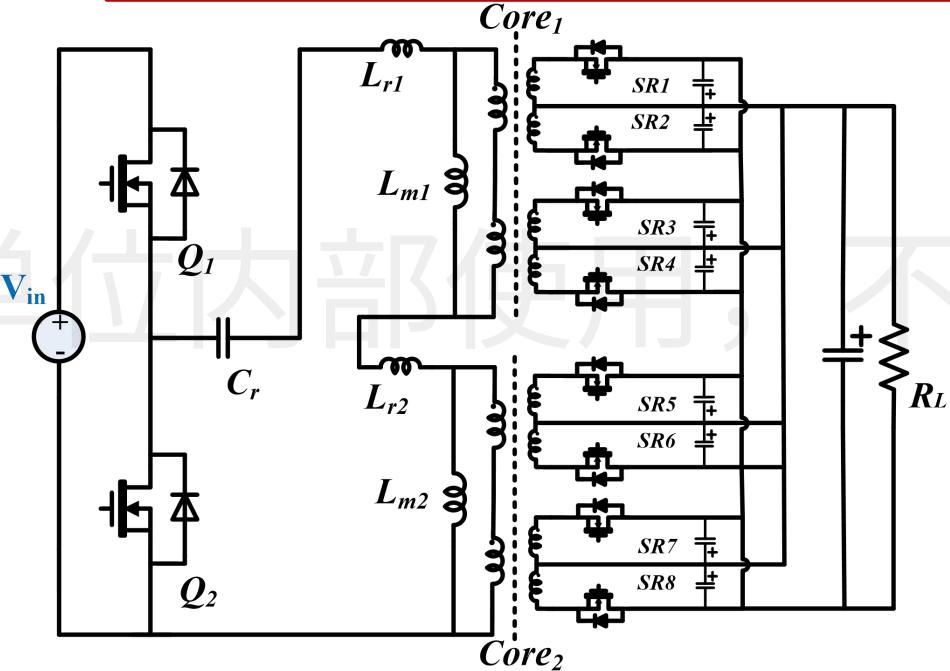


GaN
DCX 1MHz GaN
6 Layer PCB
97.5%,900W/in³
(2017)



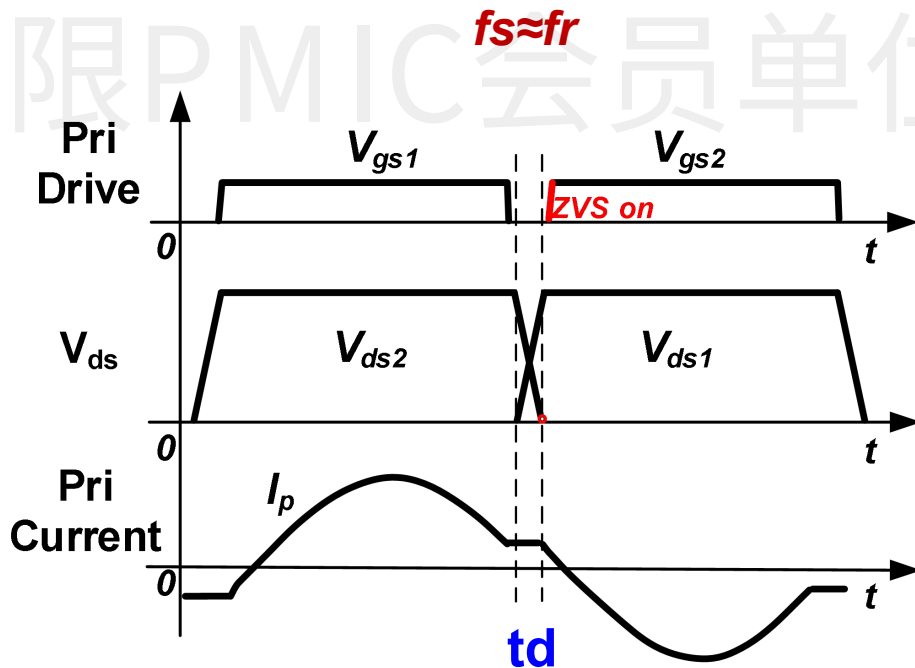
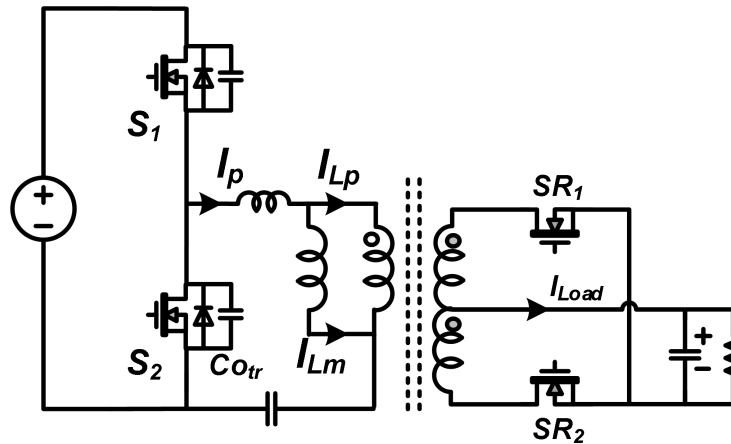
48V-12V
1MHz , >98%
(2019)

- LC series resonant topology
- Matrix transformer

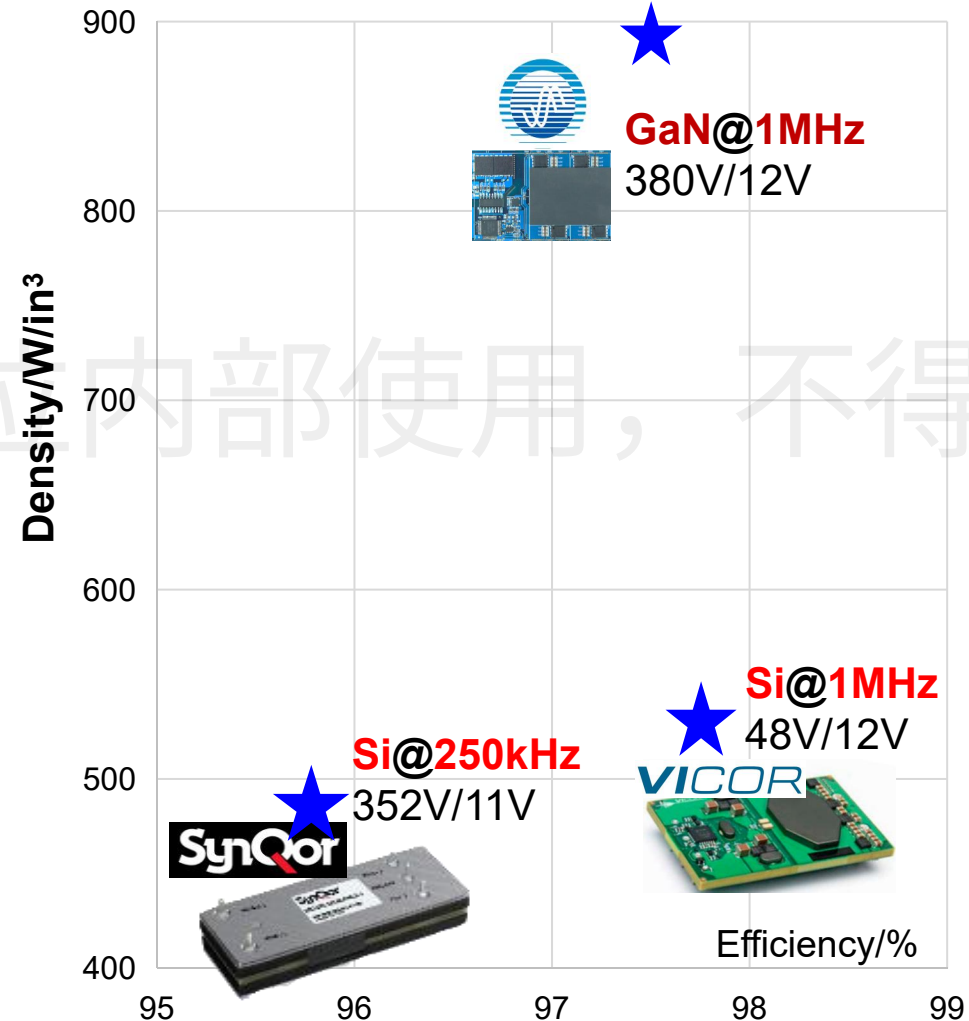


- ☺ ZVS On
- ☺ ZCS Off
- ☺ No Reverse Recovery

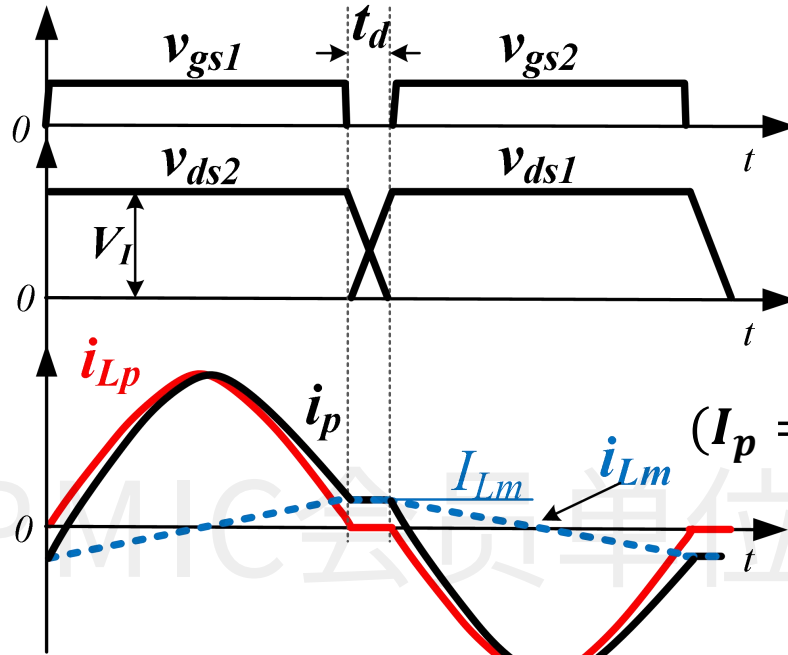
Comparison of High Frequency DCX



State of the art of DCX Module



Conduction loss of Primary Switches



Primary Conduction loss:

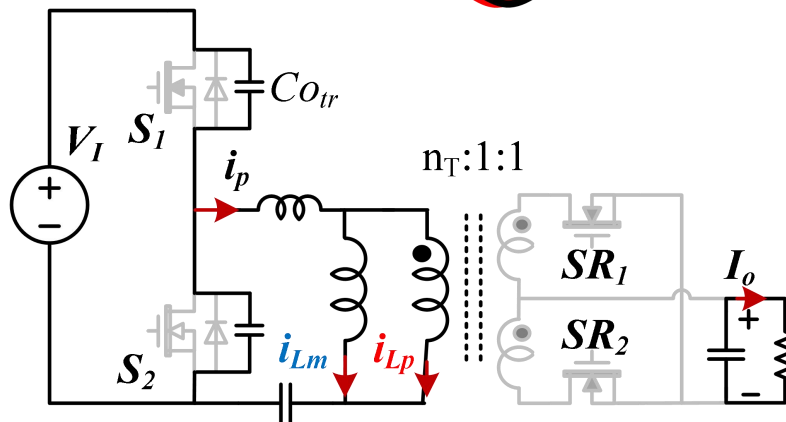
$$P_{Con} = I_{prms}^2 R_{dson}$$

1. Load current

$$I_{Lp} = \frac{I_o}{n_T}$$

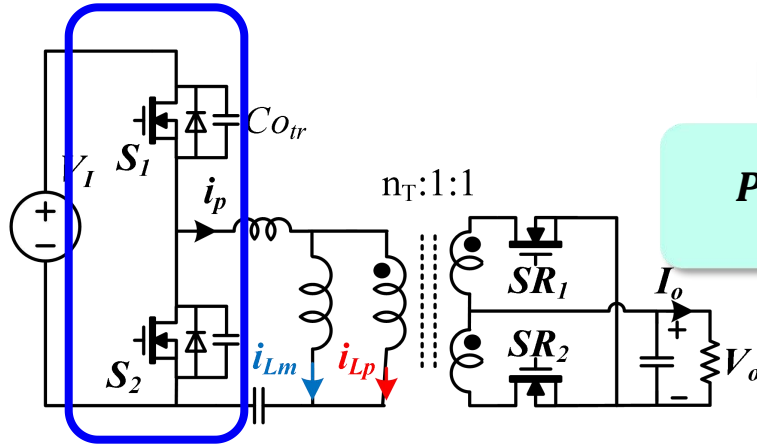
2. Magnetizing current

$$I_{Lm} = \frac{V_I \cdot 2C_{o_{tr}}}{t_d}$$



ZVS Transition in dead time

Conduction loss model



Primary Loss model

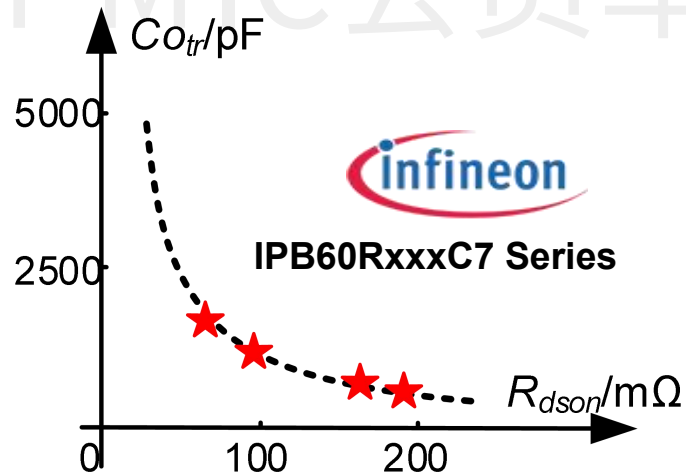
$$P_{Con}(R_{dson}, C_{otr}) = \left(\frac{8n_T^2 V_o^2 T_r \cdot C_{otr}^2}{t_d^2 T_s} + \frac{\pi^2 T_s \cdot I_o^2}{8n_T^2 T_r} \right) \cdot R_{dson}$$

Variable elimination

$$C_{otr} = \frac{NFoM}{R_{dson}}$$

Constant:

$$NFoM = R_{dson} \cdot C_{otr}$$



Simplified Conduction loss model

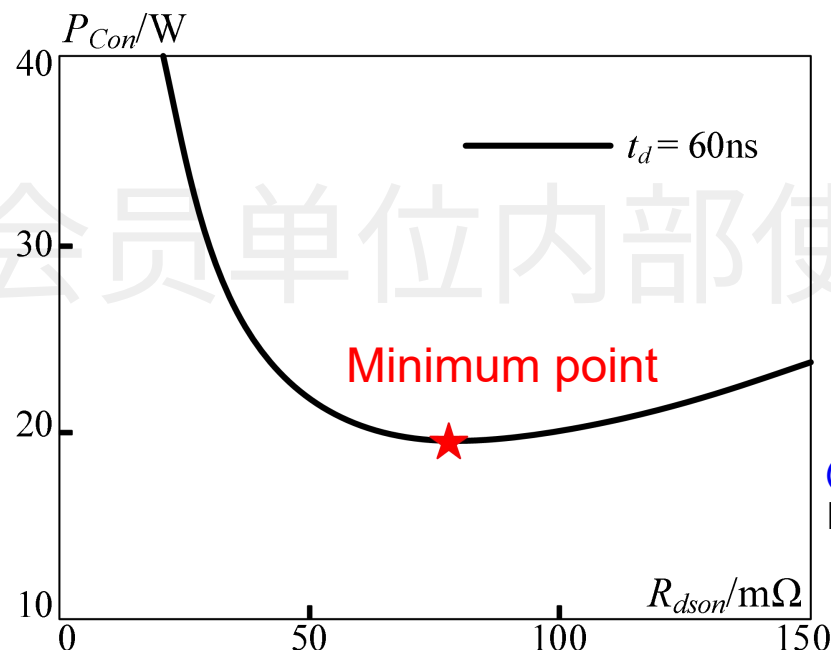
Conduction Loss model

$$P_{Con}(R_{dson}) = A \cdot \frac{1}{R_{dson}} + B \cdot R_{dson}$$

A and B: Constant

$$A = \frac{8n_T^2 V_o^2 T_r * NFoM^2}{t_d^2 T_s}$$

$$B = \frac{\pi^2 I_o^2 T_s}{8n_T^2 T_r}$$



@380V-12V/150A
IPB60Rxxx C7 Series

$$P_{Con}(R_{dson}) \geq 2\sqrt{AB} = P_{Cmin} = \frac{2\pi P_o \cdot NFoM}{t_d}$$

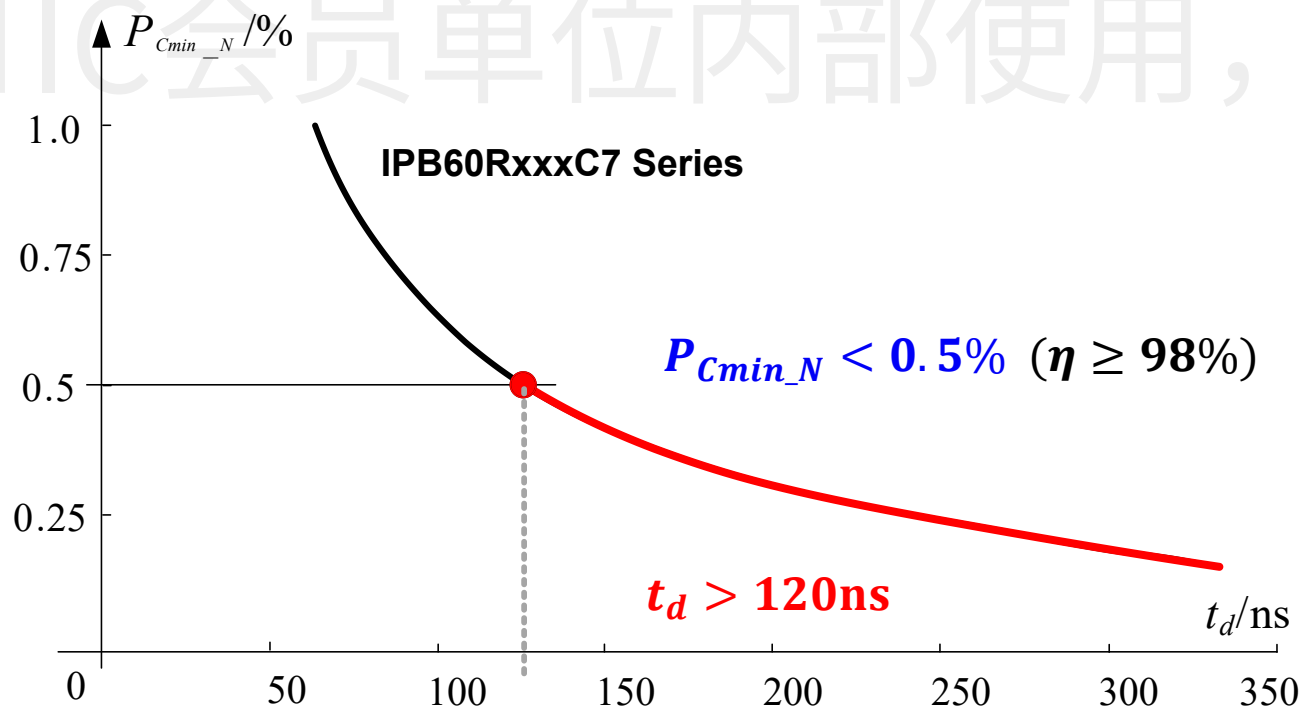
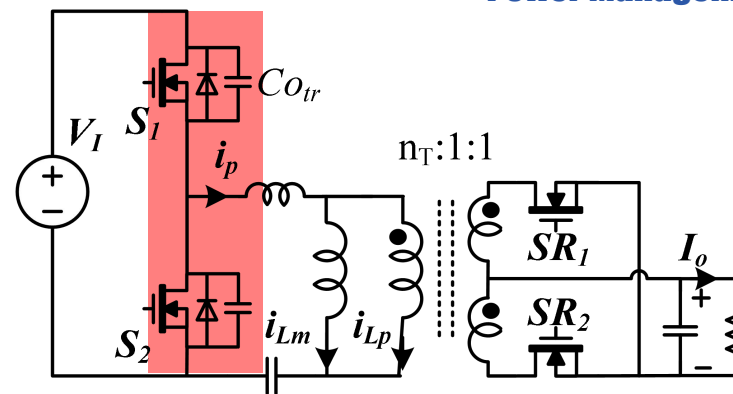


Design of t_d

Normalized primary conduction loss:

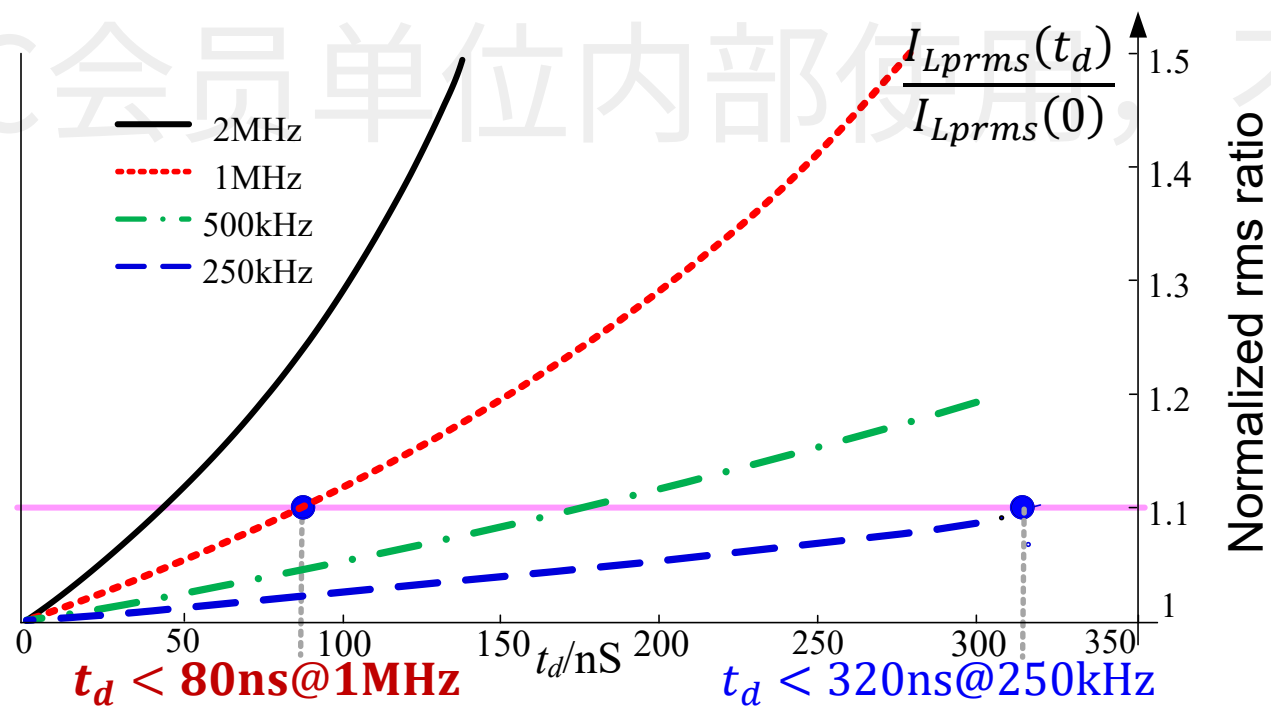
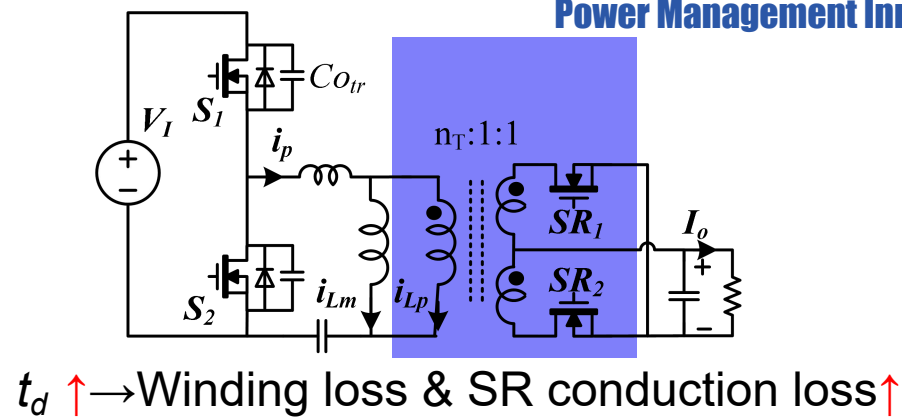
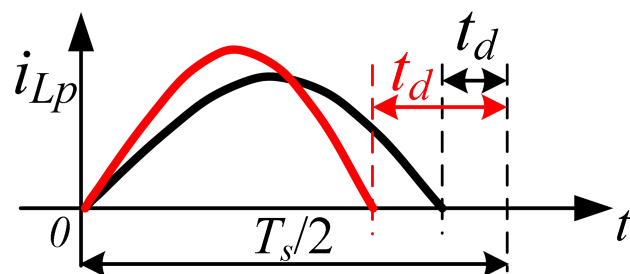
η : efficiency

$$P_{Cmin_N} = \frac{P_{Cmin}}{P_o} = \frac{2\pi\eta * NFoM}{t_d}$$



Design of t_d

RMS current vs. t_d

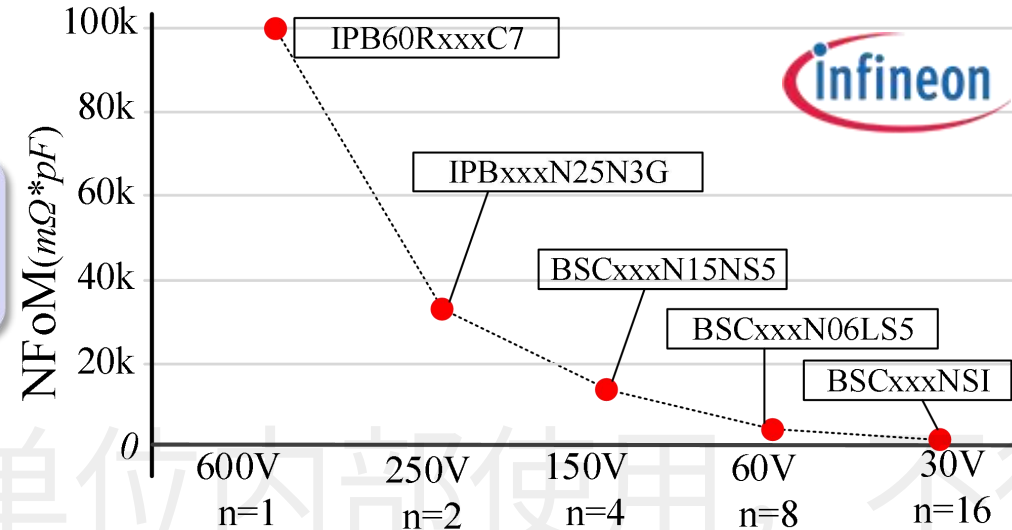


$$P_{Cmin_Normalized} = \frac{2\pi * \eta * NFoM}{t_d}$$

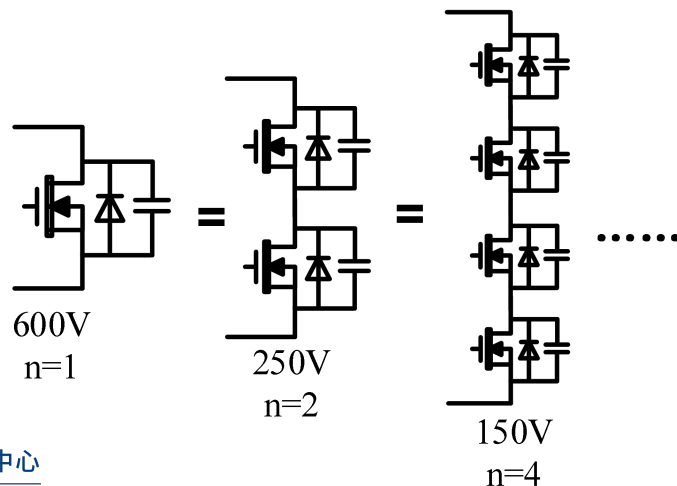

Series-connected low NFoM devices

Low $V_{(BR)DSS}$ = Low NFoM

$$P_{Cmin} = \frac{2\pi * P_o * NFoM}{t_d}$$



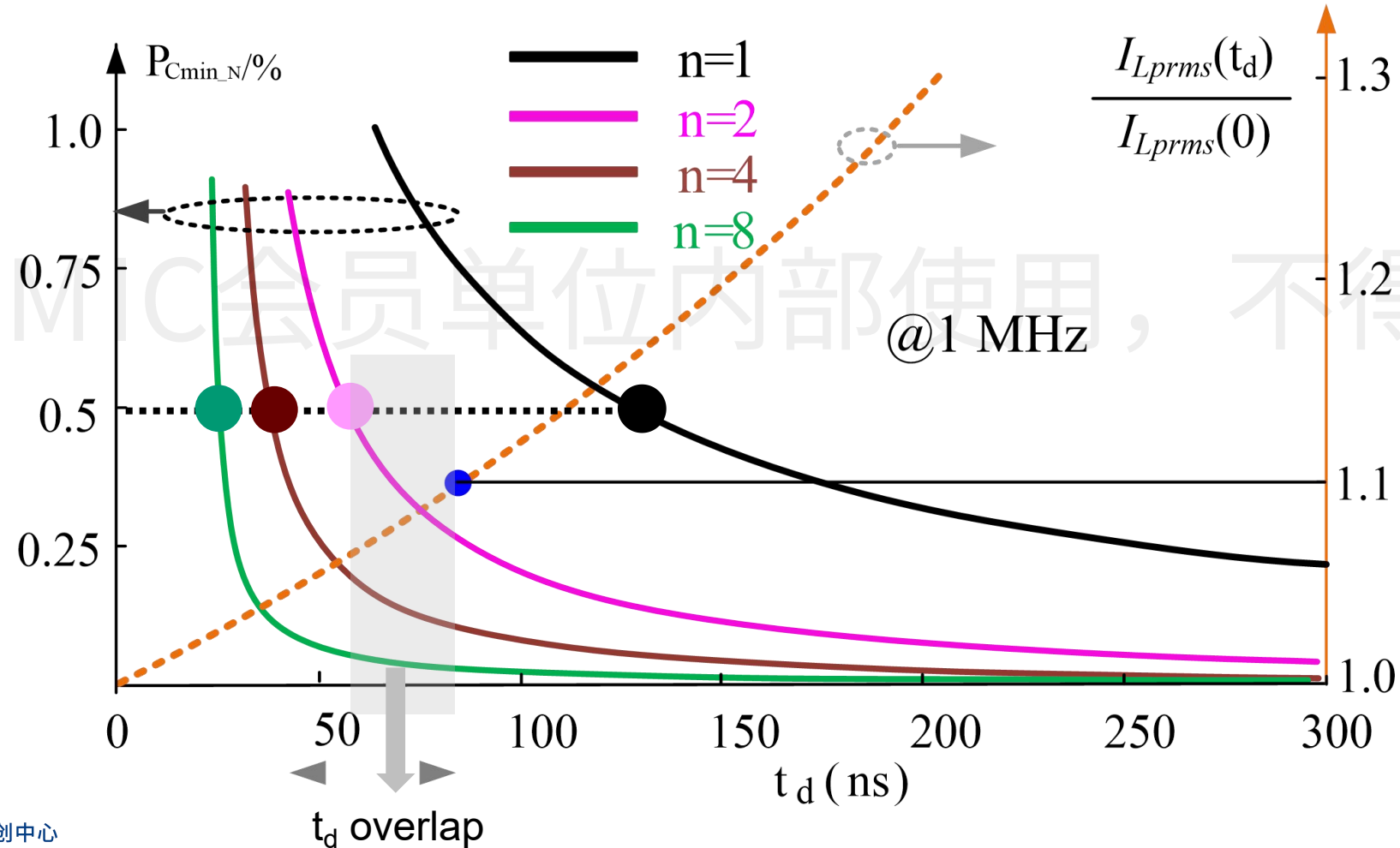
Series-connected low $V_{(BR)DSS}$ devices



$$NFoM = (\cancel{n} R_{dson}) \cdot \frac{C_{otr}}{\cancel{n}}$$

P_{Cmin} and t_d @ Different NFoM Devices

$$P_{Cmin_Normalized} = \frac{2\pi * \eta * NFoM}{t_d}$$

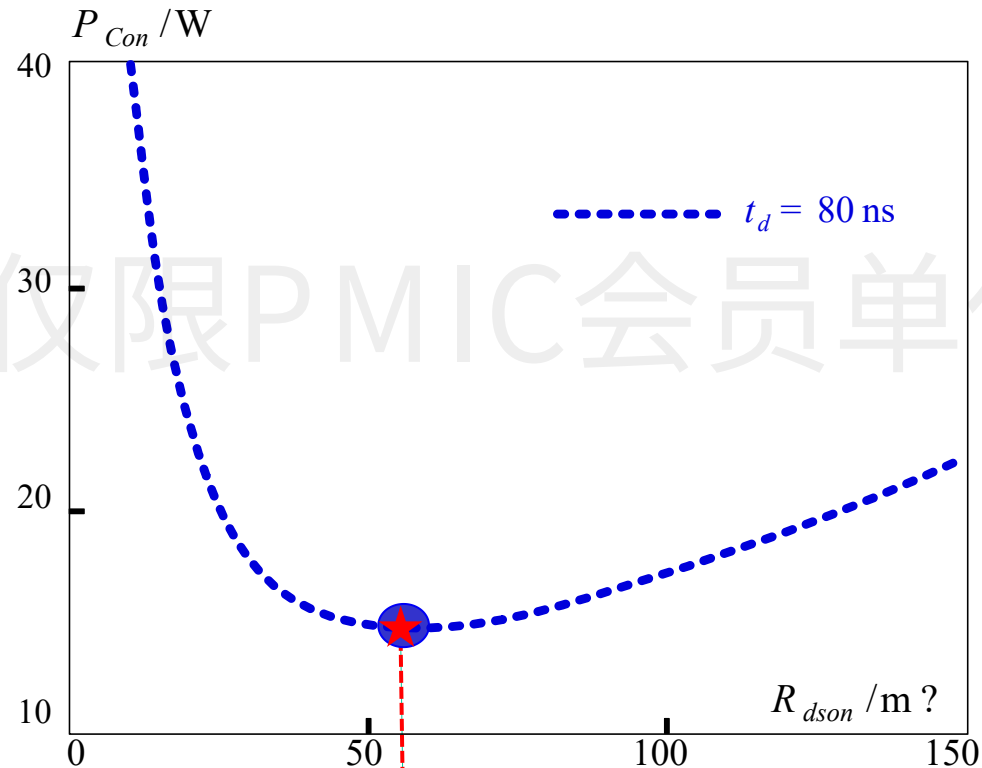


Conduction loss model

$$P_{Con}(R_{dson}) = A \cdot \frac{1}{R_{dson}} + B \cdot R_{dson}$$

$$A = \frac{8n_T^2 V_o^2 T_r \cdot NFoM^2}{t_d^2 T_s} \quad B = \frac{\pi^2 I_o^2 T_s}{8n_T^2 T_r}$$

$$R_{dson@min} = \sqrt{\frac{A}{B}} = \frac{8n_T^2 V_o T_r \cdot NFoM}{\pi t_d I_o T_s}$$



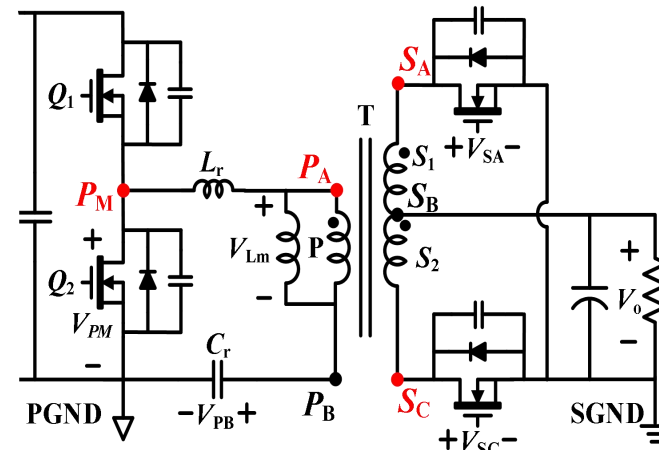
Min. Points



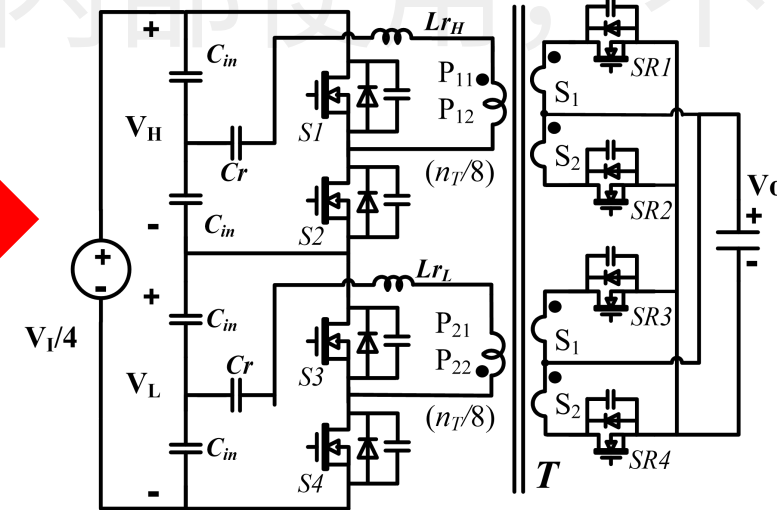
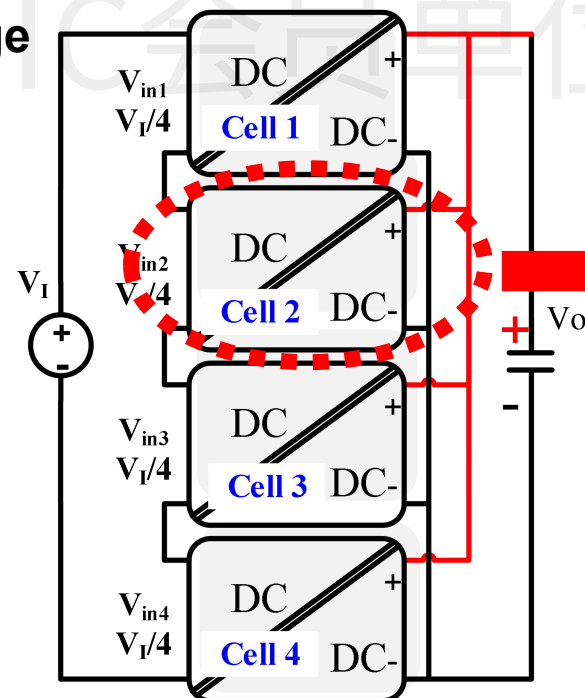
MHz DCX Topology Based on Low NFoM Devices

V_{in} : 380
 V_o : 12V/150A

High voltage
switch



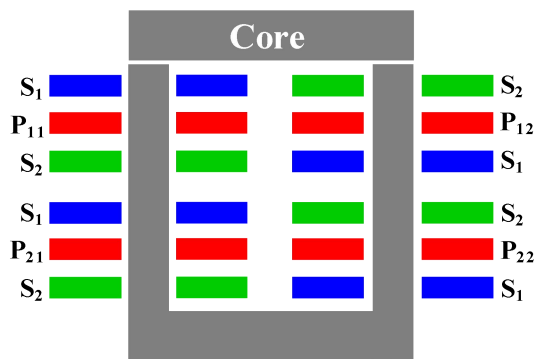
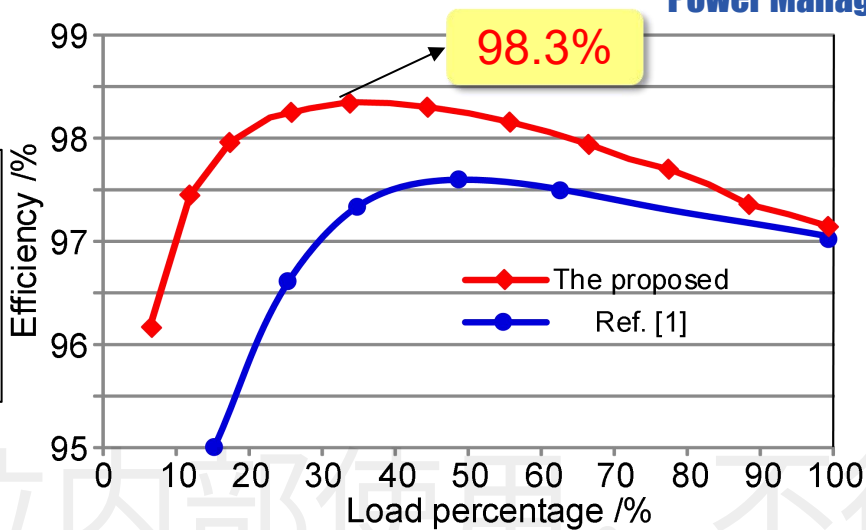
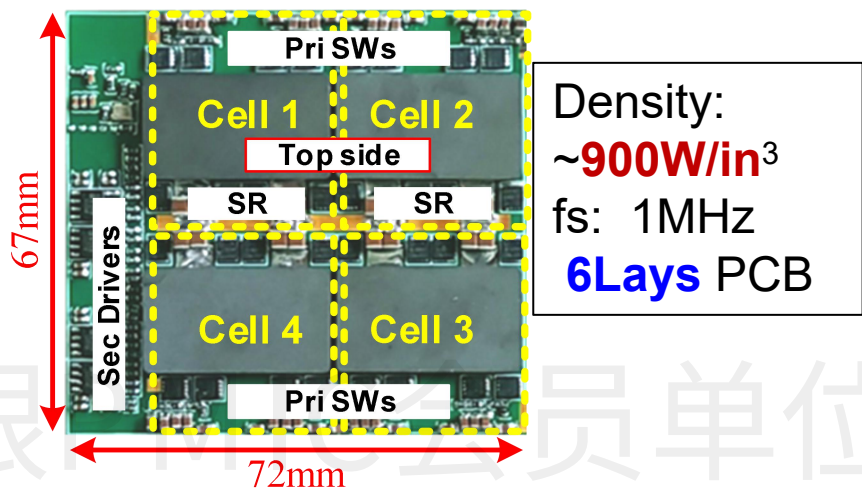
Low voltage
switch



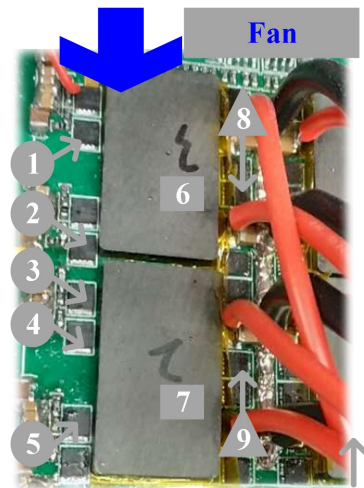
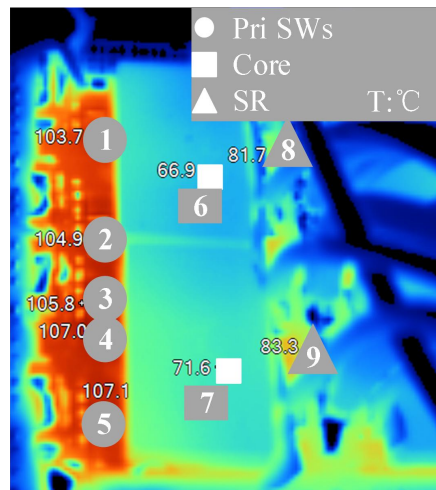
Cell circuit

SRC DCX

Verification: 380V-12V/150A DCX Prototype

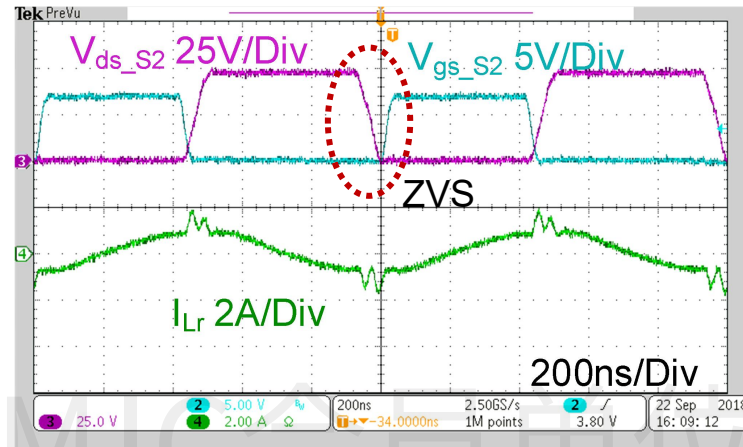


单元变压器绕组结构

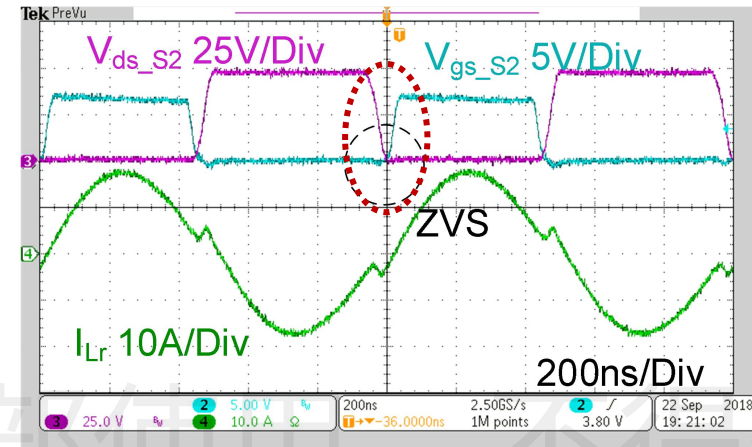


Measured Key waveforms

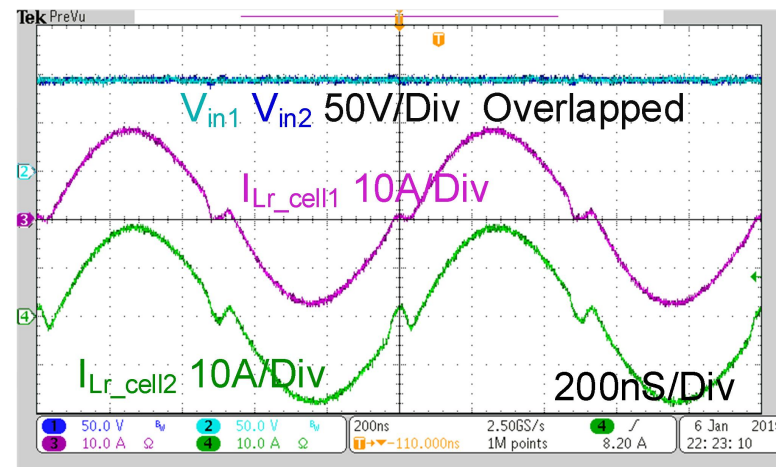
➤ Waveforms at full load range



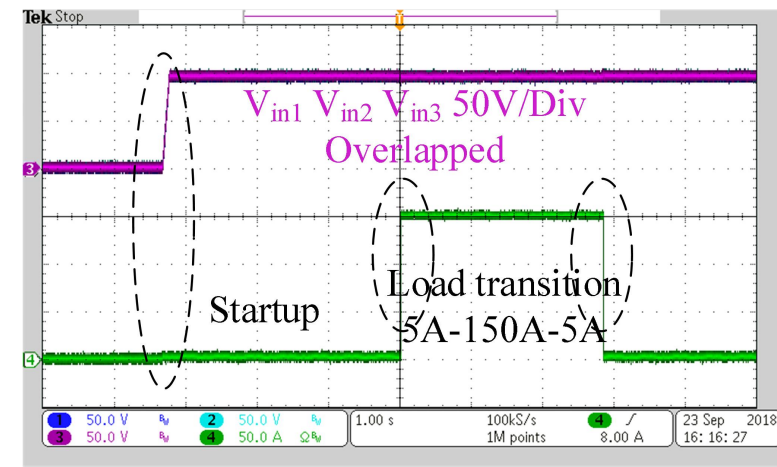
380V_{in}@null load



380V_{in}@full load



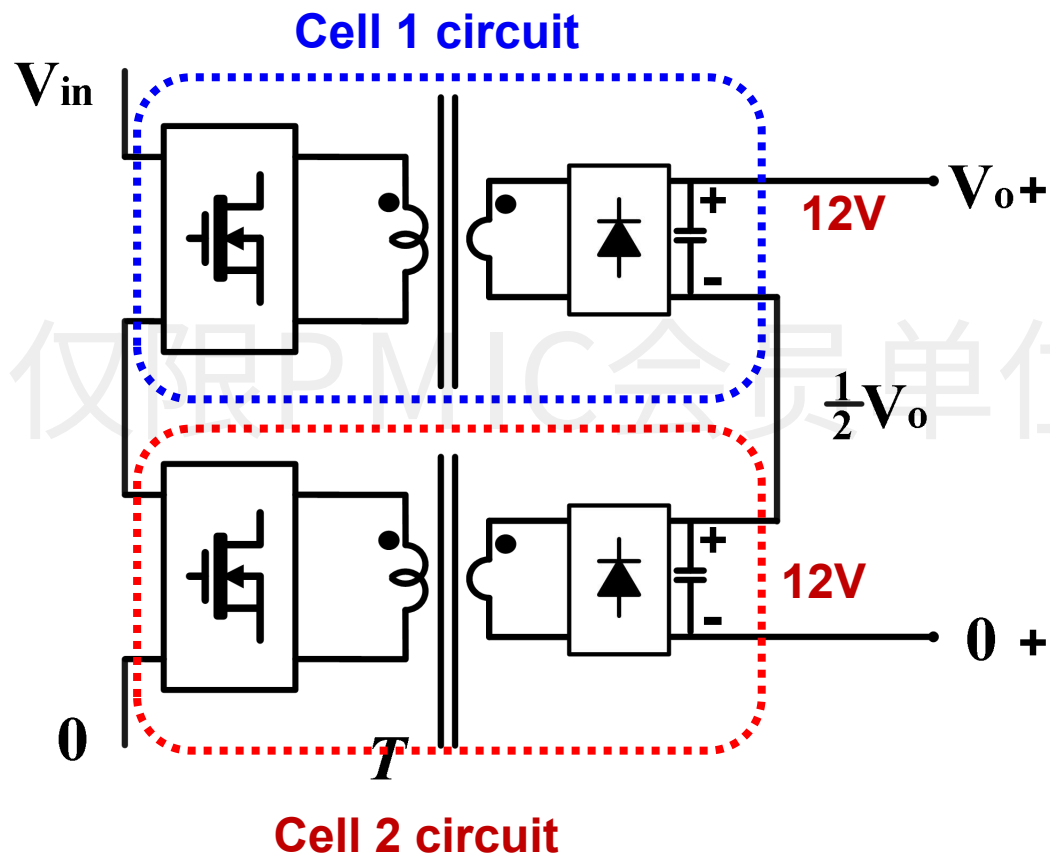
Voltage and current sharing



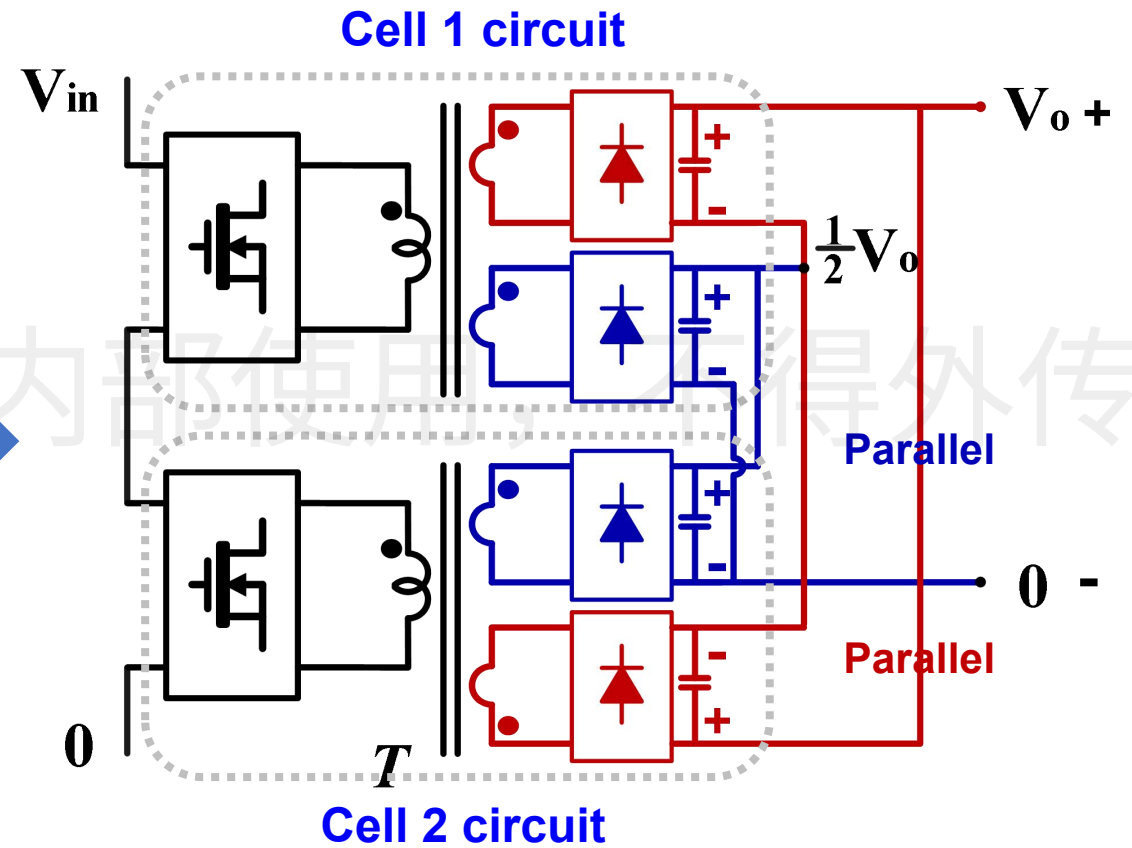
Start up and load transition

380V-48V Output DCX -Input-series Output-series (ISOS)

□ voltage sharing

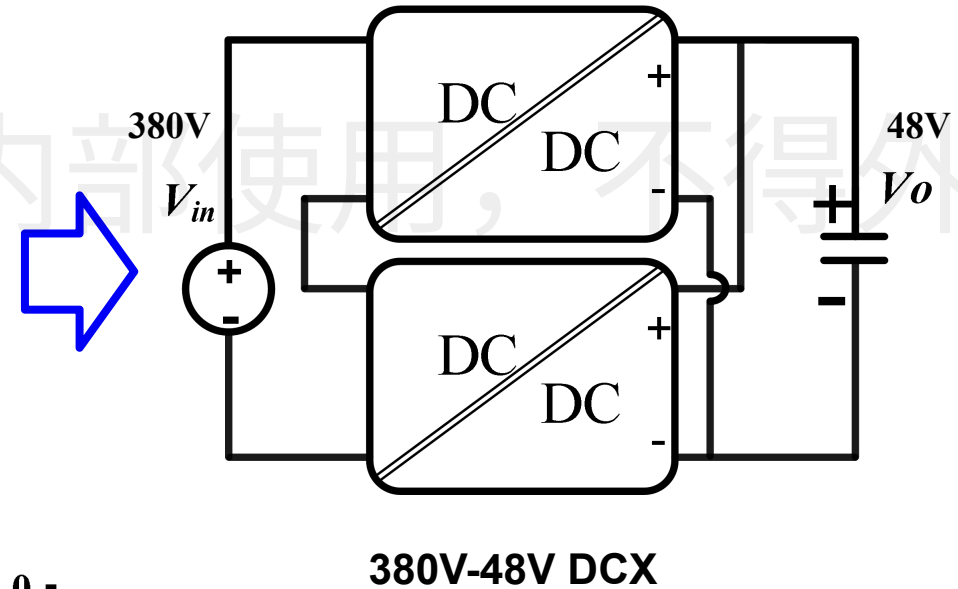
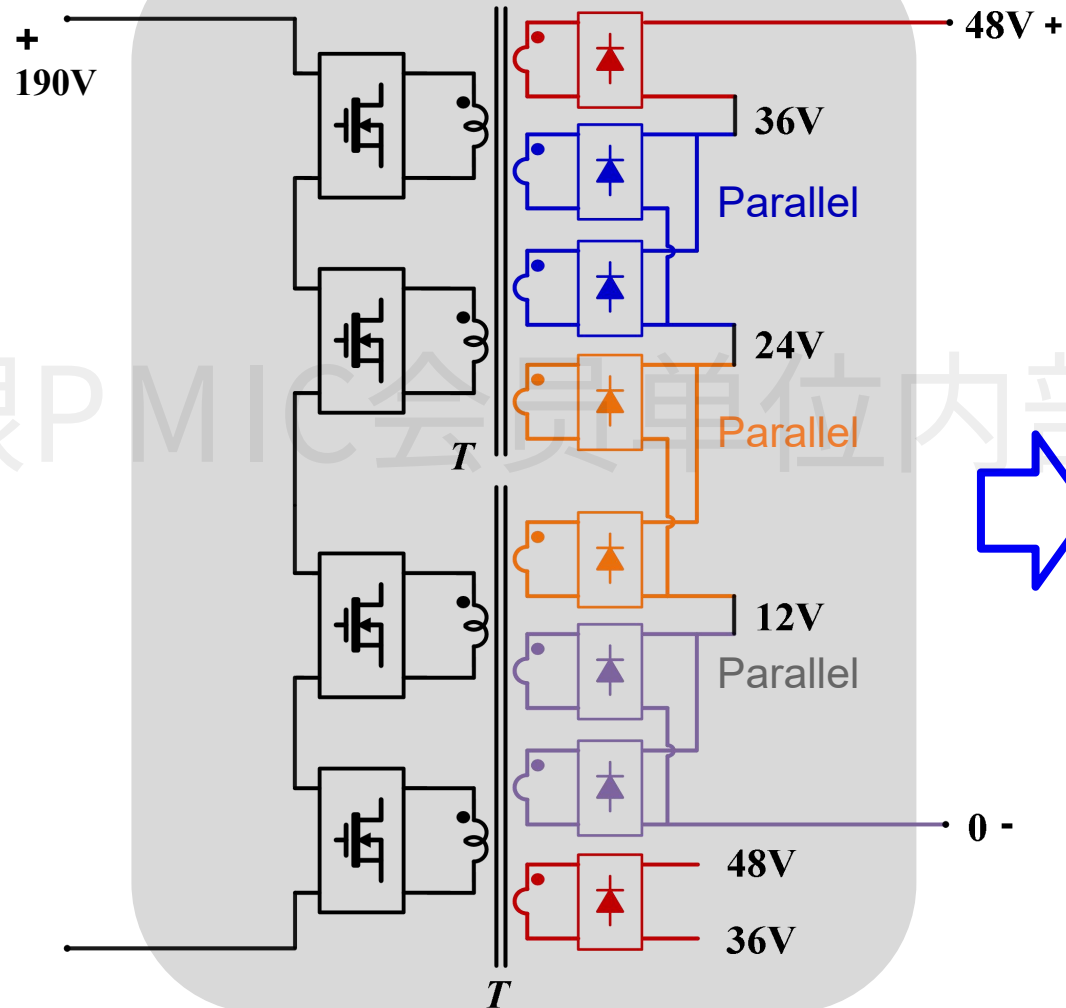


ISOS

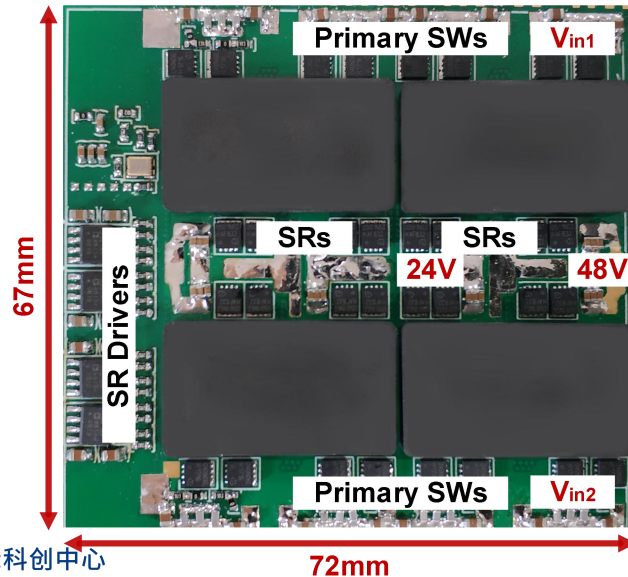
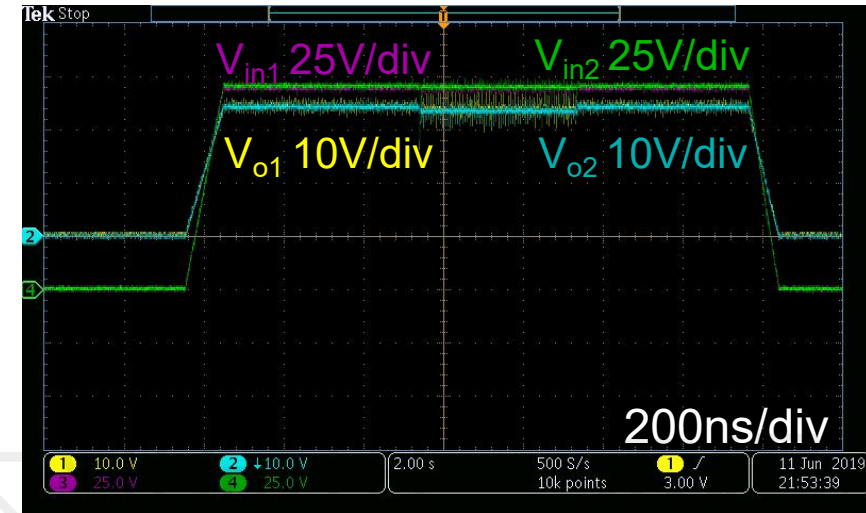
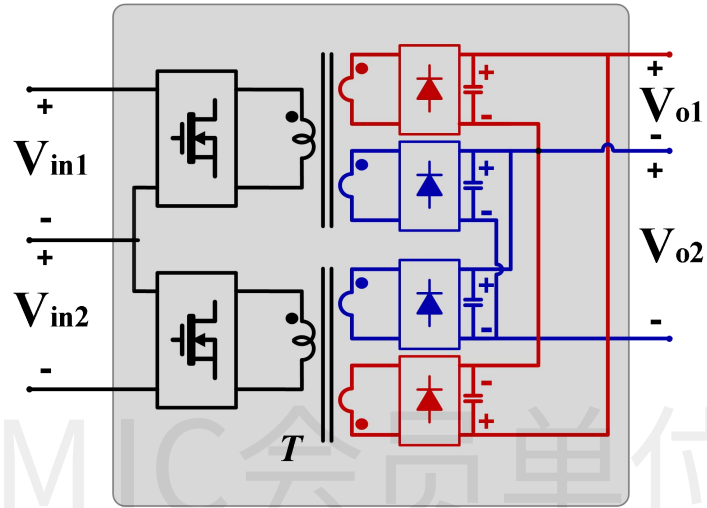


Parallel-series Hybrid

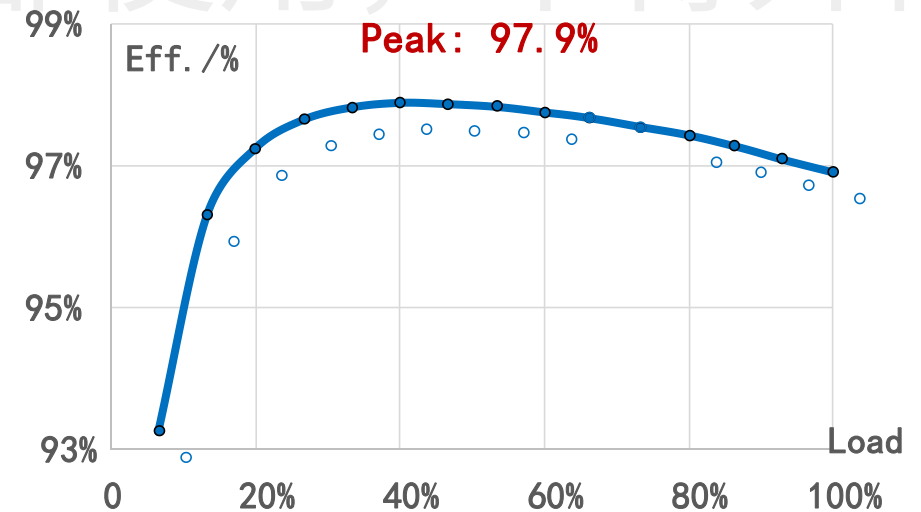
Daisy Chain Structure for 48V output



Experimental verifications



Density:
~**900W/in³**
fs: 1MHz
6Lays PCB

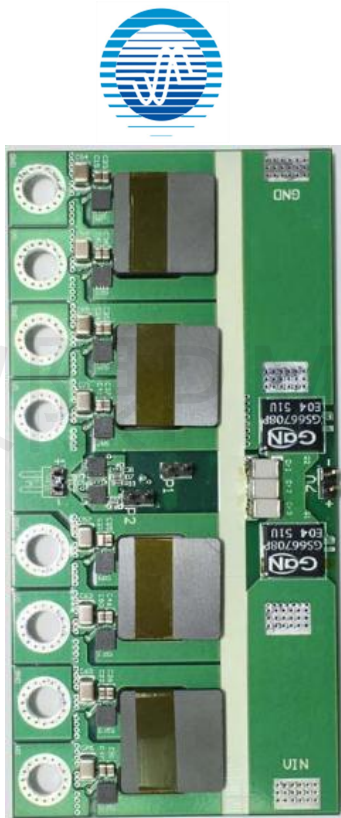


3.2 EMI design considerations of planar PCB transformer

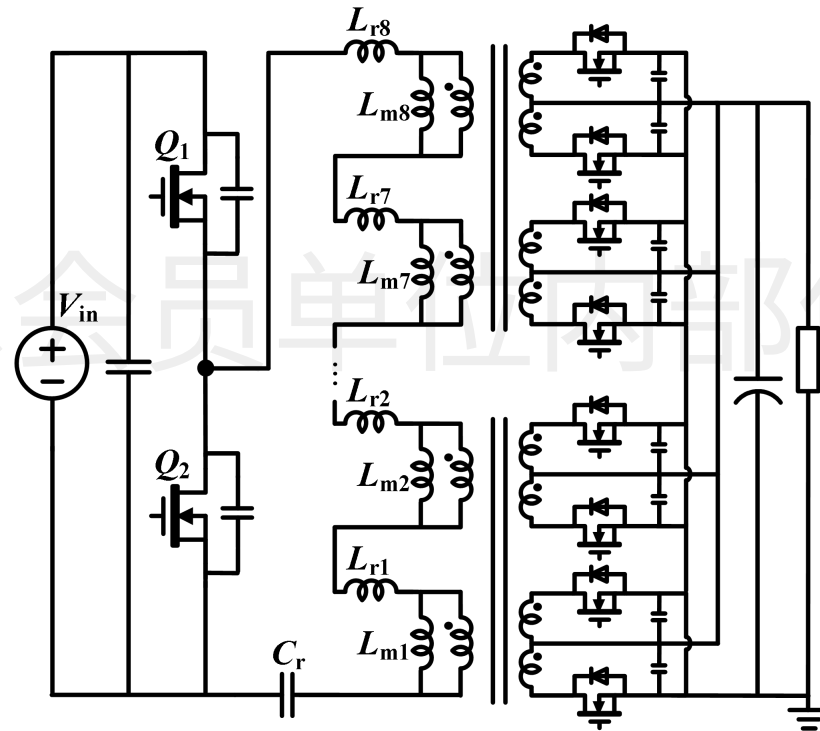


EMI Issue of PCB transformer in MHz DCX

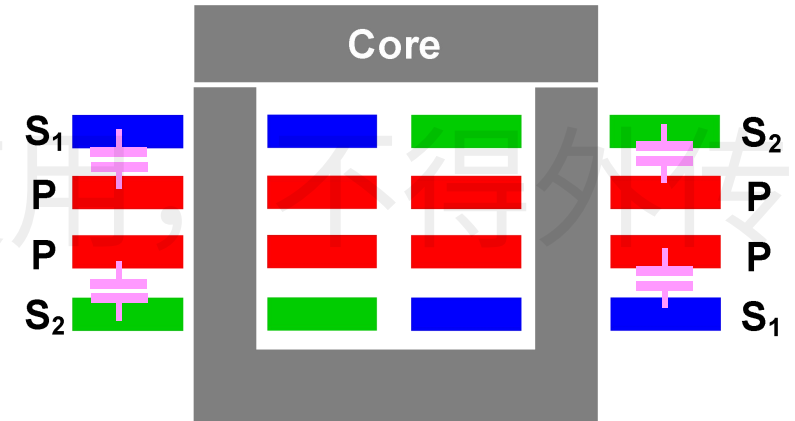
□ Large Inter-winding capacitance



97% 700W/in³



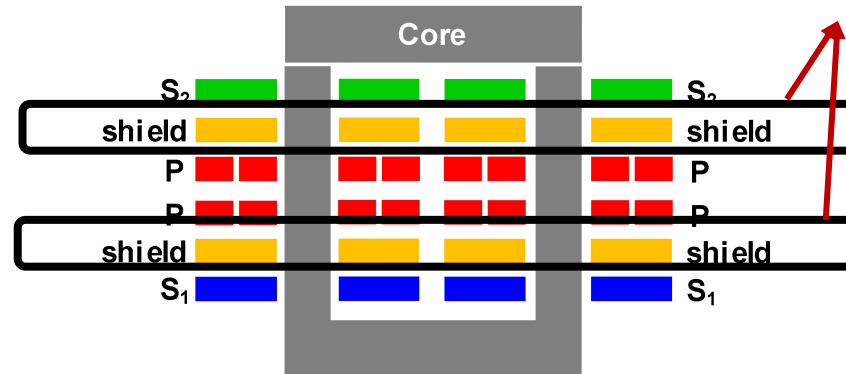
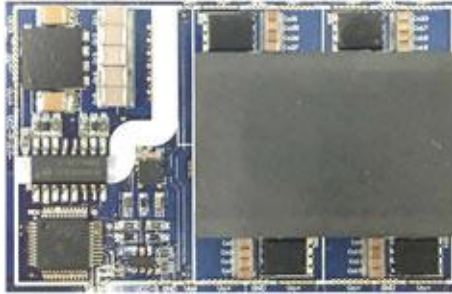
4-core matrix transformer



- ◆ small termination loss
- ◆ slight proximity effect
- ◆ **serious CM noise**

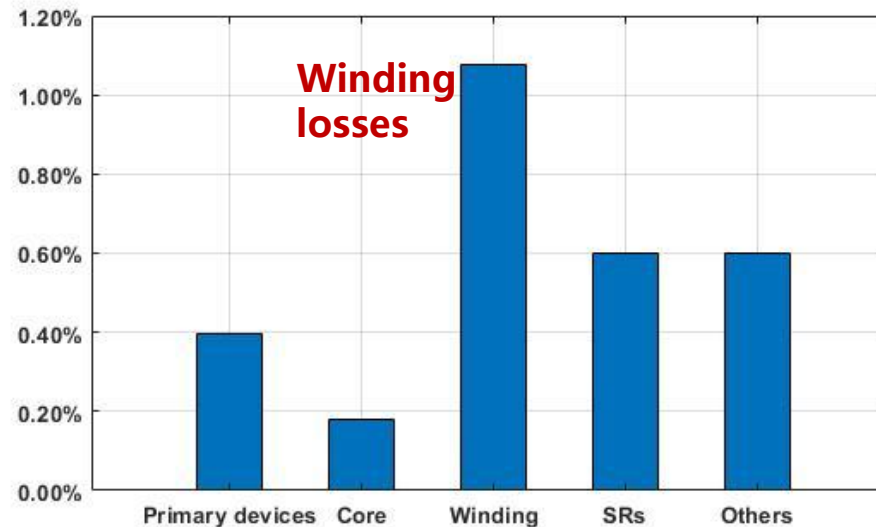
Matrix transformer with shielding layers

Matrix transformer with shielding



97.7% 900W/in³

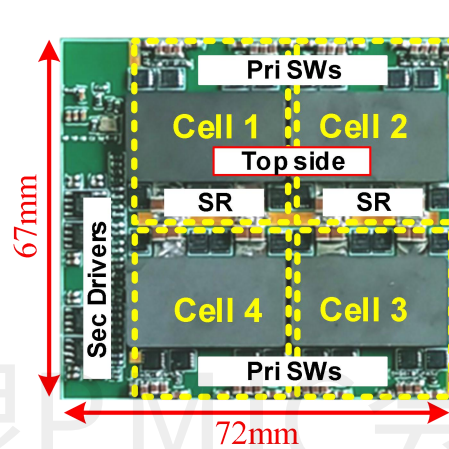
- ◆ small CM noise
- ◆ low winding usage



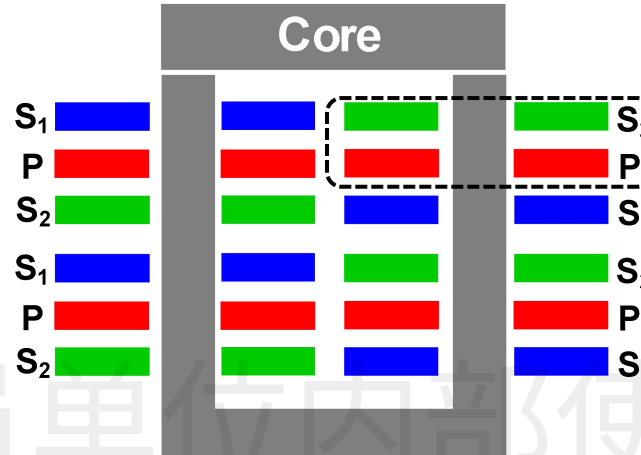
[1] C. Fei, Y. Yang, Q. Li and F. C. Lee, "Shielding Technique for Planar Matrix Transformers to Suppress Common-Mode EMI Noise and Improve Efficiency," in IEEE Transactions on Industrial Electronics, vol. 65, no. 2, pp. 1263-1272, Feb. 2018.

6-layers PCB Transformer

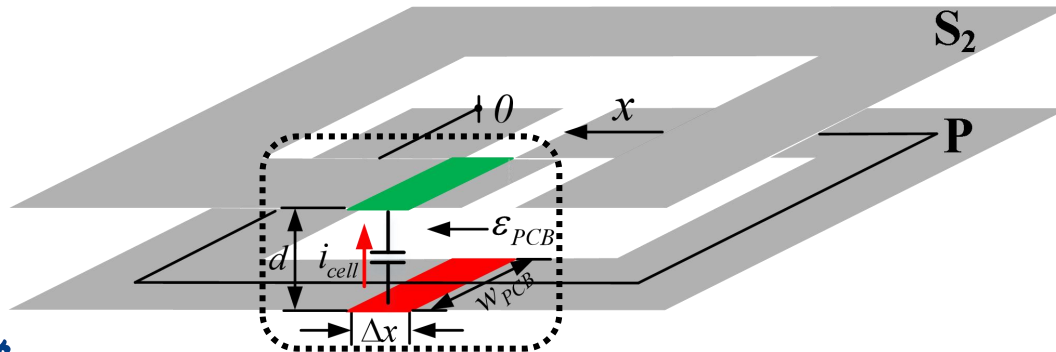
6-layers matrix transformer



Vin: 380
Vo: 12V/150A
Fs: 1MHz



- ◆ full winding usage
- ◆ winding loss reduced

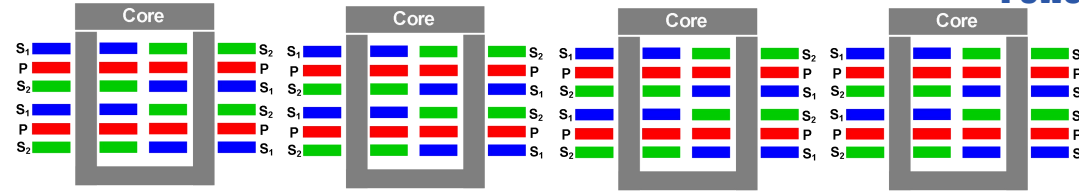


L: the length of winding

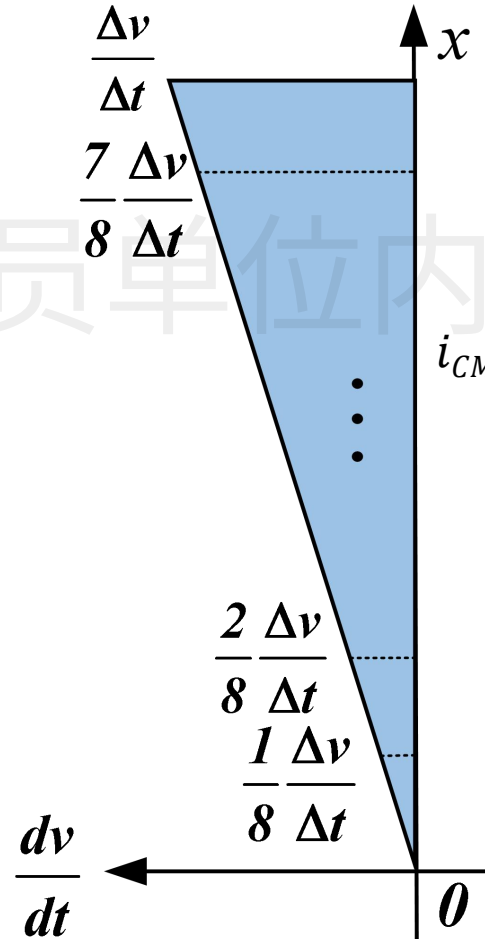
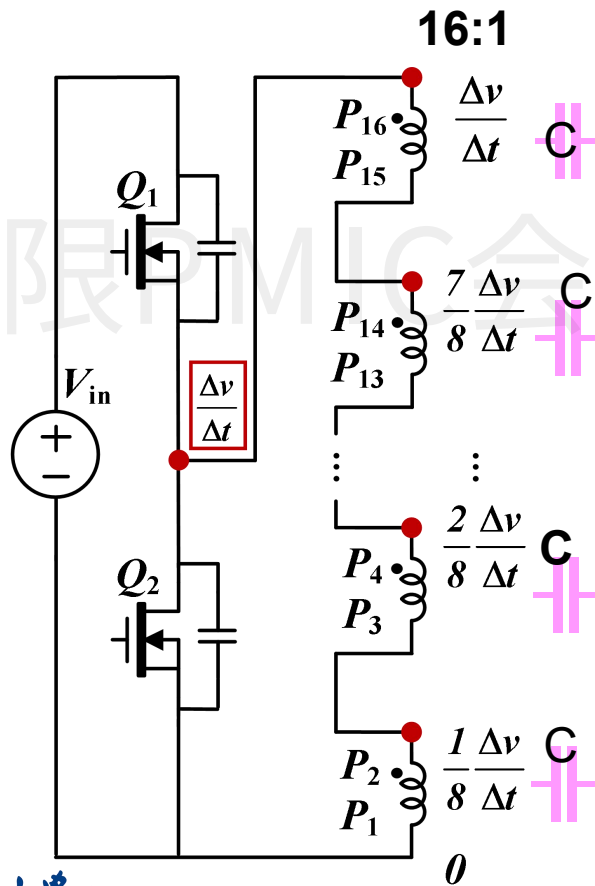
C: the physical layer-to-layer capacitance

$$C_{cell} = \frac{\epsilon_0 \cdot \epsilon_{PCB} \cdot W_{PCB} \cdot \Delta x}{d} = \frac{C}{L} \Delta x$$

i_{CM} in conventional GaN scheme

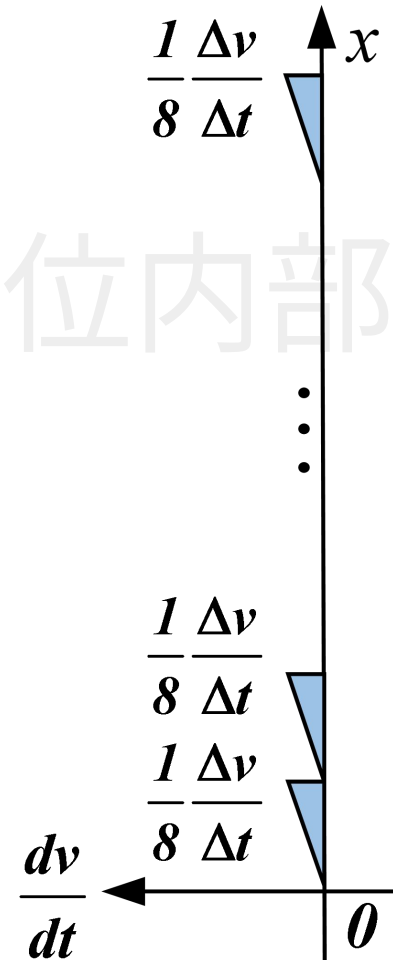
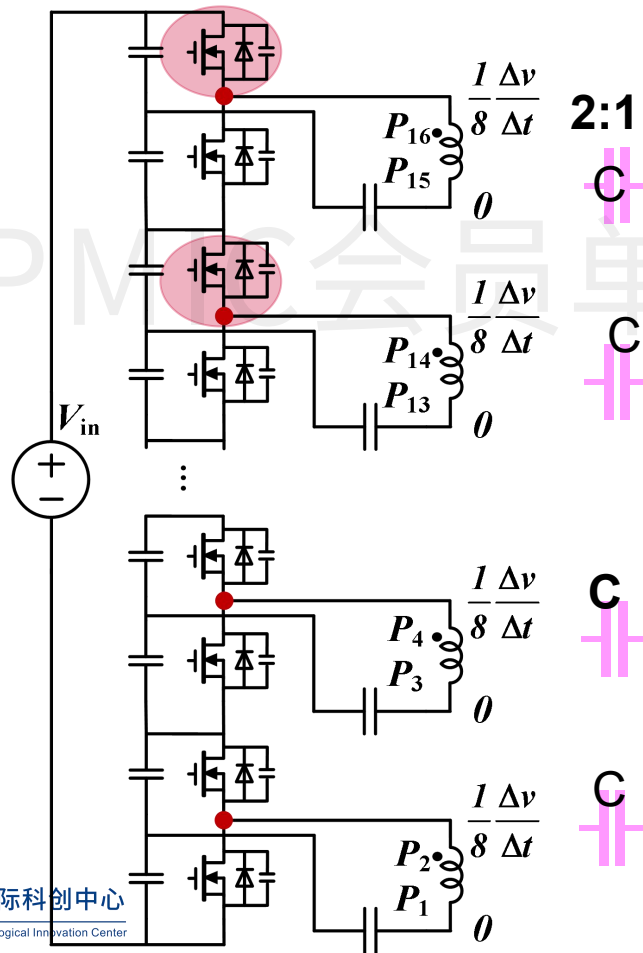


Conventional scheme



Total CM current

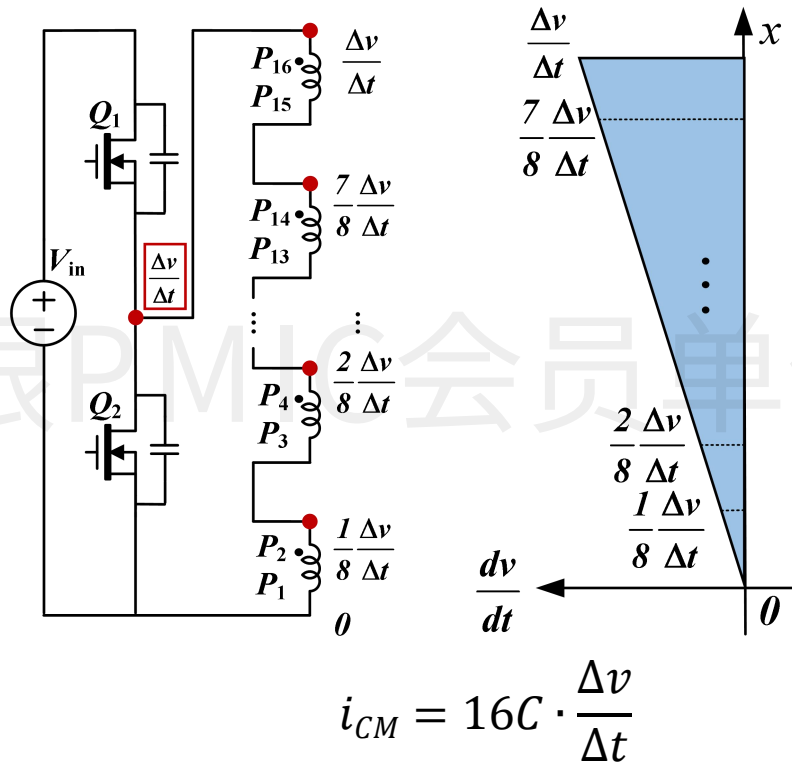
$$i_{CM} = \left(2C \cdot \frac{0 + \frac{1}{8} \frac{\Delta v}{\Delta t}}{2} + 2C \cdot \frac{\frac{1}{8} \frac{\Delta v}{\Delta t} + \frac{2}{8} \frac{\Delta v}{\Delta t}}{2} \right. \\ \left. + \dots + 2C \cdot \frac{\frac{7}{8} \frac{\Delta v}{\Delta t} + \frac{\Delta v}{\Delta t}}{2} \right) \cdot 2 \\ = 16C \cdot \frac{\Delta v}{\Delta t}$$


$$i_{CM}' = 2C \cdot \frac{0 + \frac{1}{8} \frac{\Delta v}{\Delta t}}{2} \cdot 8 \cdot 2$$

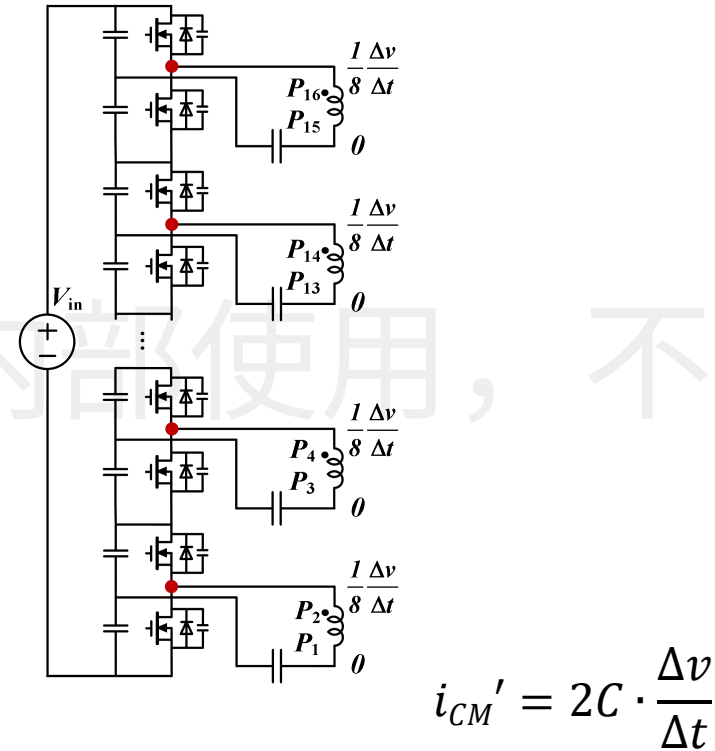
$$= 2C \cdot \frac{\Delta v}{\Delta t}$$

Single switch VS. input-series

single high switch scheme



Multi-switch Input-series scheme



$$i_{CM}' = \frac{1}{8} i_{CM}$$

$$20 \log \left(\frac{i_{CM}'}{i_{CM}} \right) = -18dB$$

CM current has 18dB reduction

Experimental Comparison

Conventional



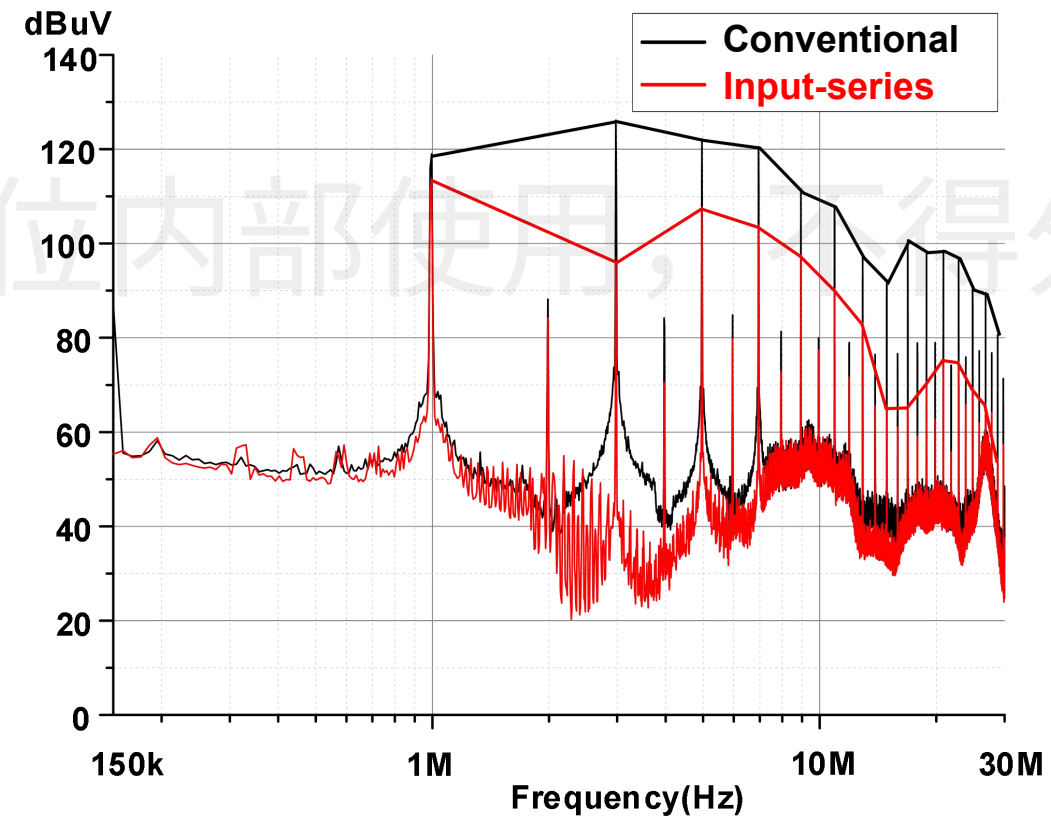
600V GaN

Identical PCB winding structure

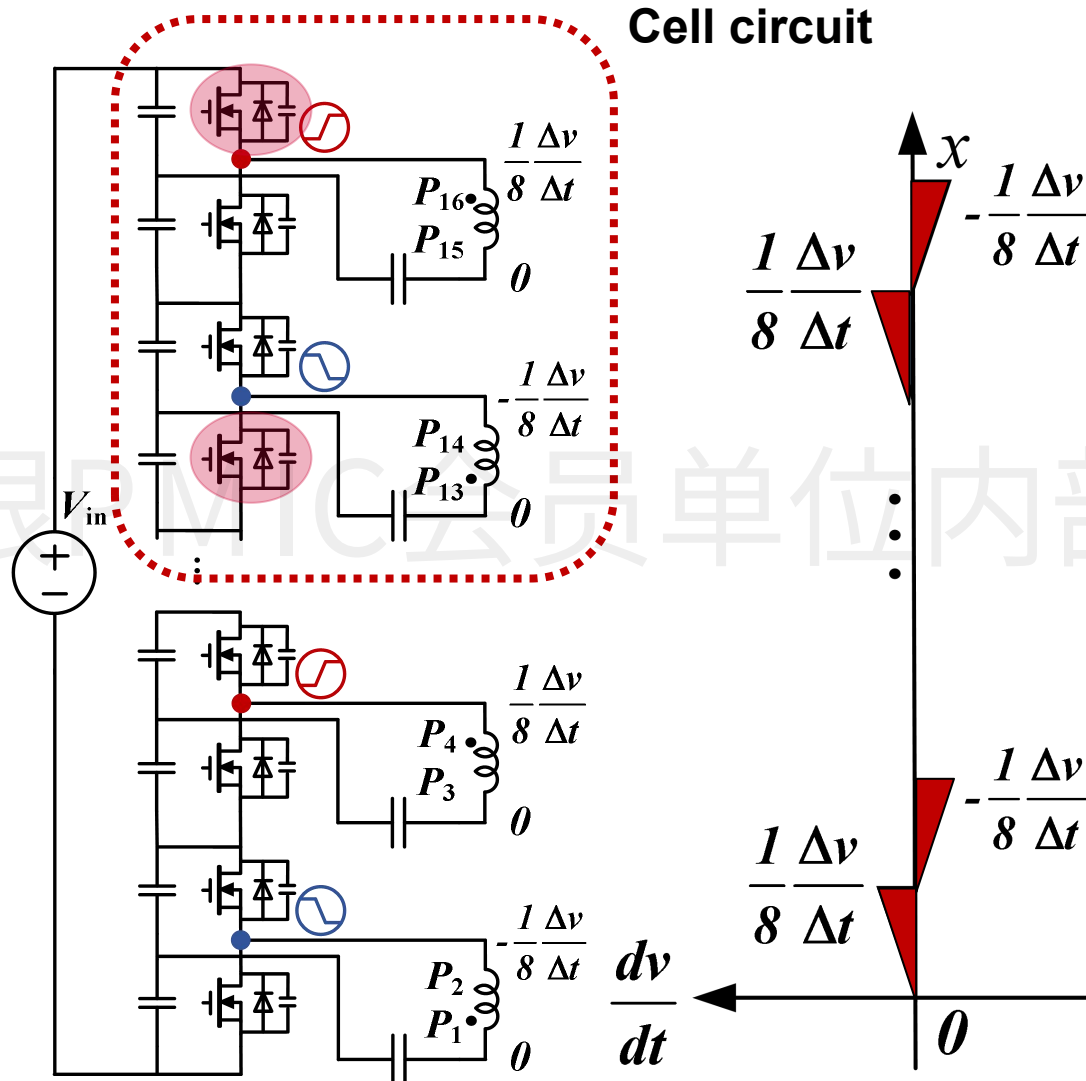


80V Si

Average **20dB** reduction
within test frequency range



Complementary control scheme in Cell



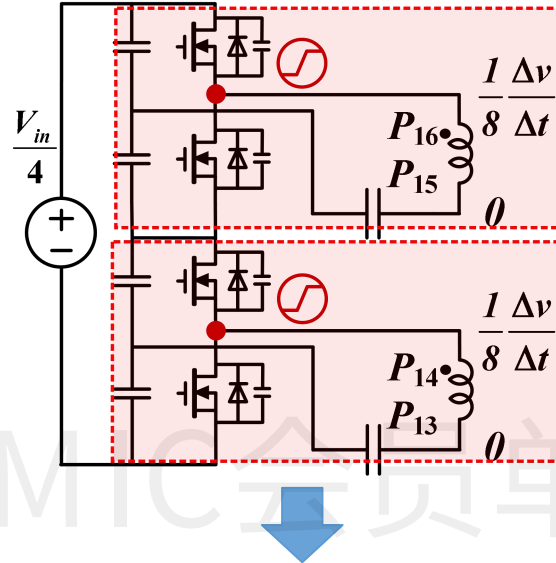
Total CM current

?

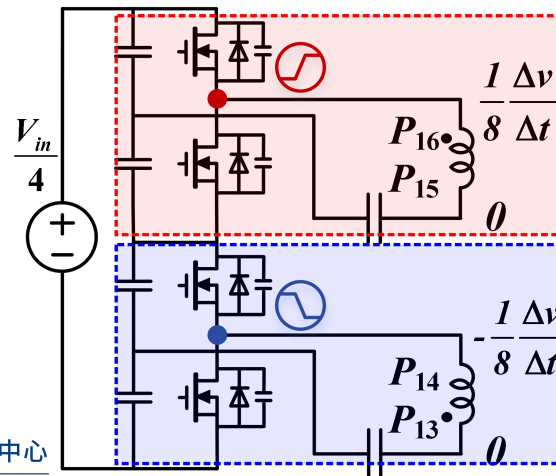
Cancellation?

Experimental result

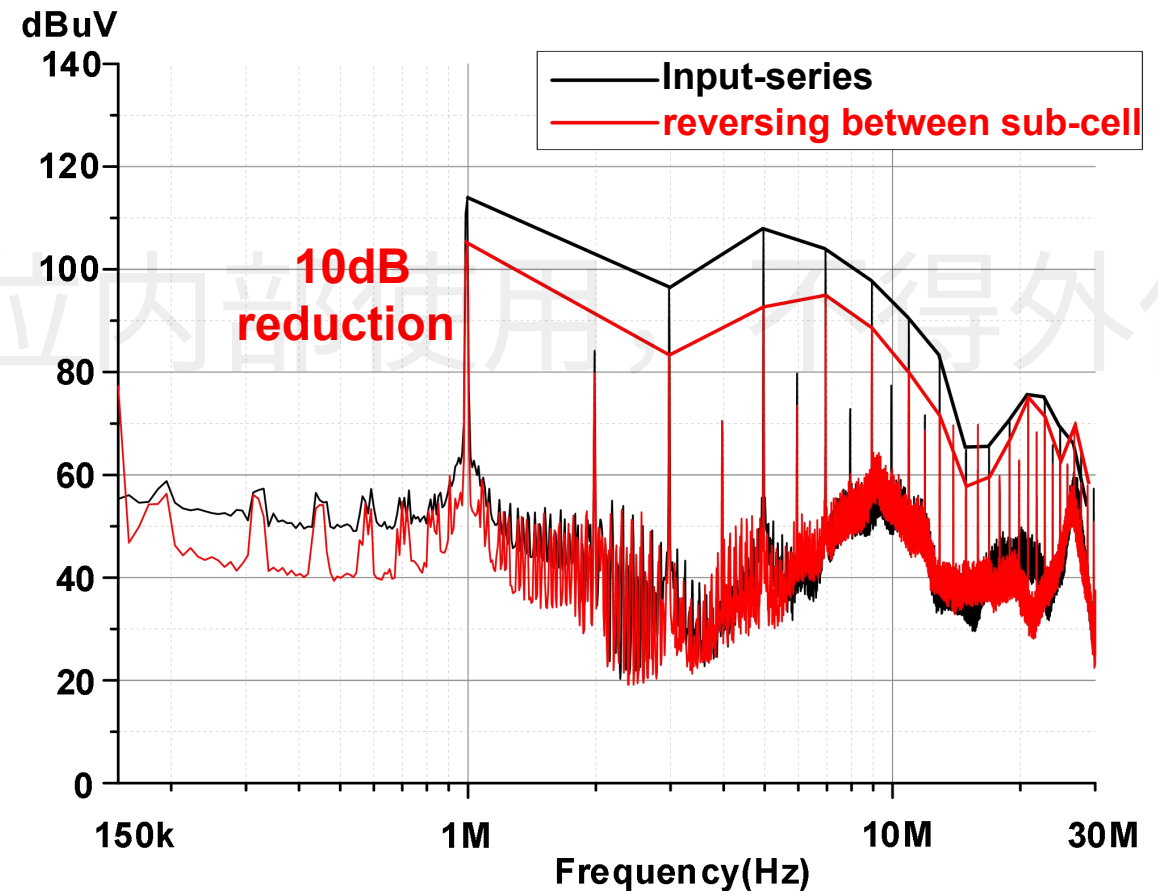
Input-series



interleave within each cell

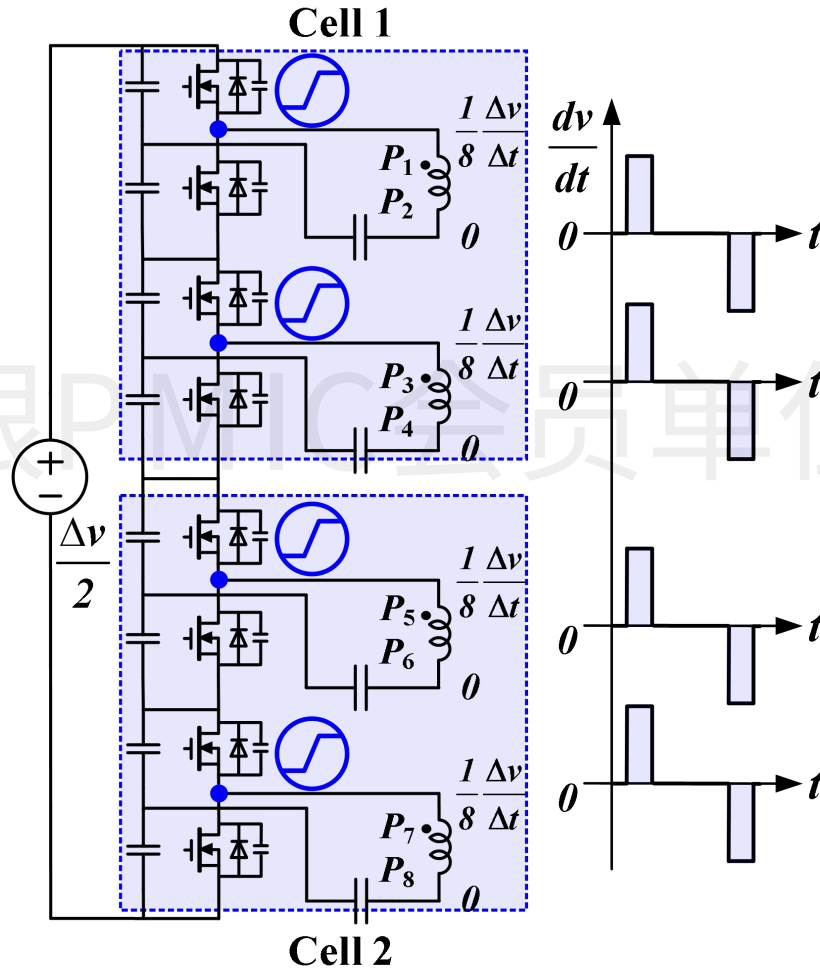


Asymmetry traces in cell PCB
transformer deteriorate the cancellation

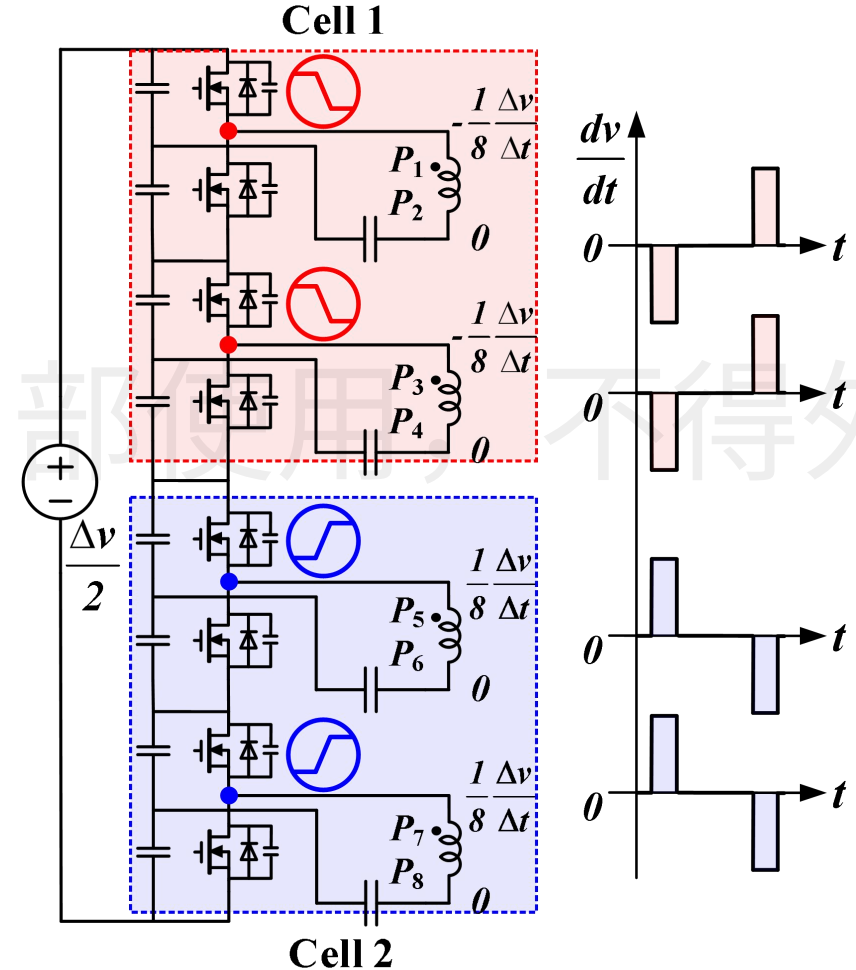


Optimization of control scheme (2)

Input series scheme

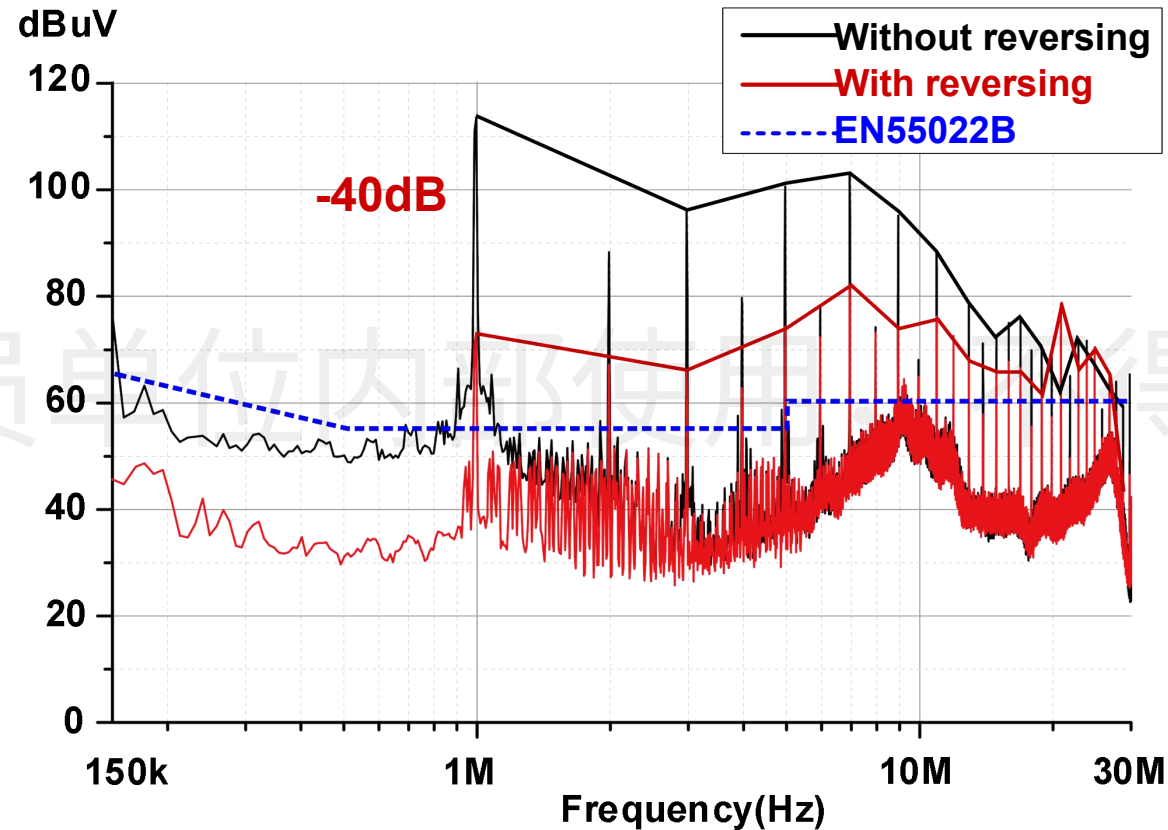
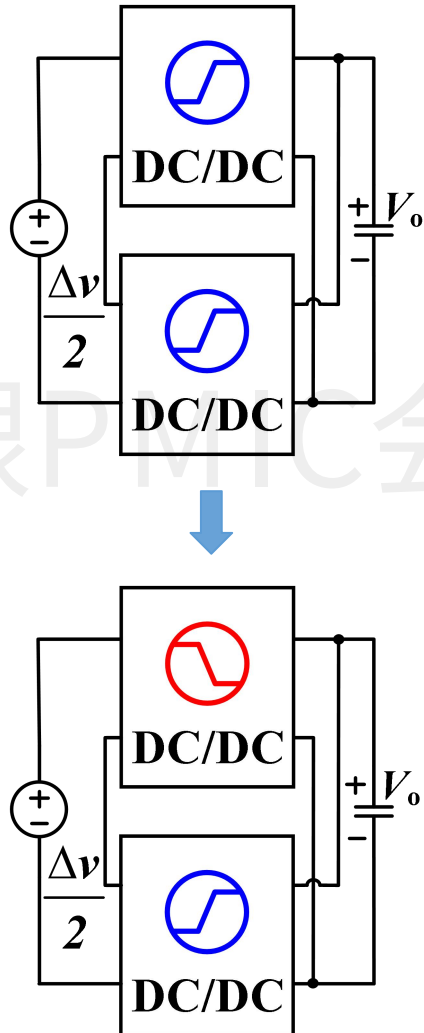


interleave between cells



cancellation effect on CM noise

Symmetry PCB transformer of cells

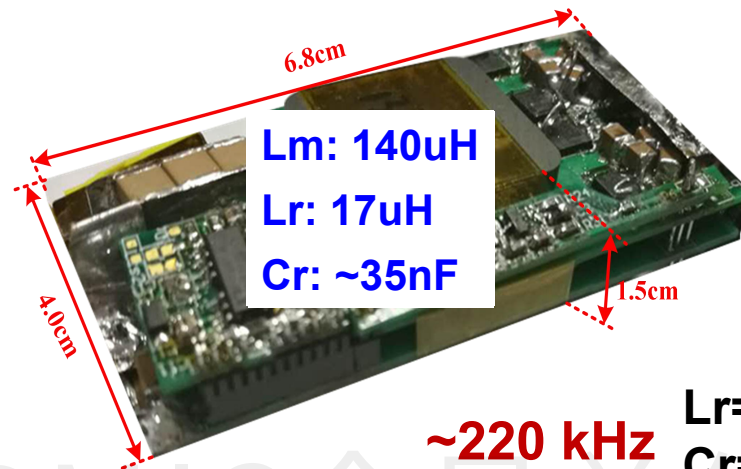


40dB reduction
at fundamental frequency

3.3 Tight regulated 380V-48V/12V conversion

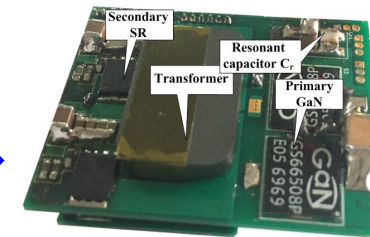


Frequency Control MHz LLC

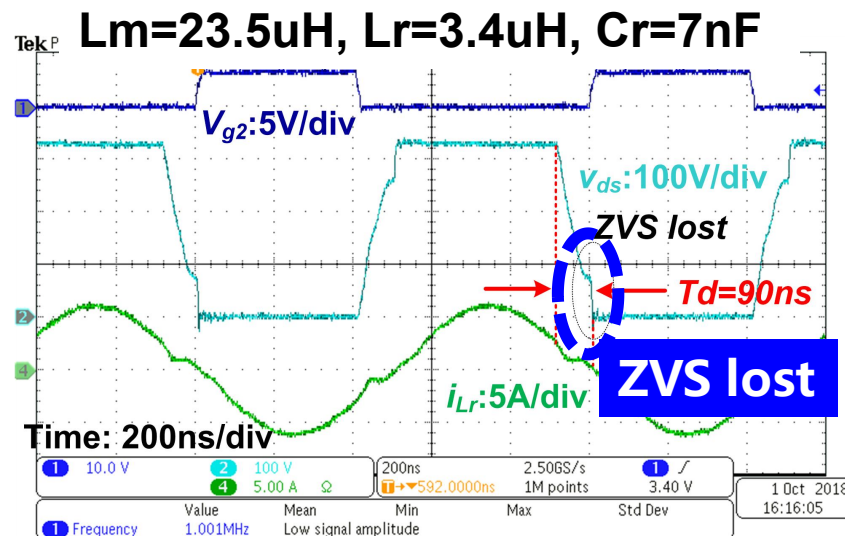


360-400V
input **12V/62A**
output
(750W)

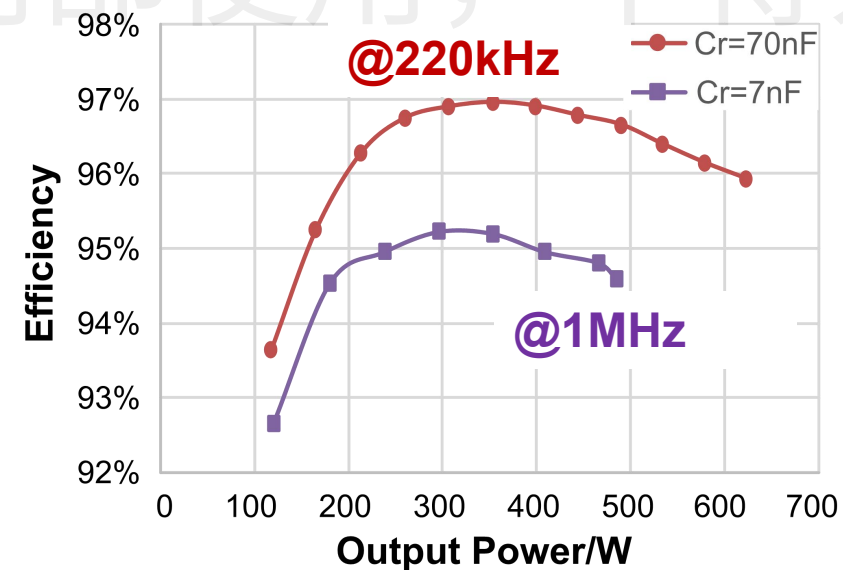
The Same Q



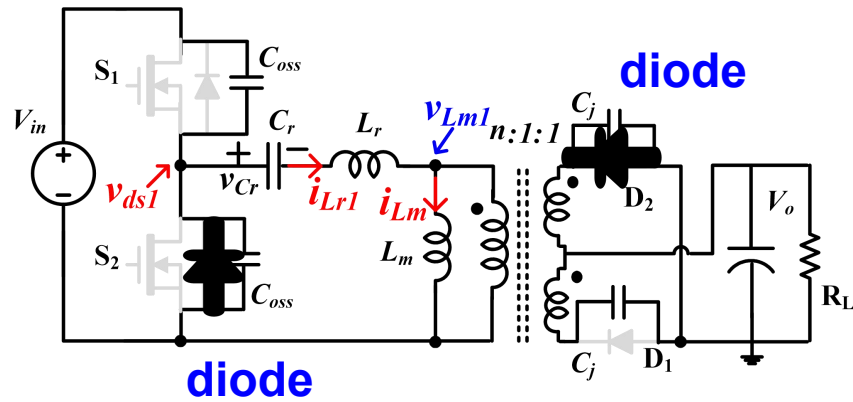
Lr=3.4uH, Cr=7nF @1MHz



@ 500W

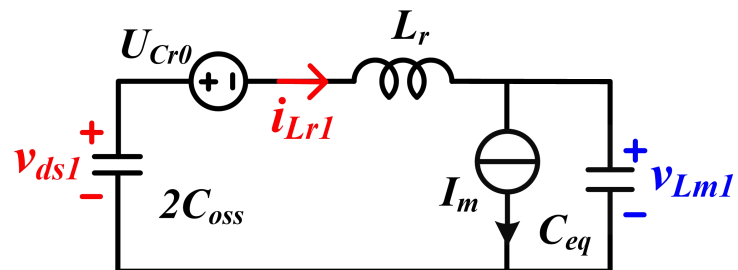


Issue 1: SR Voltage Transition Bypassing magnetizing current

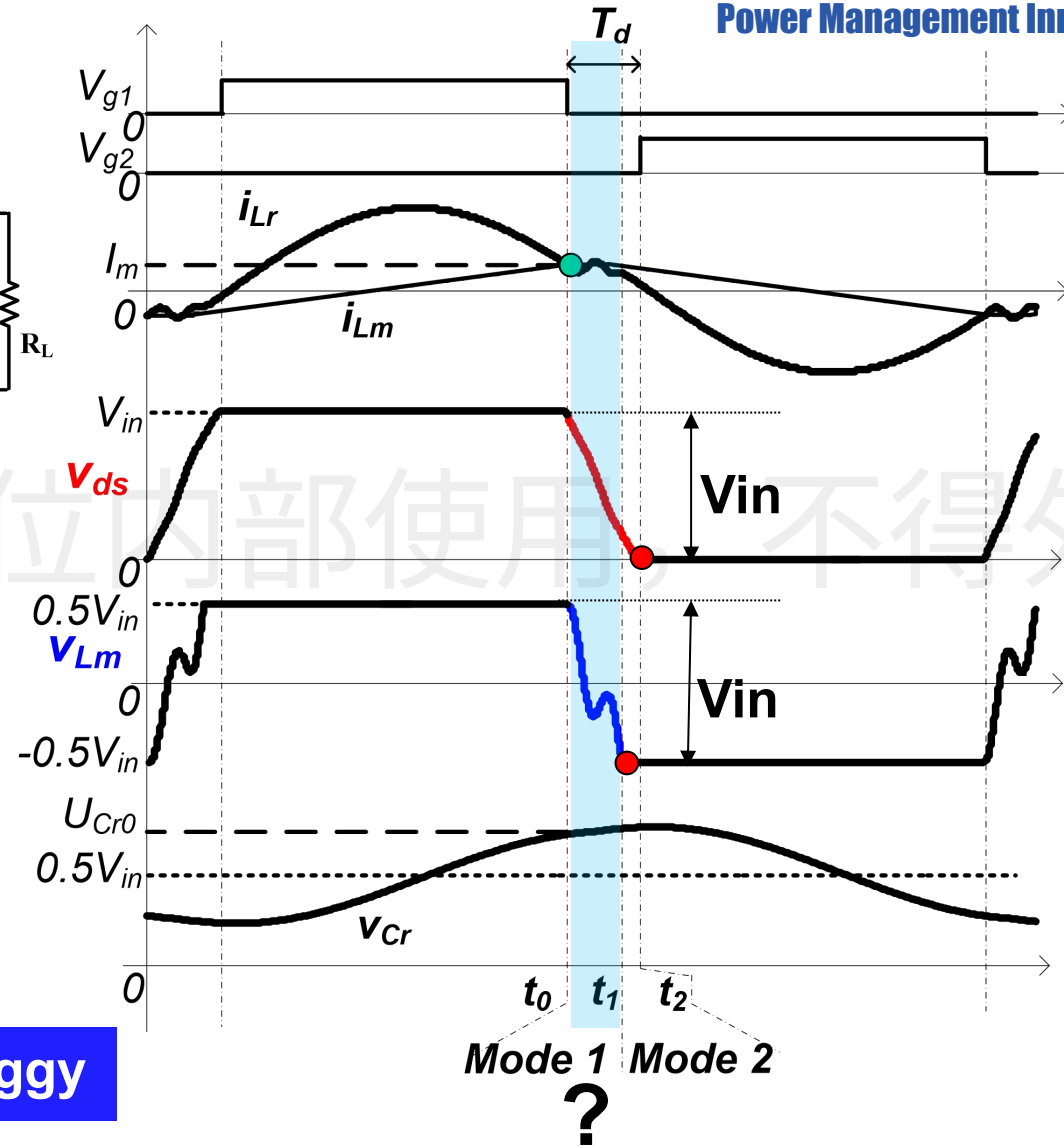


$$L_m \gg L_r$$

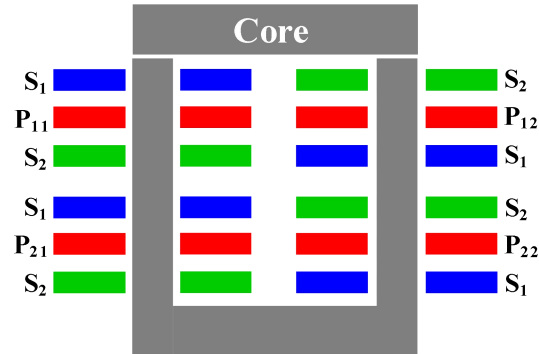
$$C_r \gg C_{oss} \text{ \& } C_{eq} \quad C_{eq} = 2C_j/n^2$$



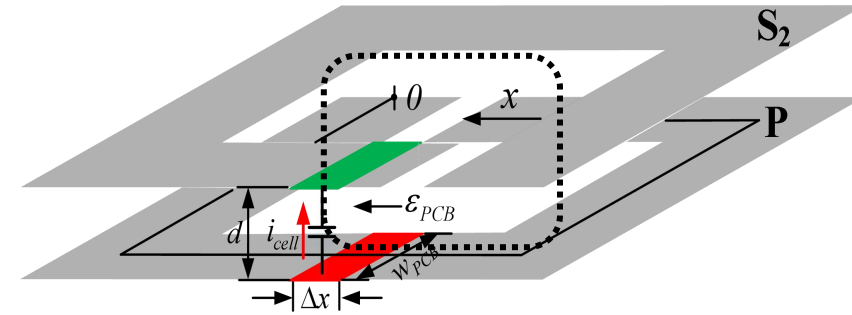
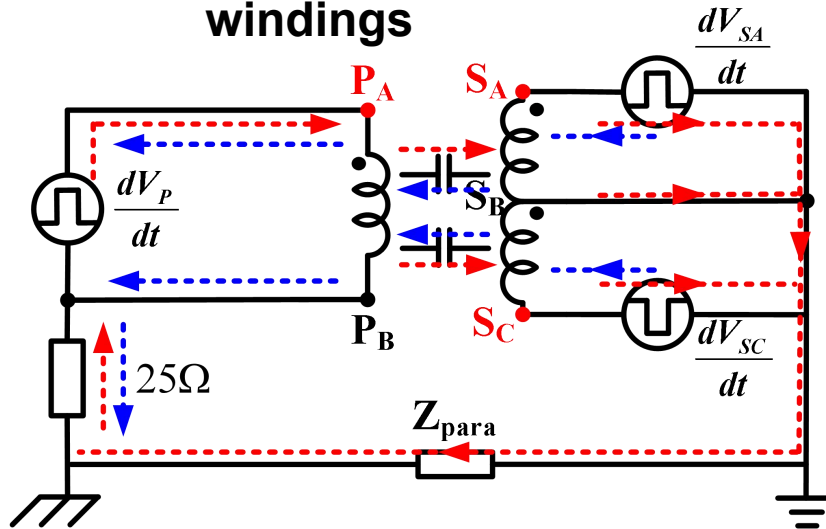
Lower L_r leads to less energy



Issue 2: Inter-capacitance sink magnetizing current



CM current between PCB windings



L: the length of winding

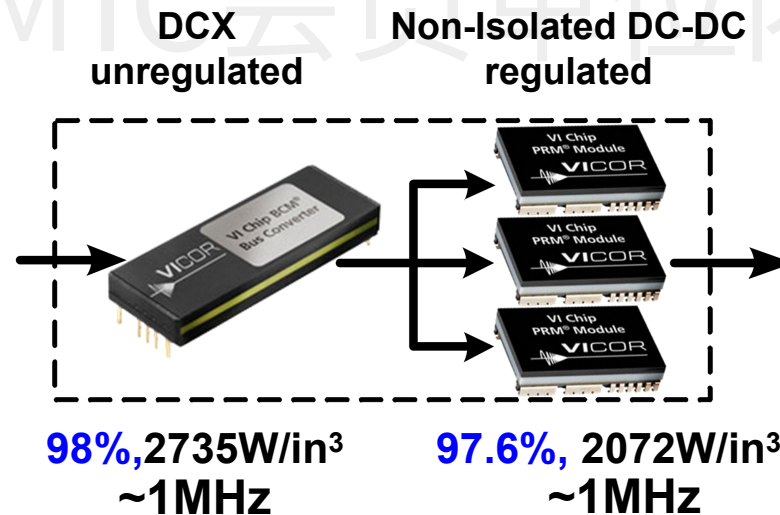
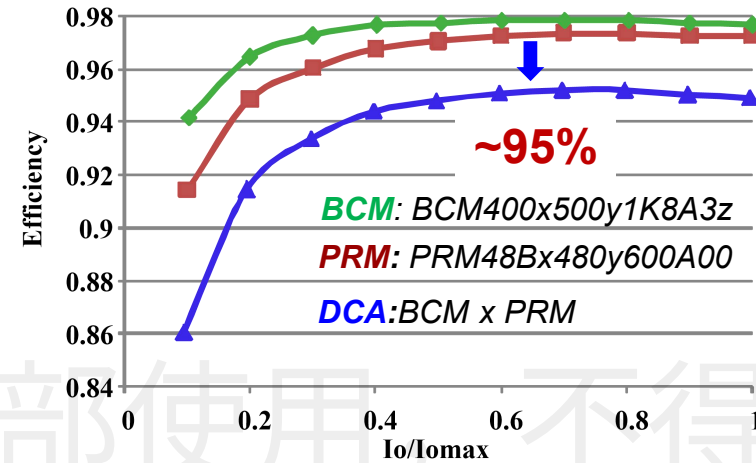
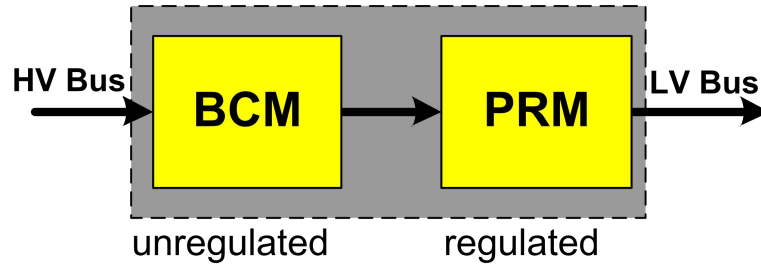
C: the physical layer-to-layer capacitance

$$C_{cell} = \frac{\epsilon_0 \cdot \epsilon_{PCB} \cdot W_{PCB} \cdot \Delta x}{d} = \frac{C}{L} \Delta x$$

PCB intra-winding capacitance sinks magnetizing current

Two stage efficiency sacrifice

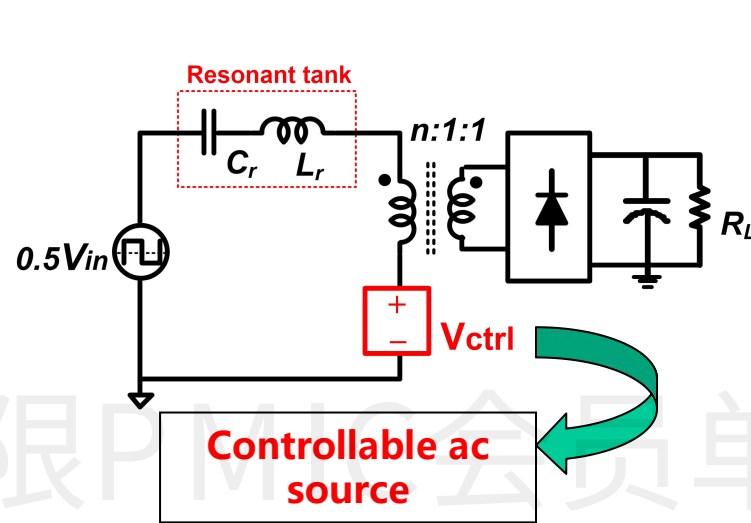
□ Two-stage for on-board power module



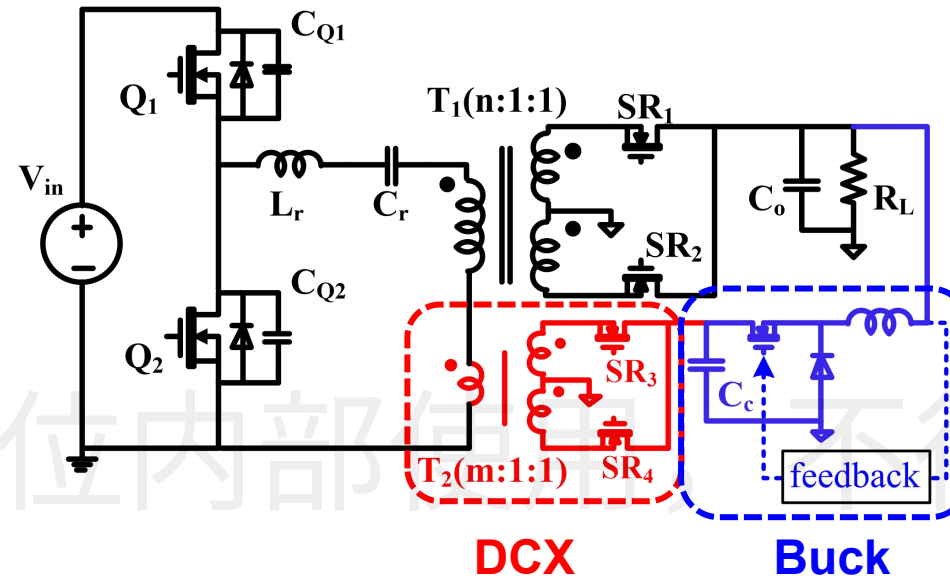
Efficiency decrease

Source: BCM400x500y1K8A3z
PRM48Bx480y600A00

□ AC series/ DC parallel



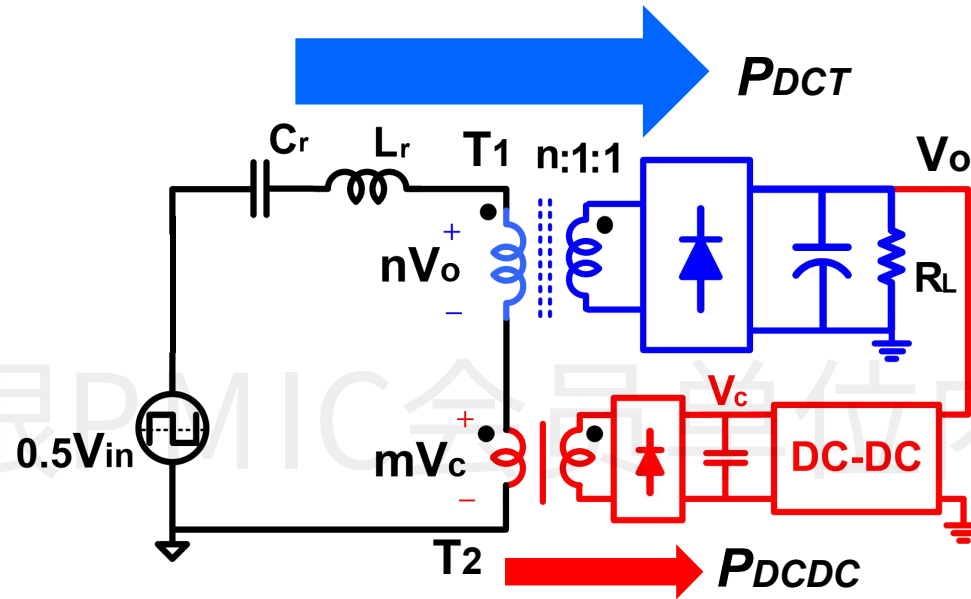
☺ Tight regulated
(Quasi-single stage)



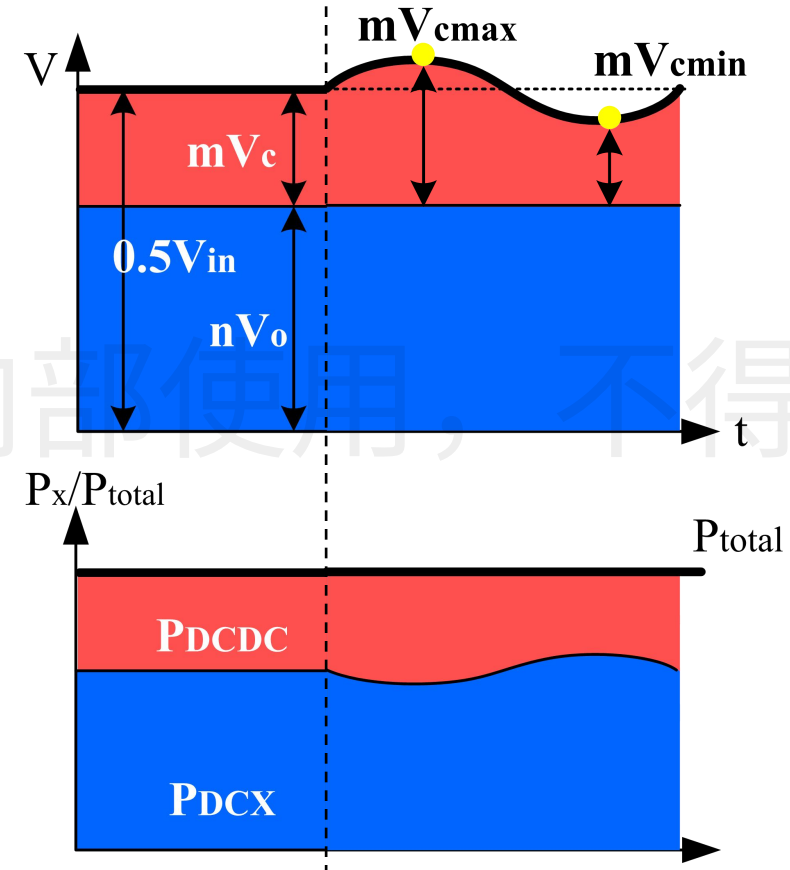
DCX & D2D non-synchronous

- ☺ Fixed switching frequency for resonant converter
- ☺ Simple PWM controller to regulated output
- ☺ High frequency, high efficiency
- ☺ The frequency of PWM is independent to DCX

RDCX Operating Principle

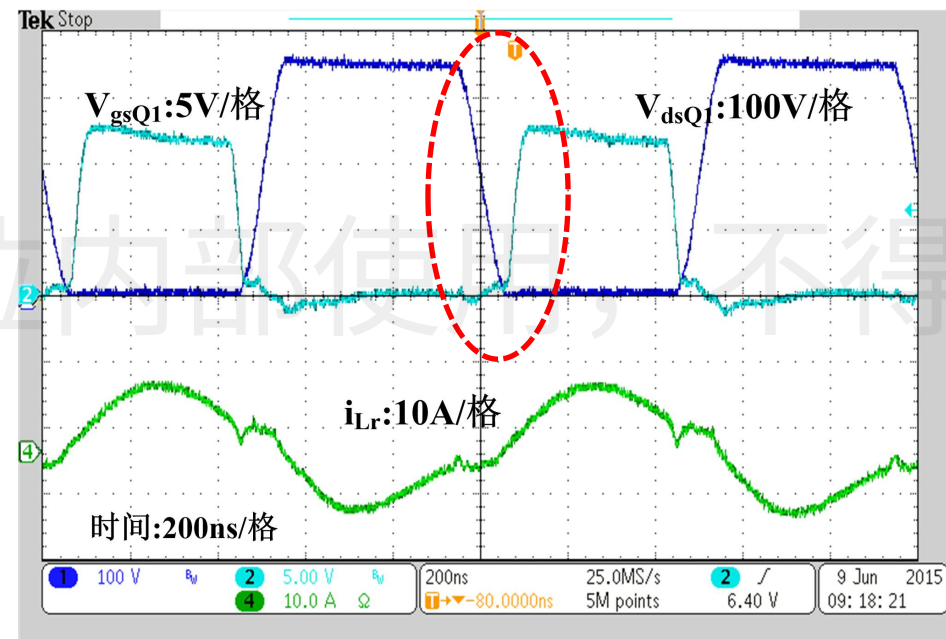
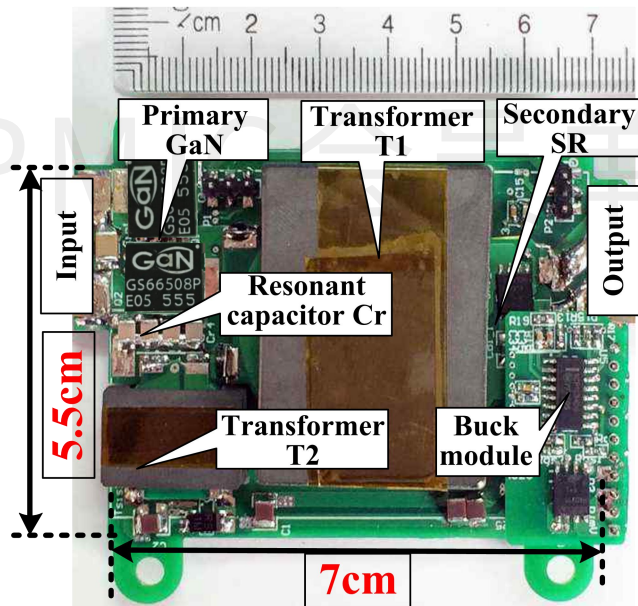


$$k = \frac{P_{dcdc}}{P_{total}} = \frac{mV_c}{mV_c + nV_o}$$



Prototype and Key waveforms

V_{in} : 350-380VDC
 f_s : 1MHz
 V_o : 40V/25A (1kW)
Density: $\sim 700\text{W}/\text{in}^3$

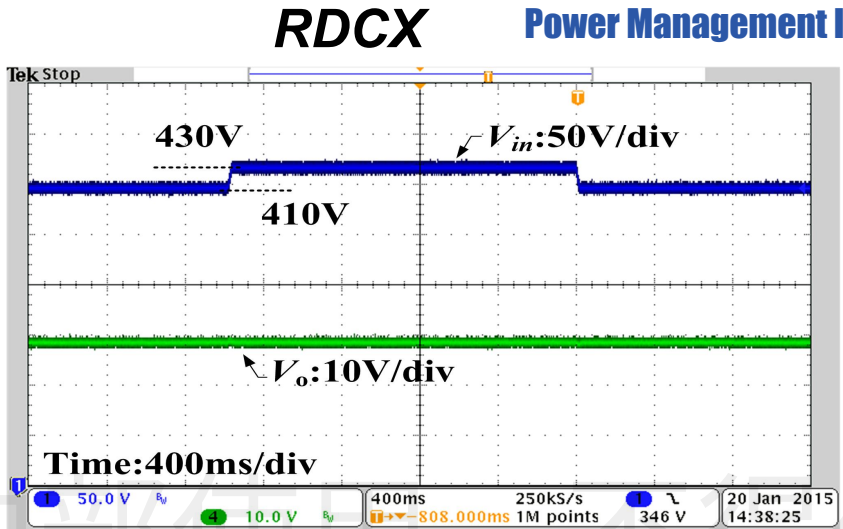
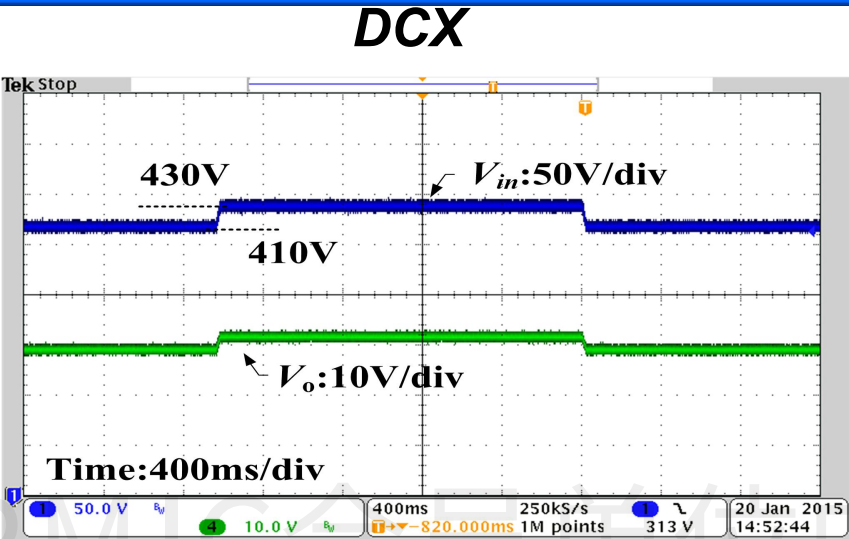


Full load, $I_o=25\text{A}$

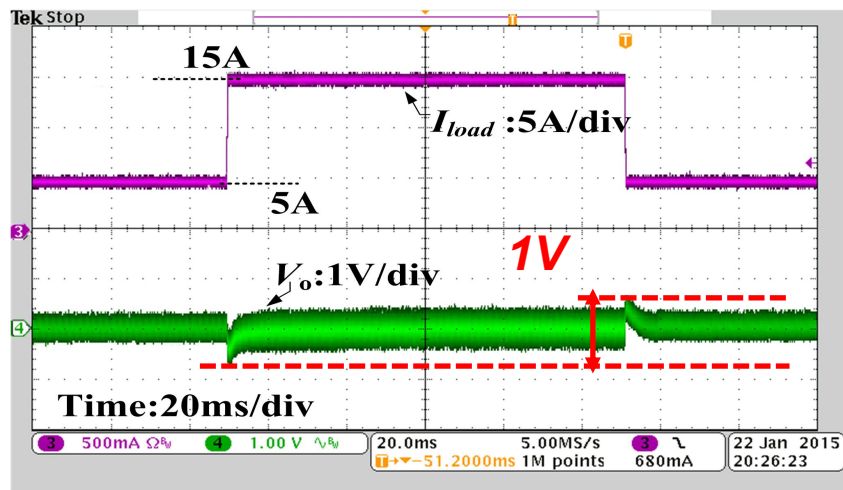
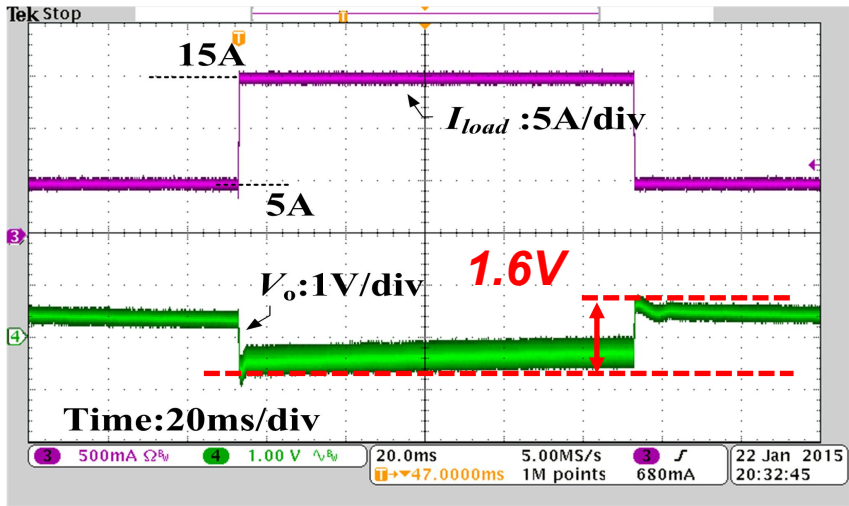
(year: 2015)

Prototype of RDCX

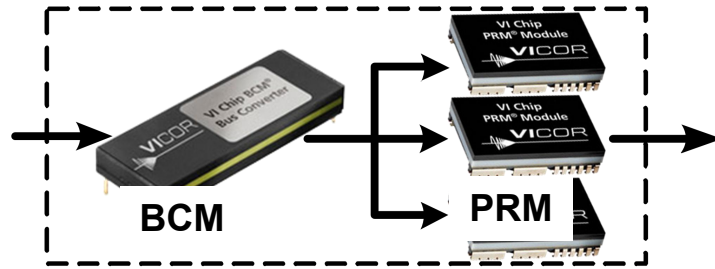
Tight regulating capability of RDCX



➤ **Vo tight regulation with load jump**

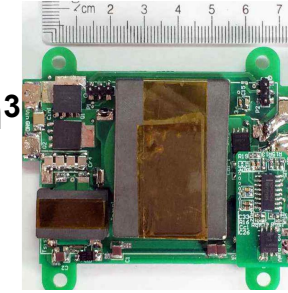


Comparison between RDCX and two stage

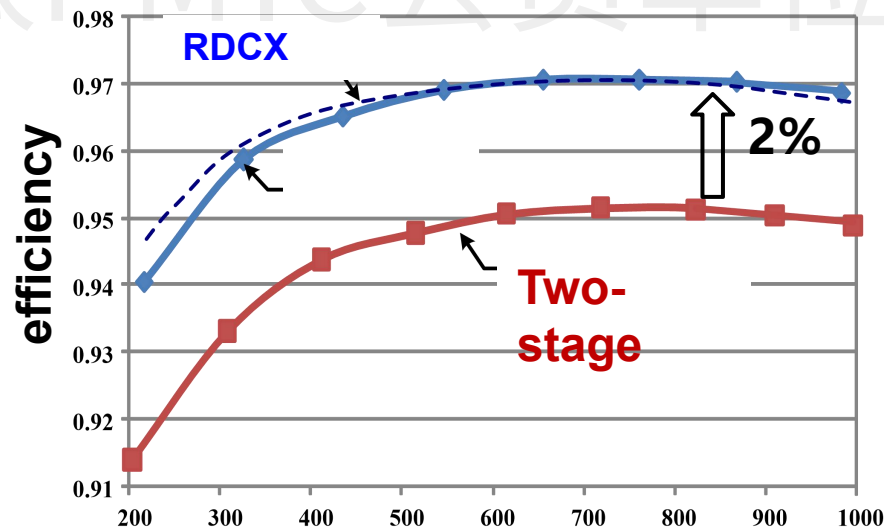


Two-stage
scheme

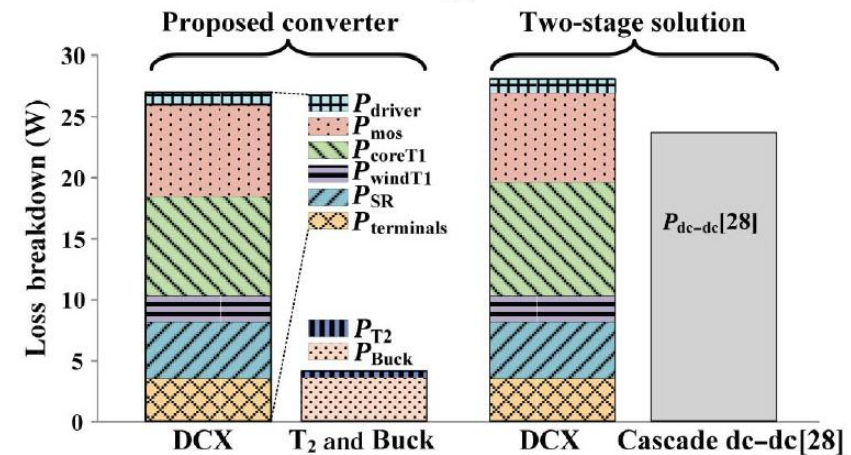
Density: $>700\text{W}/\text{in}^3$
 $\sim 1\text{MHz}$



Proposed 380V-40V
RDCX

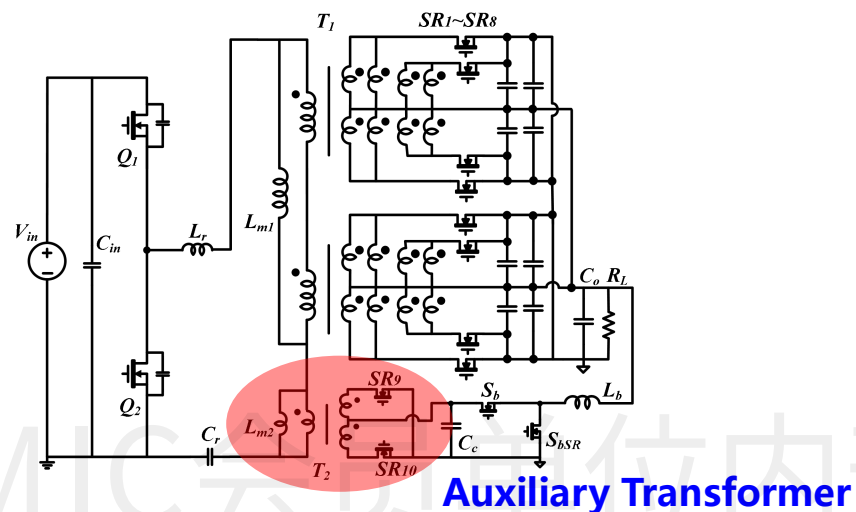


(a) Measured efficiencies vs.
commercial two-stage products

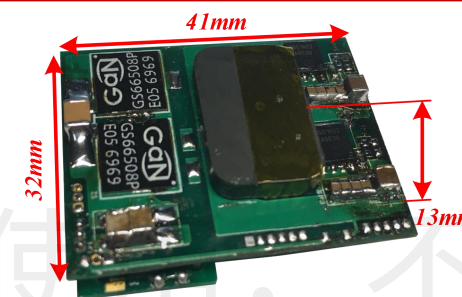


(b) Loss Breakdown

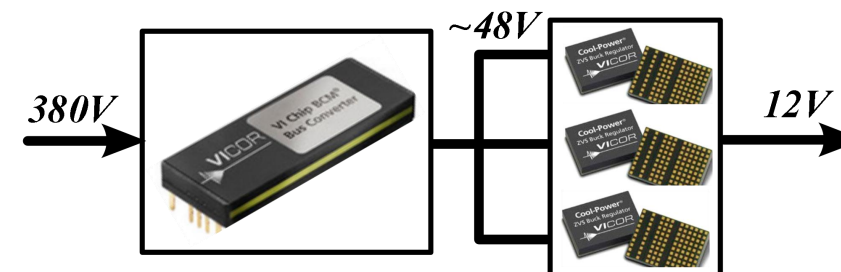
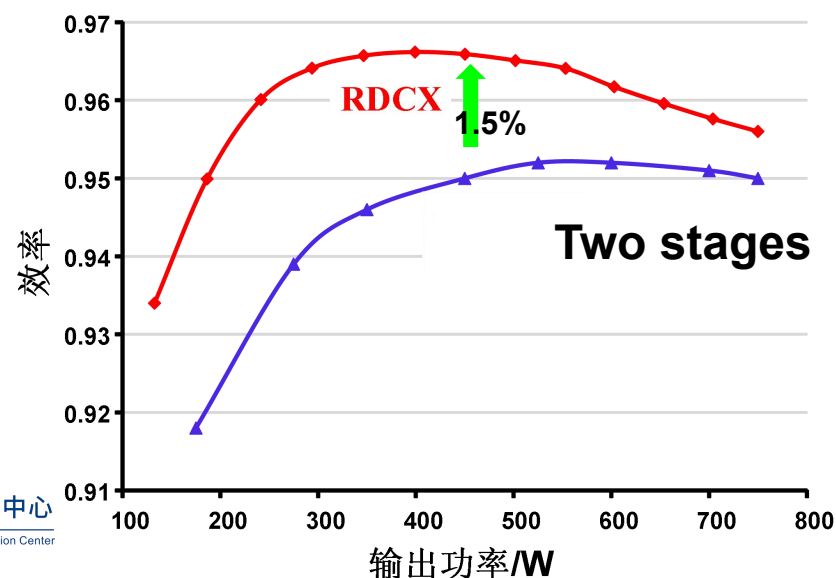
380V-12V RDCX verification



V_{in} : 340V-380VDC;
 V_o : 12V/65A
 f_s : 1MHz



RDCX Density: 720W/in³



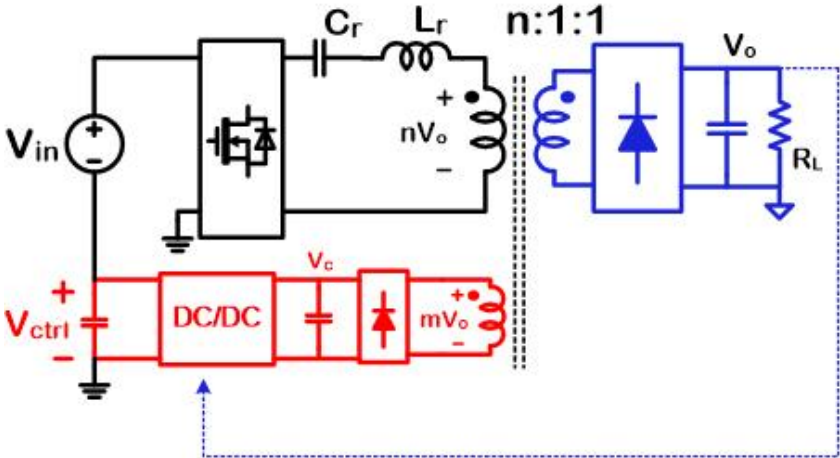
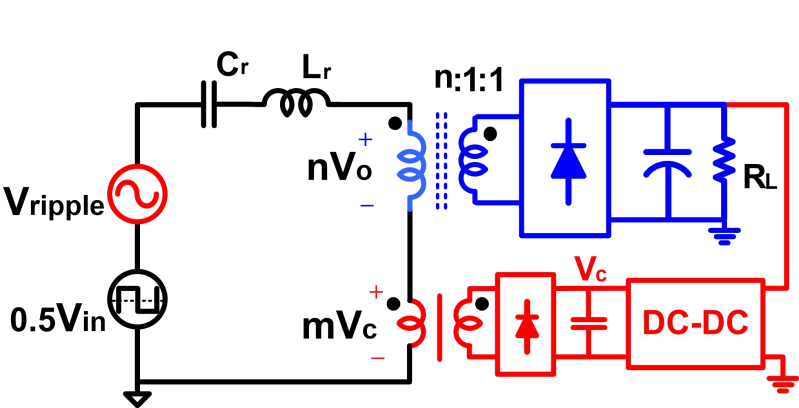
Two stages density: 560W/in³

Ref: BCM6123xD1E5117yzzPI3526-00-LGIZ

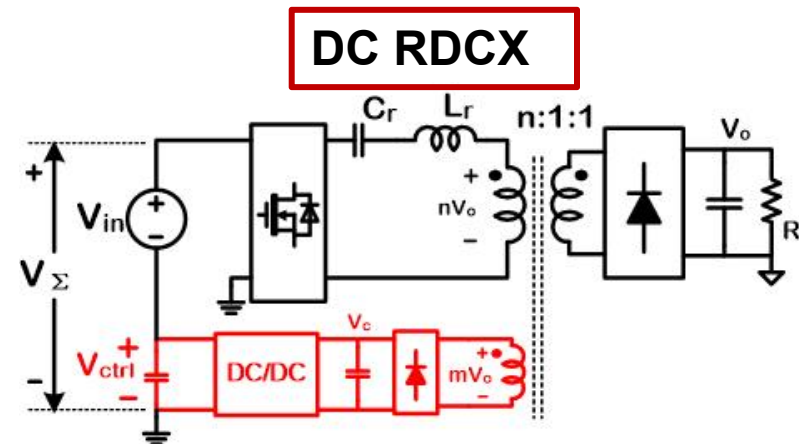
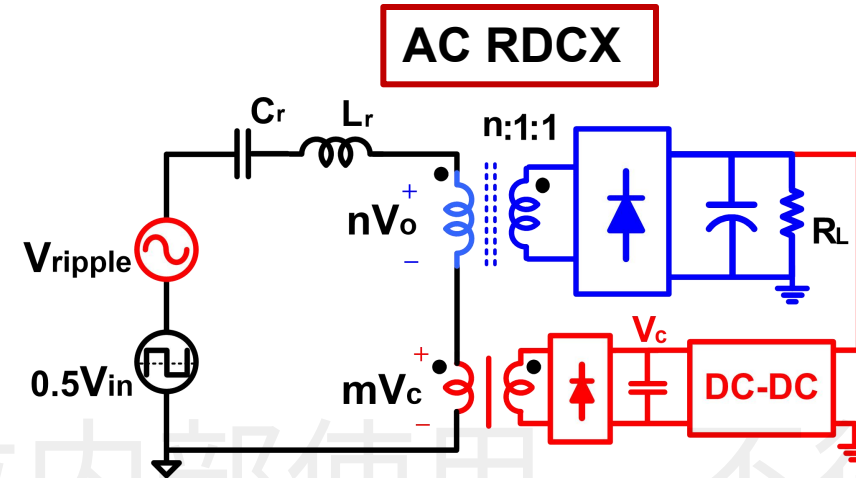
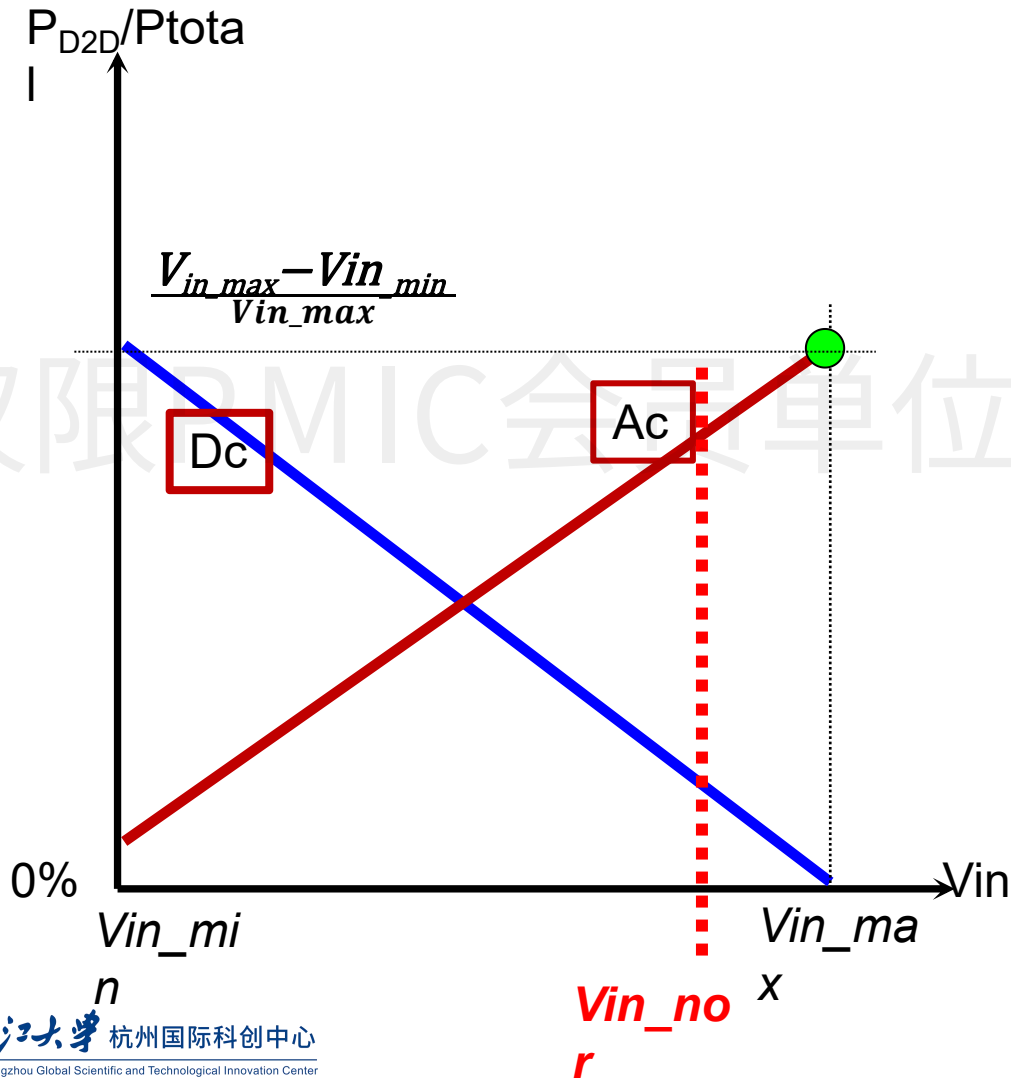
Stresses Comparison among Two RDCXs and LLC

Main power stage stresses

	LLC	AC series	DC series
Voltage stress	V_{in_max}	V_{in-max}	$N \cdot V_o \approx V_{in-max}$
Current stress	$\frac{\pi \cdot P_{o\ max}}{2V_{in\ min}} \cdot \frac{f_r}{f_{s\ min}}$	$\frac{\pi \cdot P_{o\ max}}{2V_{in\ min}}$	$\frac{\pi \cdot P_{o\ max}}{2V_{in\ min}}$



D2D Power Comparison between Two RDCXs



- ❑ **High voltage DCX using Low NFoM device in stead of high voltage switch**
 - ❑ **Achieving MHz High frequency and high efficiency**
 - ❑ **Low common mode EMI**
 - ❑ **Reduced conduction loss and flexible output**
- ❑ **Regulated DCX (RDCX) instead of two-stage scheme**
 - ❑ **MHz high efficiency dc-dc with regulating capability**
 - ❑ **Fixed switching frequency for DCX and PWM converter**
 - ❑ **Most power is transferred to load by DCX, small portion power is transferred to load by two stage.**

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1. The ZVS on and ZCS off for MHz DC-DC converter are necessary ,whatever for 48 or 380V applications.
2. Single switch DCX topologies are preferred for low power (<100W) low voltage application at MHz frequency.
3. The topologies for ZVSZCS MHz DCXs can be derived by integrating unidirectional resonant tanks.
4. The tight regulation of the MHz converter can be implemented by partial voltage (power) regulation.
5. The partial voltage(power) regulation topology (RDCX) can be derived according to the inserting points of two-ports network structure. Different RDCX topologies have different suitable voltage range and different nominal operating points.
6. Cellular circuit structure with low voltage MOSFETs can be utilized to improved the switching frequency and efficiency for high voltage applications at MHz frequency.

***Thank You _{for}
Your Attention***

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