DC Injection Criteria for PV Systems & Inverter Designs

Karl M.H. LAI (3035273084)

Note:
Some of referred paper are not published. This PowerPoint is ONLY for internal use.

What matters?

Shayestegan, M. et al (2018), An Overview on Prospects of New Generation Single-Phase Transformerless Inverters for Grid-Connected Photovoltaic (PV) Systems

- IEEE 1547-2018 requires grid-connected inverter system shall not inject DC current >0.5% of full rated output current.

Summary of two prominent standards in grid-connected PV systems

Issue	IEEE1547	IEC61727
Nominal power	30 kW	10 kW
Maximum current THD	5%	5%
Power factor at 50% of rated power	–	0.9
DC current injection	Less than 0.5% (rated output current)	Less than 0.1% (rated output current)
Voltage range (normal operation)	88–110% (97–121 V)	85–110% (196–253 V)
Frequency range (normal operation)	59.3–60.5 Hz	50 ± 1 Hz

Denmark requires **HPFI Relay-30mA**; Italy, Japan, UK, US, Switzerland requires **DC detection device** with inverter disable required.

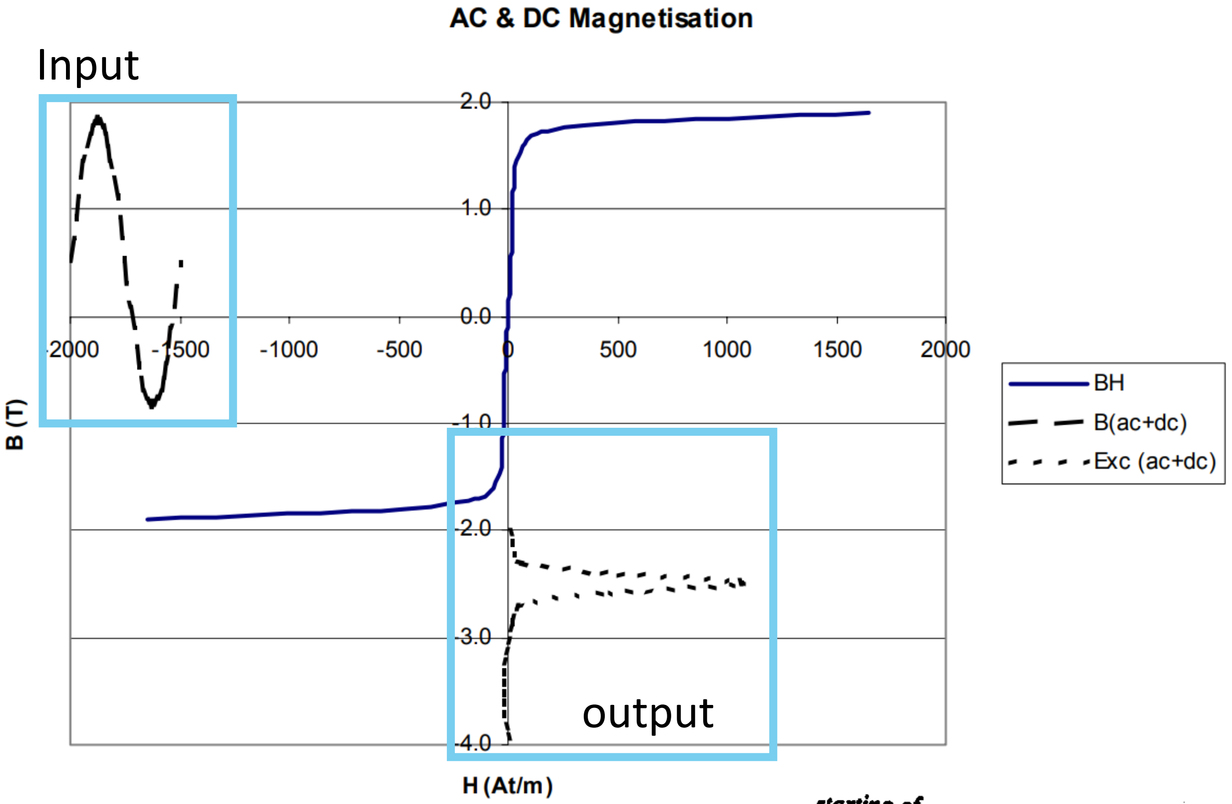
DC injection limit in different countries

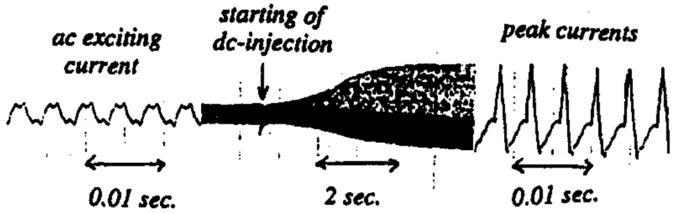
País	Standares	
USA	IEEE 929–2000	The PV system should not inject current >0.5% of rated power inverter ground output current into the AC interface under either normal or abnormal operation conditions.
Japan	Technical guideline for the grid interconnection of dispersed power generating systems	DC injection detection device with inverter disable is required for transformerless inverters. Maximum allowable DC current level is 1% of inverter rated current.
Germany	DIN VDE 126	DC sensitive residual current device required. Disconnection required if a step of 30 mA or larger within 1 s occurs, or the continuous residual current exceeds 60 mA per kVA or inverter rated power. DC injection detection device with inverter disconnection is required for transformerless inverters. Detection threshold is 1 A.
Spain	RD 1663/2000	No limits.
Australia	AS 3300	DC current not to exceed 5 mA. Guidance form AS3300 50 Hz transformer interface between DC and AC preferred transformerless inverters must have DC injection detection device.
The United Kingdom	G83 England G77	Use of an isolation transformer is recommended. A DC injection detection device with inverter disable is required for transformerless inverters, the maximum DC current limit is 5 mA.

What's matter?

Gubia, E. et al. (2007), Ground currents in single-phase transformerless photovoltaic systems, Prog. Photovoltaics
Akhmad, K. et al. (1997), AC side harmonics and phenomena accompanying DC-injection of utility-interactive PV system

- Problems of DC Injection:
  - shift the transformer operation point, transformer saturation
  - waveform distortion → pulsating torque/overheat in machine
  - electrochemical corrosion for underground cable
  - malfunction of protection equipment



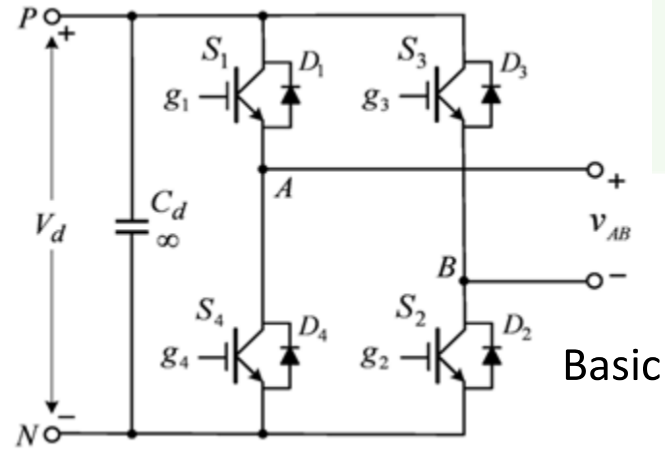


Namboodiri A & Wani H.S (2014), Unipolar and Bipolar PWM Inverter

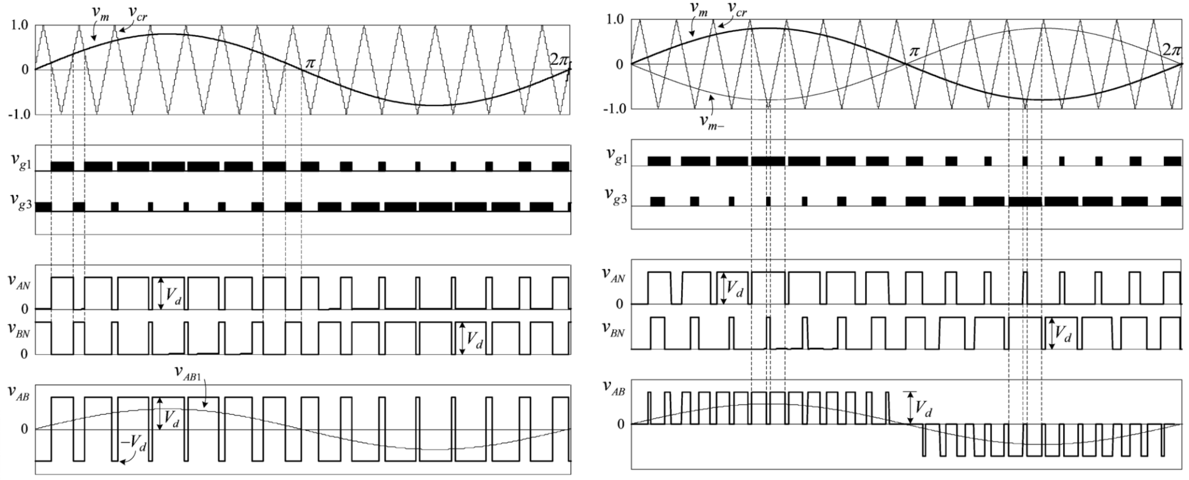
Khan A. (2017), Review and Simulation of Leakage Current in Transformerless Inverter for PV

What's matter?

- DC Injection is from:
  - detection error (delay, A/D, current sensors)
  - tolerance of power switching devices
  - asymmetry of PWM gating driving pulses
  - ground current flowing between inverter output and DC stage (due to stray capacitance between PV panels and ground)
  - ON-state forward saturation voltage & ON-state resistance (switch)



Basic Inverter



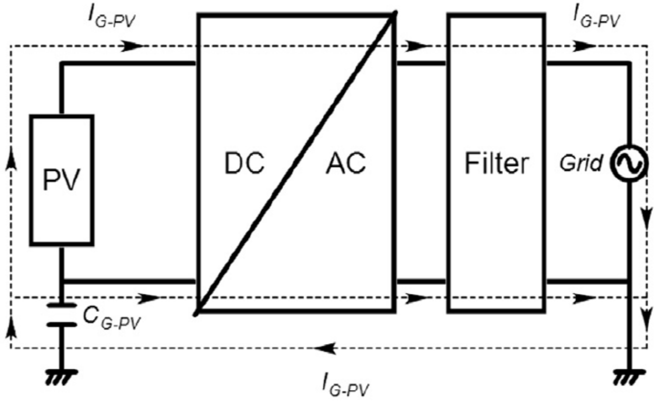
Bipolar Switching

Unipolar Switching

$$v_{cm} = \frac{v_{AN}+v_{BN}}{2} = \text{const. for Bipolar Switching}$$

(but fluctuating for Unipolar)

Bipolar will lead to voltage swing, high switching loss

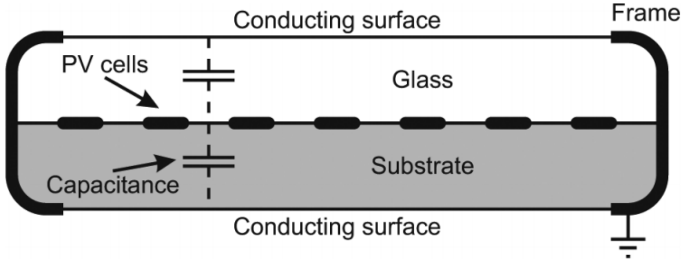


Ground Current Leakage in Transformerless PV Systems

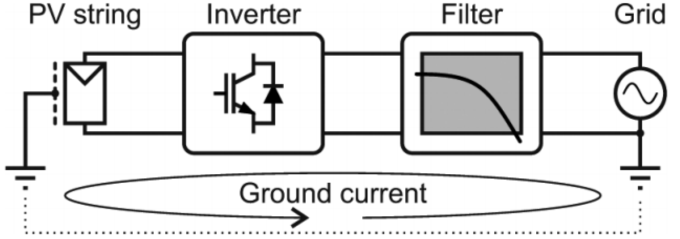
PV Panel Ground Capacitance

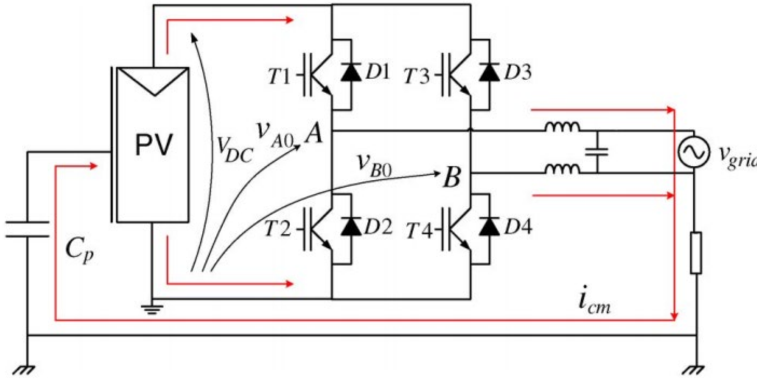
What's matter?

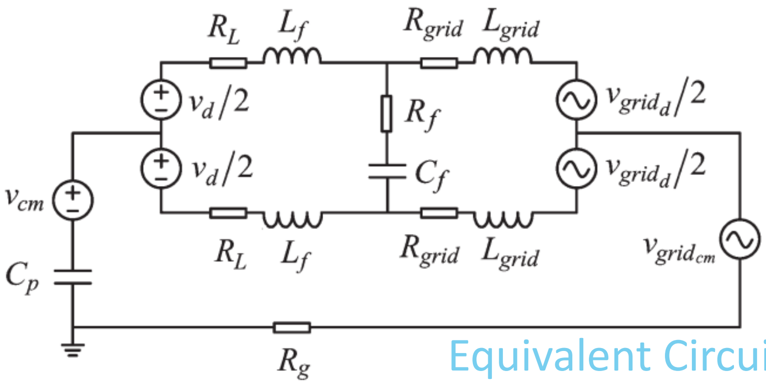
Barater D, et al (2014) Active Common Mode Filter for Ground Leakage Current Reduction in Grid Connected PV Converters Operating with Arbitrary Power Factor
Lopez O, et al (2010) Eliminating Ground Current in a Transformerless Photovoltaic Application



- Ground Current Injection (Common Mode)







Equivalent Circuit

$$v_{cm} = \frac{v_{A0} + v_{b0}}{2} \qquad i = C\frac{dv_{cm}}{dt}$$

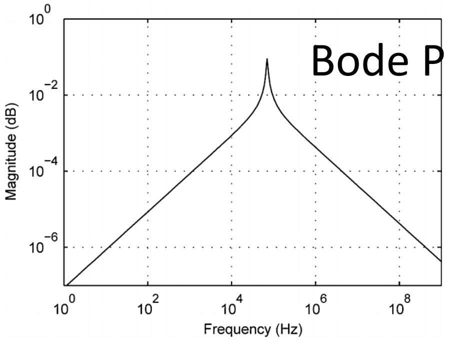
Ground current depends on the **change** of common mode voltage (voltage at the output of full bridge inverter)

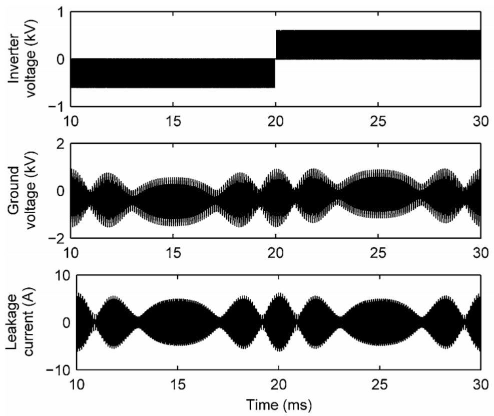
Ground current appears due to **unipolar switching** (vs bipolar switching)

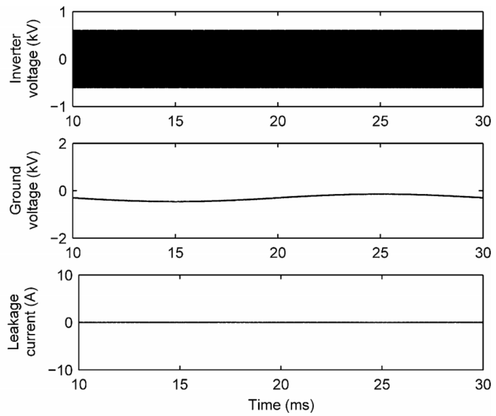
Transformless Design should take care of **resonance** due to ground current loop

Ground current can be eliminated with stabilizing v_{CM} with **reference to grid voltage**

Safety and **noise** are concerns.





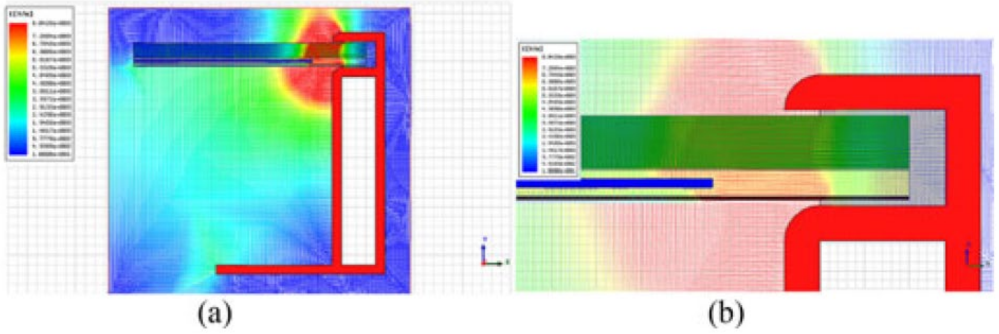


Unipolar Switching

Bipolar Switching

Chen, W. et al (2016), Leakage Current Calculation for PV Inverter System Based on Parasitic Capacitor Model
Shayestegan, M. et al (2018), An Overview on Prospects of New Generation Single-Phase Transformerless Inverters for Grid-Connected Photovoltaic (PV) Systems

Common Mode in a Nutshell



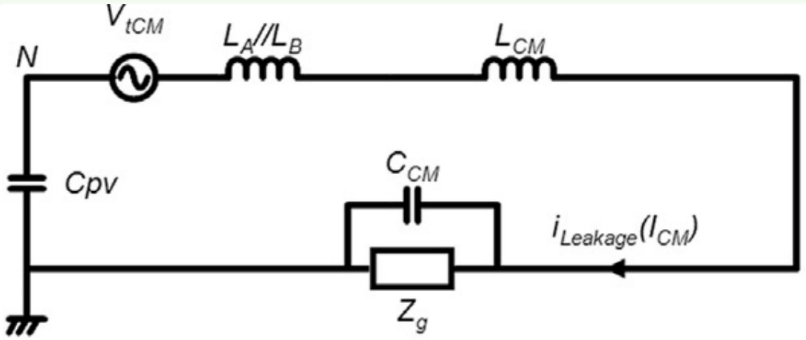
E-field around PV and metal frame

Parasitic Capacitance ranges from uF to nF, depending on ground nature, weather, topology, module structure.

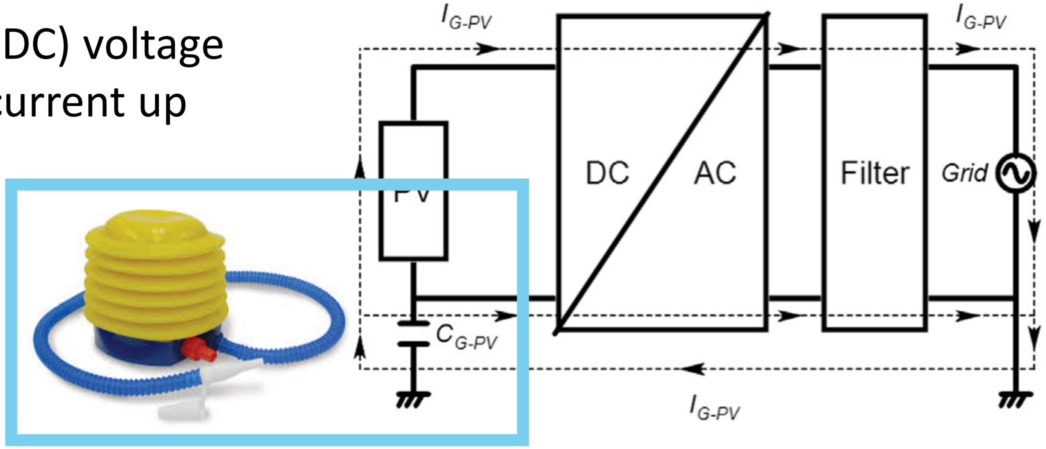
Equivalent Circuit for CMV:

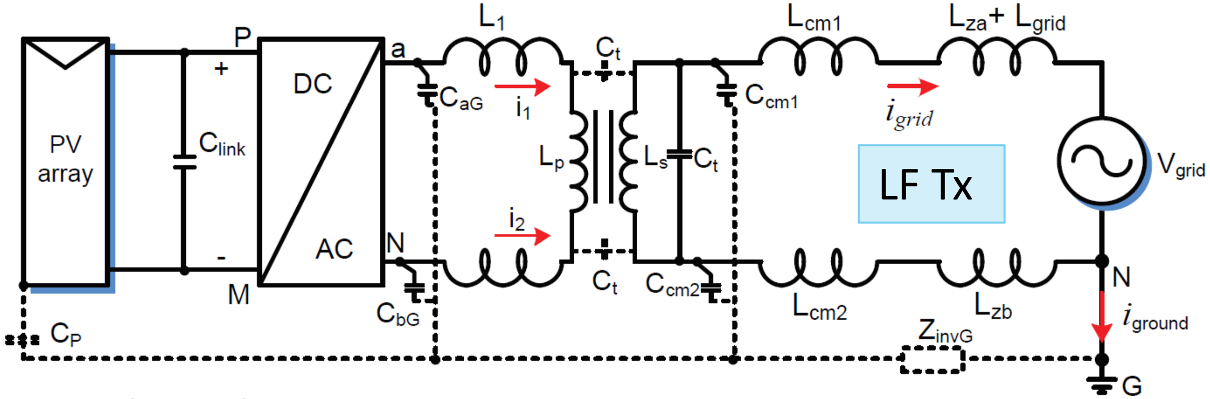
$$V_{tCM} = V_{CM} + \frac{V_{DM}}{2}\frac{L_B - L_A}{L_A + L_B}$$

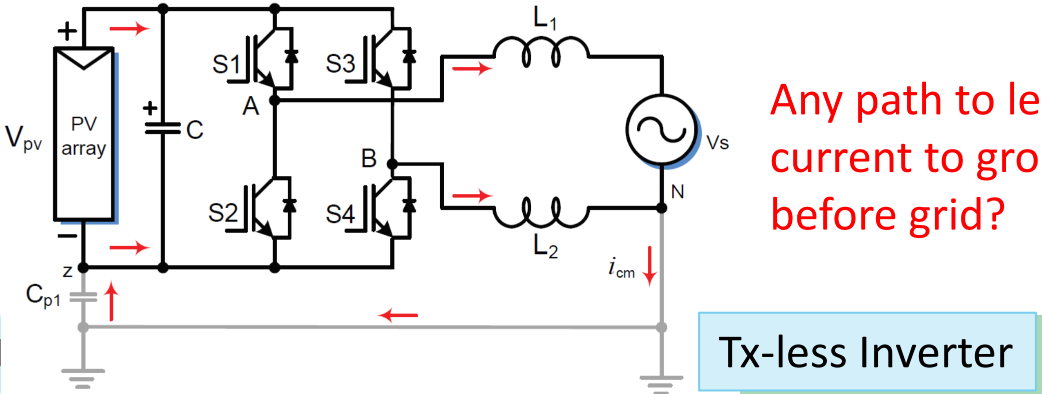
$$V_{CM} = \frac{1}{2}(V_{AN} + V_{BN})$$



Change of (DC) voltage will pump current up





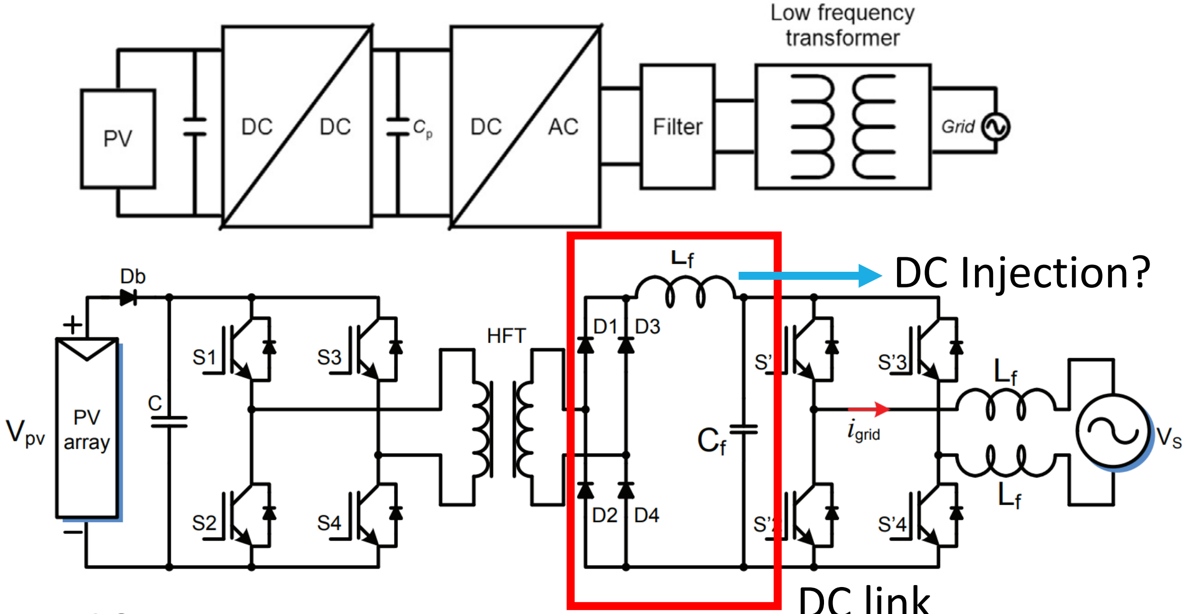


Any path to leak CM current to ground before grid?

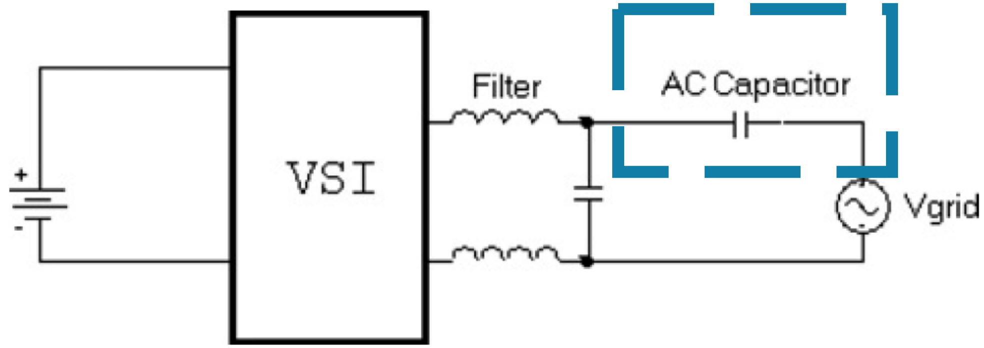
Common Solutions

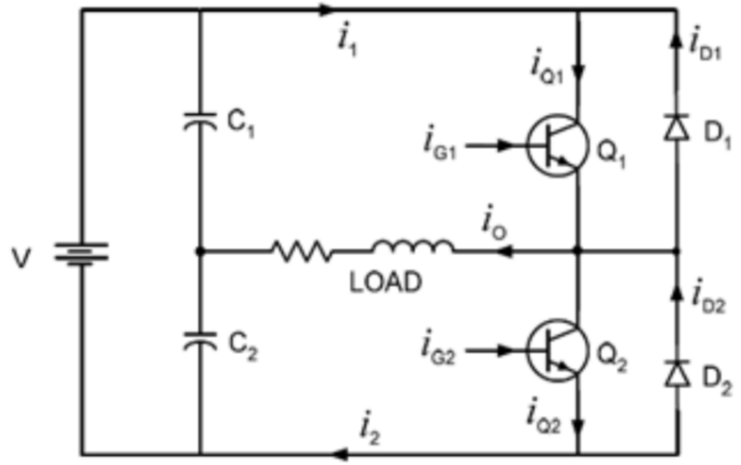
Berba, F. et al. (2014), A new approach of prevention of DC Current Component in Transformerless Grid-Connected PV Inverter Application

- Isolation Transformer
  (or High Frequency Transformer)



- Blocking capacitor





- Half-Bridge Inverter

  Prevent current flow but requires twice DC bus voltage and stronger switches and capacitor

Amount of DC

Salas V. et al. (2006), DC Current Injection into the Network from PV Grid Inverters

Medina A. et al. (2014), DC Current Injection into the Network from Transformerless and LF Transformer Photovoltaic Inverter

Past Data:
Laptop: 0.04A DC (7.7% of rated)
Desktop: 0.03A DC (11.2% of rated)
Lighting: 0.34A DC (0.53% of rated)
Some may have DC more than PV's

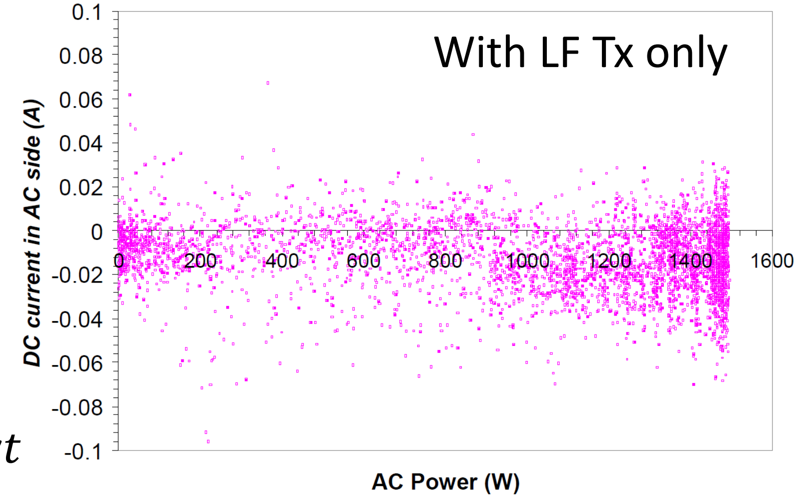
DC comes from Fourier Series:

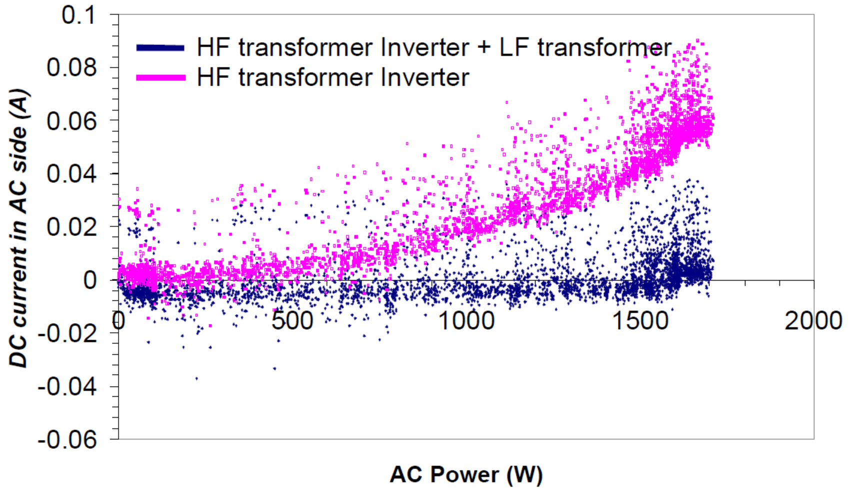
$$f(t) = a_0 + \sum a_n \cos nwt + b_n \sin nwt$$

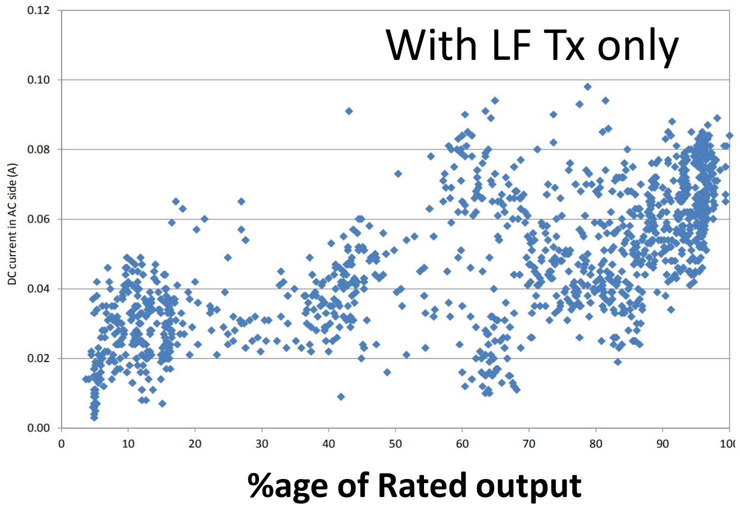
where $a_0 = \frac{1}{T}\int_t^{t+\boxed{T}} f(t)dt$ (average)
which is the DC component.

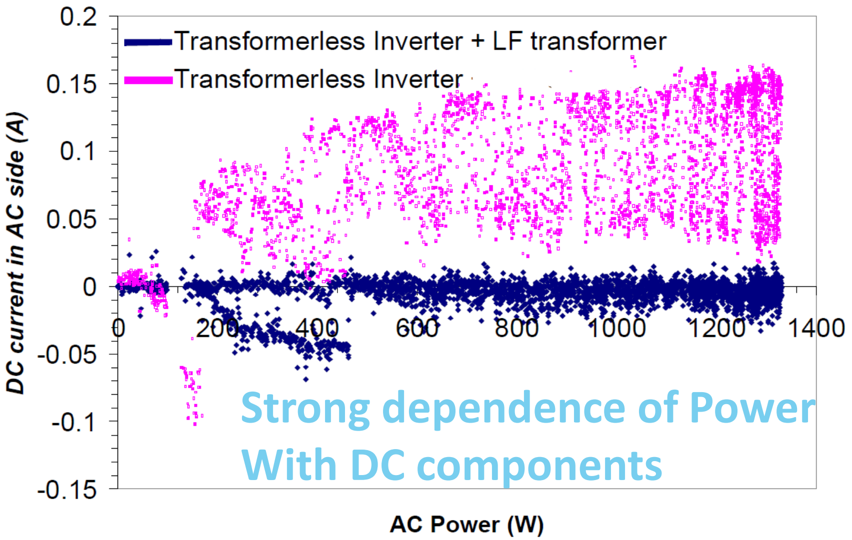
Even there is LF transformer,
There can be DC. (gate triggering)

Comparing DC component,
Transformerless > HF Tx > LF Tx



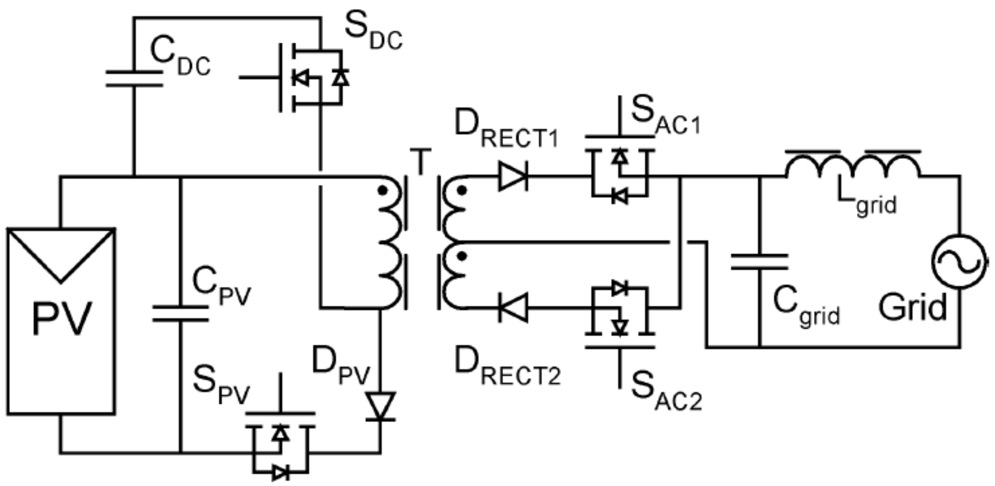




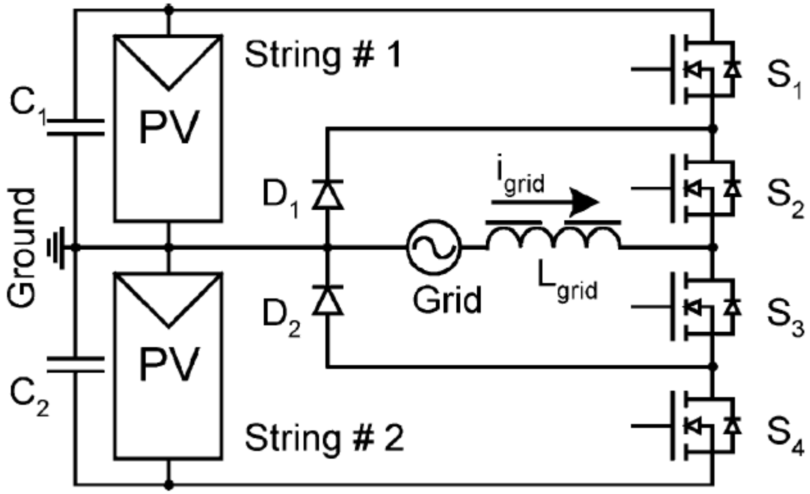


Common Inverter Topology to be used

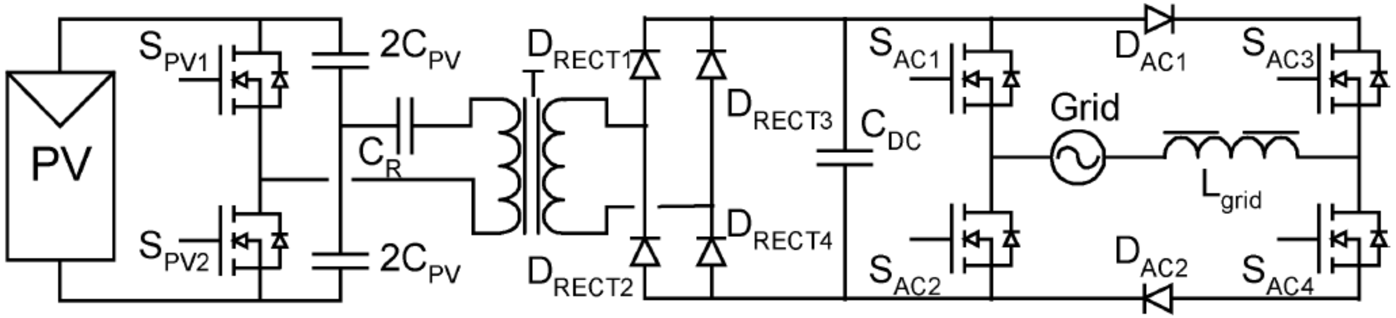
Kjaer S. B. et al (2005), A Review of Single Phase Grid Connected Inverter for PV Module



Flyback inverter with high power decoupling



Half-bridge diode clamped three level inverter



Series resonant converter with bang-bang dc-ac inverter

Flyback applies transformer, series cap and diode offset to mitigate DC
Series Resonant Converter has high step-up ratio and series cap to mitigate DC
Half bridge converter stops DC flowing from ground

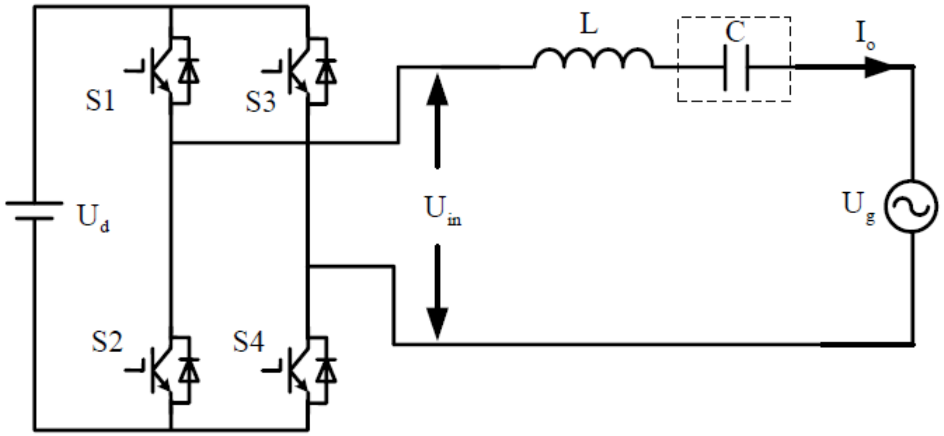
Latest Solution

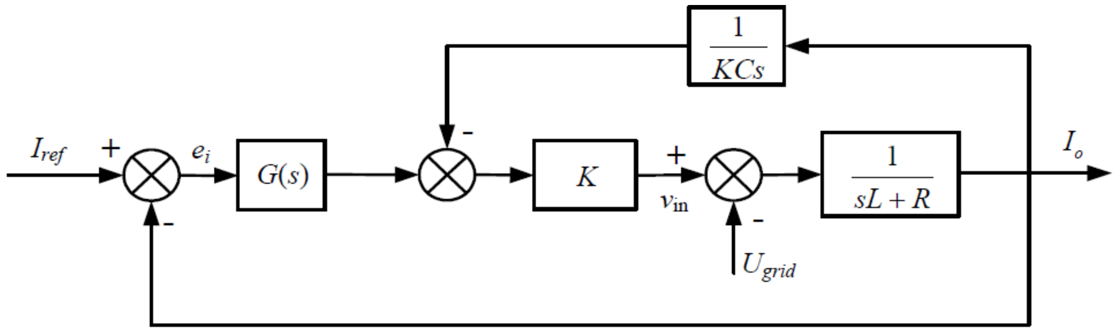
Guo X. et al. (2008), DC Injection Control for Grid-Connected Inverters Based on Virtual Capacitor Concept

- Virtual Capacitor

Assume: - DC Bus voltage is constant
- Switching Freq is high enough
- Inverter output does not saturate

To avoid using large and expensive capacitor, we include capacitor effect in the output of inverter.

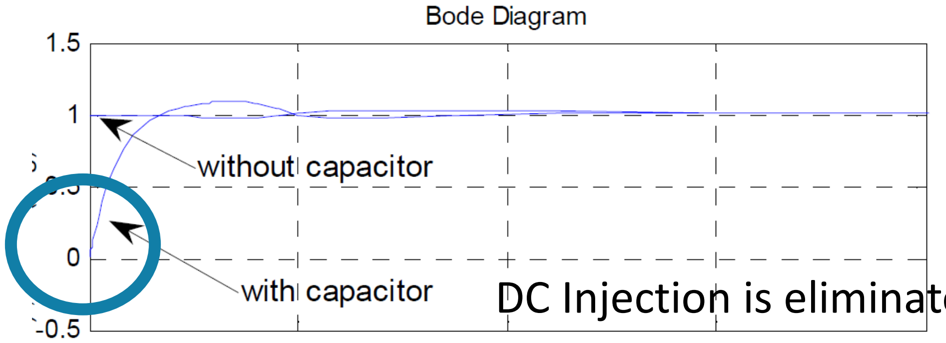




$$G(s) = k_p + \frac{k_i s}{s^2 + \omega^2} \qquad U_{in} = L\frac{di_o}{dt} + \frac{1}{C}\int i_o dt - U_g$$

$$\frac{i_o(s)}{U_{in}(s) - U_g(s)} = \frac{Cs}{LCs^2 + RCs + 1}$$

$$I_o(s) = \frac{KG(s)}{Ls + R + KG(s) + \frac{1}{Cs}} I_{ref}(s) - \frac{1}{Ls + R + KG(s) + \frac{1}{Cs}} U_{grid}(s)$$



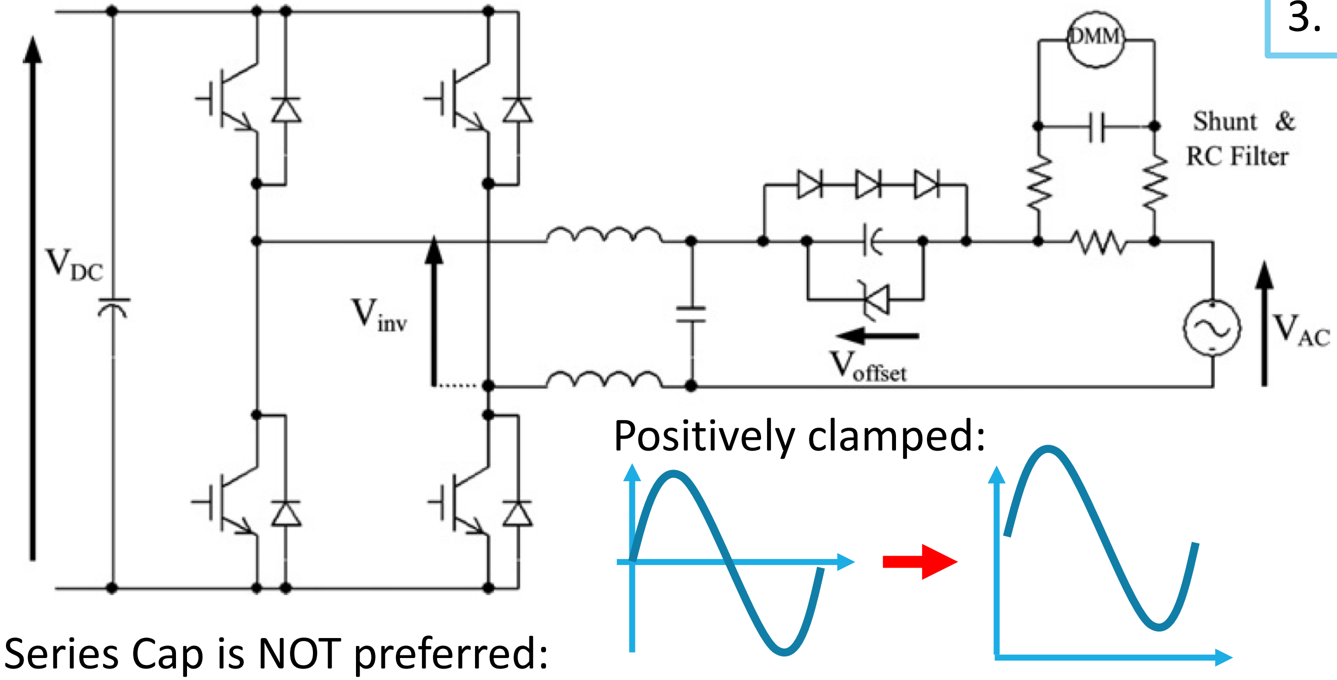
DC Injection is eliminated.

Latest Solution

Blewitt W.M. et al. (2008), Approach to low-cost prevention of DC Injection in Transformerless Grid Connected Inverters
Armstrong M, et al. (2006), Auto-Calibration DC Link Current Sensing Technique for Transformerless, Grid Connected, H-Bridge Inverter Systems
Butler J.W. & Concordia C. (1937), Series Capacitor Application Problem

- DC offsets and autocalibration

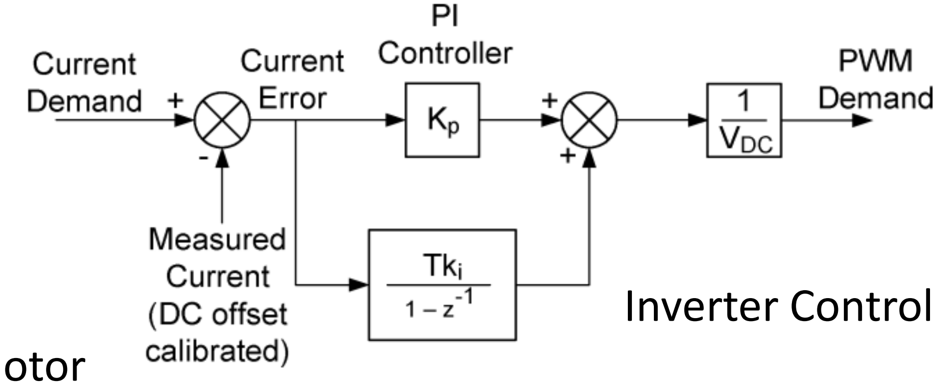
1. Electrolytic Capacitor with offset voltage is used
2. Diode clamp to protect the cap from reverse polarity
3. Shunt/ RC filter install to obtain DC current value



To tune V_{inv} to control I_{out}:

$$V_{\text{inv}} = V_{\text{ac}} + V_L$$
$$V_L = j\omega L I_{\text{out}}$$
$$I_{\text{out}} = \frac{V_{\text{inv}} - V_{\text{ac}}}{j\omega L}$$

Positively clamped:



Inverter Control Algorithm

Series Cap is NOT preferred:
1. Overshoot for flickers and voltage rise
2. Distorted and large Tx exciting current -> saturation
3. Hunting of synchronous machine/ self-excitation of induction motor

Latest Solution

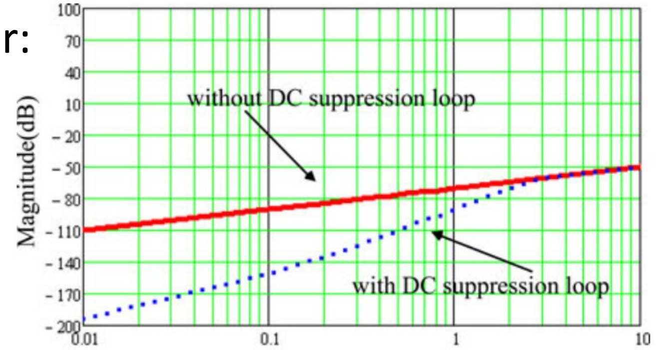
He G.F. et al. (2015), A novel control strategy of suppressing DC current injection to the grid for single-phase PV inverter
Li, S. et al, (2014), Suppressing Method for Photovoltaic Power Station DC Component Injection

- DC Suppression Loop (with PI controller)

Mainly focused on differential mode.

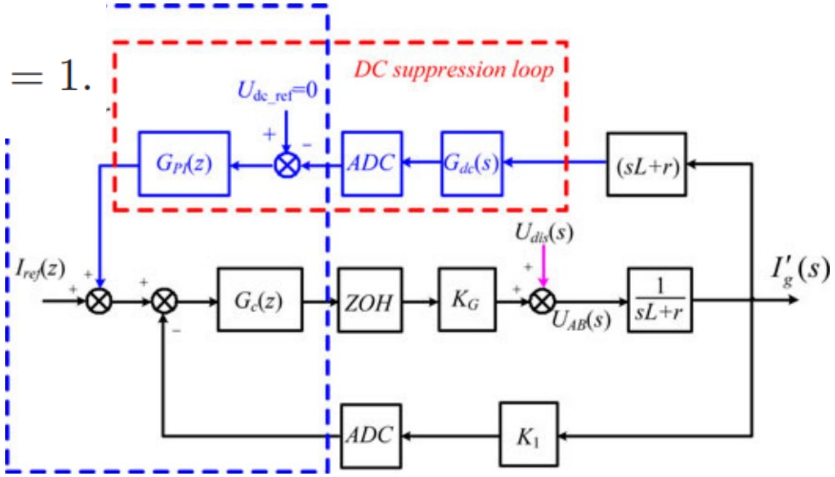
Feedback gain with LPF and Diff. Amplifier:

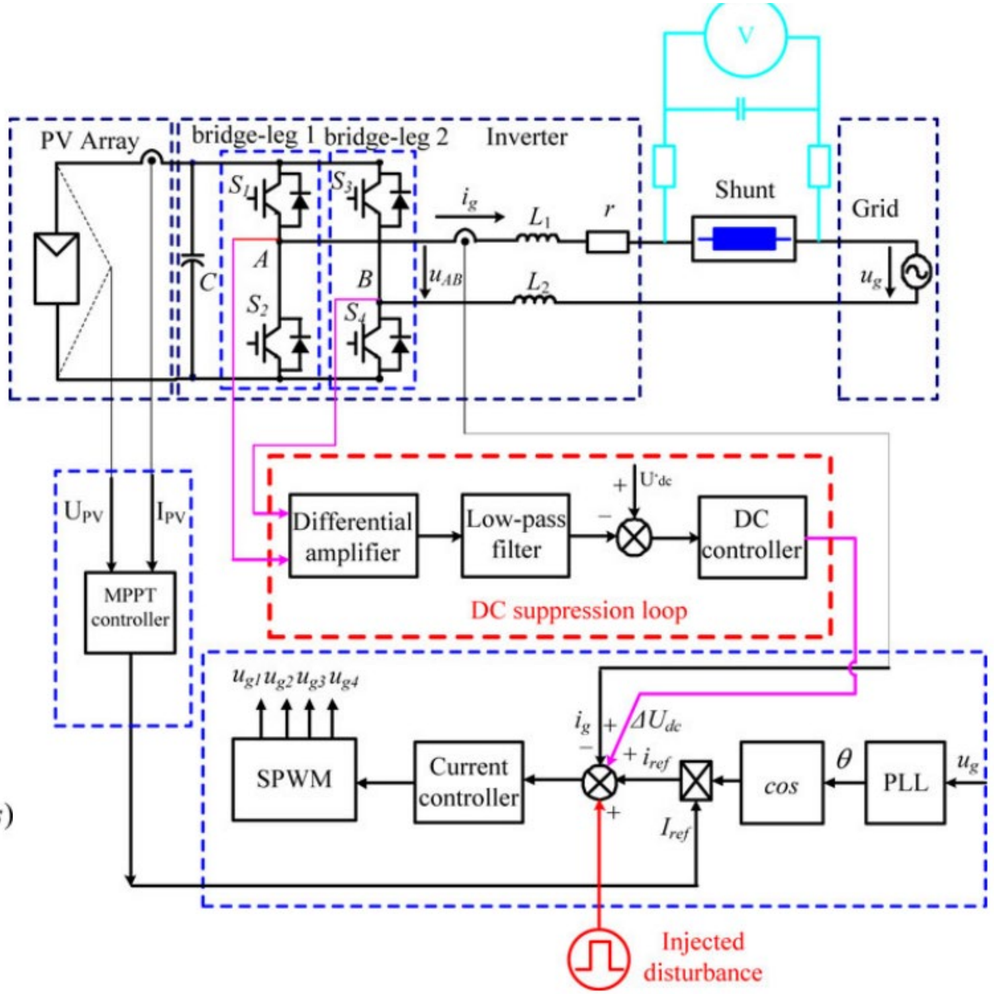
$$G_{\mathrm{dc}}(s) = \frac{2}{\left(1 + \frac{s}{2\pi f_{LP}}\right)^2}$$



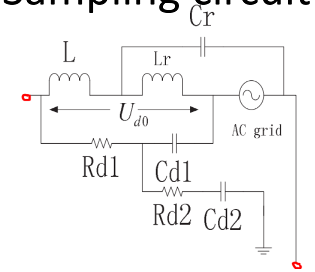
Assigning K_P and K_I, with turn point 5Hz:

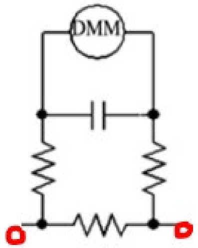
$$\begin{cases} \dfrac{K_{id}}{2\pi K_{pd}} = 5 \\ \left| G_{\mathrm{dc\_offset}}(s) \cdot \dfrac{(K_{pd}s + K_{id})}{s} \right|_{s=2\pi\cdot 1} = 1. \end{cases}$$





Sampling circuit:

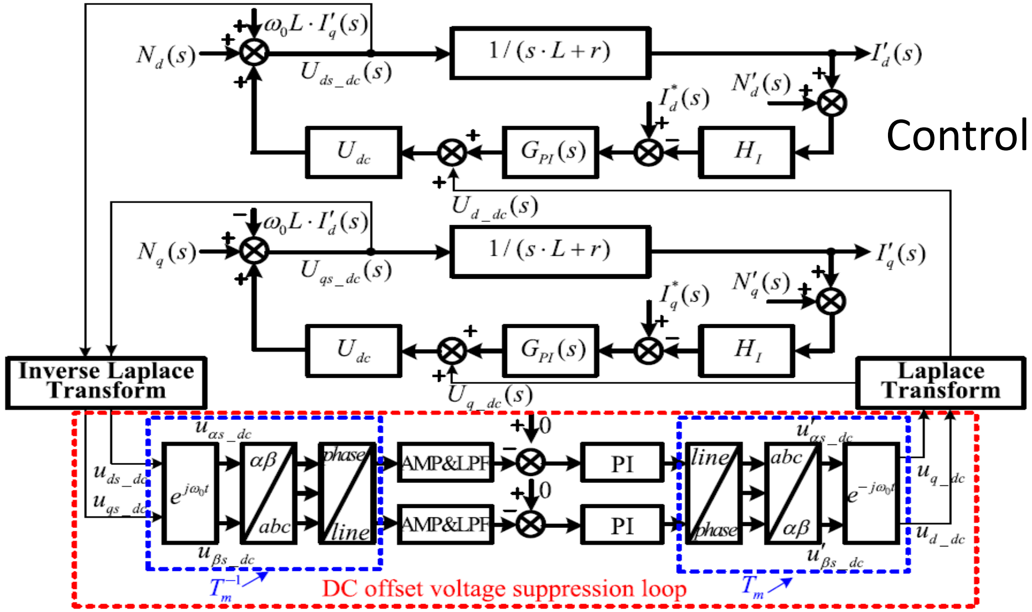




Latest Solution

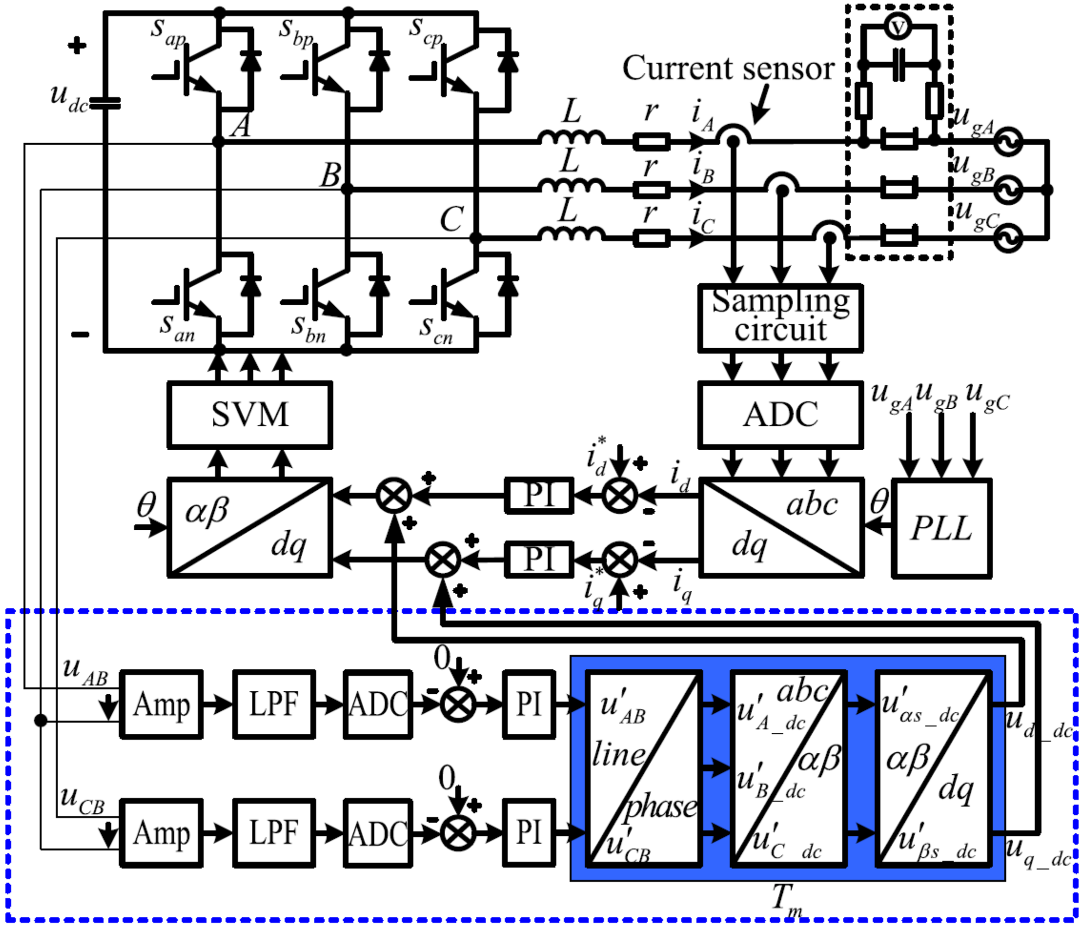
Chen, M. et al. (2018), A Novel DC Current Injection Suppression Method for Three-phase Grid Connected Inverter Without Isolation Transformer

- Synchronous Frame Control



Control Loop

Three phase Grid Connected Inverter



DC offset voltage suppression loop

Mainly focus on Differential Mode Current

e = detection error

R = sampling circuit error

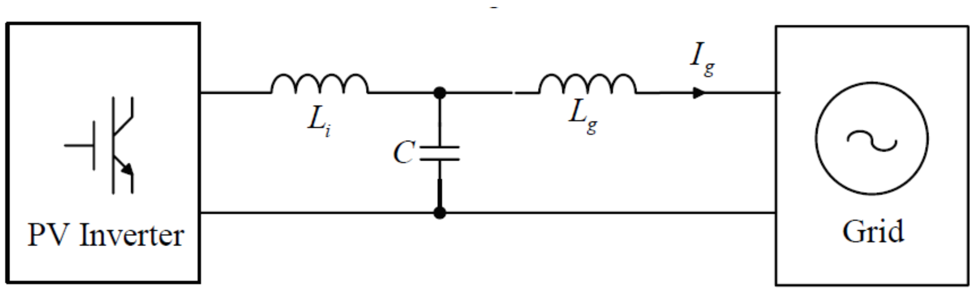
(1+M)/2^N = ADC resolution error

$$\Delta I_A = \pm\left(e\% + R\% + \frac{1+M}{2^N}\right) \times I_{p\text{-}p}$$

Latest Solution

Wang, B. et al (2010), Real-time DC Injection Measurement Technique for Transformerless PV Systems

- Better Measurement Technique



$$I_g(t) = I_{dc} + I_{ac} = I_0 + \sum_{=1,2,3,\dots} I_n \sin(2\pi n f_1 t + \varphi_n)$$

$$I_b(t) = \frac{1}{T}\int_{t_0}^{t_0+T} I_0 dt = I_0$$

Proposed Measurement
$T = 1/f_1$

$$I_c(t) = \frac{1}{T}\int_{t_0}^{t_0+T} I_g(t)dt$$

$$= \frac{1}{T}\int_{t_0}^{t_0+T} [I_0 + \sum_{n=1,2,3,\dots} I_n \sin(2\pi n f_1 t + \varphi_n)]dt$$

$$= I_0$$

When PV freq (f_0) is different from grid freq (f_1)

$$I_c(t) = \frac{1}{T}\int_{t_0}^{t_0+T} I_g(t)dt$$

$$= \frac{1}{T}\int_{t_0}^{t_0+T} [I_0 + \sum_{n=1,2,3,\dots} I_n \sin(2\pi n f_1 t + \varphi_n)]dt$$

$$= I_0 + \sum_{n=1,2,3,\dots} \boxed{\frac{f_0}{\pi n f_1}\sin(\frac{\pi n f_1}{f_0})} \times I_n \sin(2\pi n f_1 t_0 + \varphi_n + \frac{\pi n f_1}{f_0})$$

Error Amplitude

Double Integration solves the problem

$$I_{cc}(t) = \frac{1}{T^2}\int_{t_0}^{t_0+T} I_c(t)dt$$

$$= \frac{1}{T^2}\int_{t_0}^{t_0+T} [\int_{t_0}^{t_0+T} I_0 + \sum_{n=1,2,3,\dots} I_n \sin(2\pi n f_1 t + \varphi_n)dt]dt$$

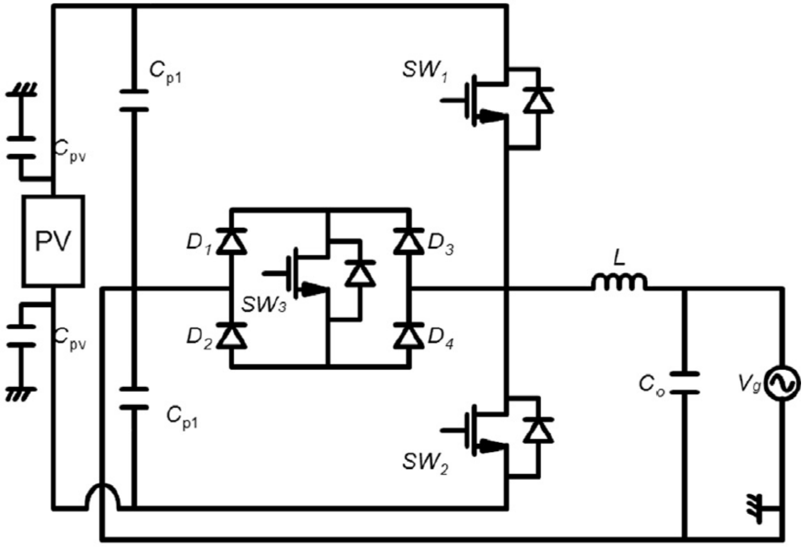
$$= I_0 + \sum_{n=1,2,3,\dots} [\frac{f_0}{\pi n f_1}\sin(\frac{\pi n f_1}{f_0})]^2 \times I_n \sin(2\pi n f_1 t_0 + \varphi_n + \frac{2\pi n f_1}{f_0})$$

Latest Solution

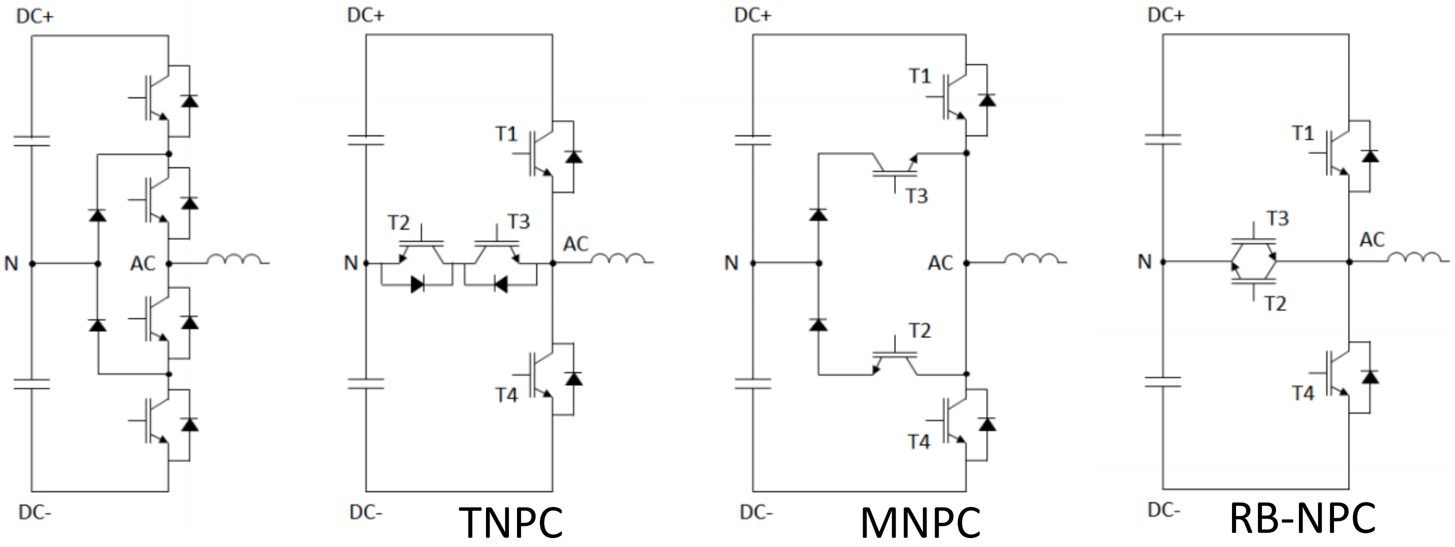
Hasanzadeh A. (2012), Reduced Switch NPC-based Transfromerless PV Inverter by Developed Switching Pattern

- Conergy Neutral Point Clamped (NPC) topology

Half-bridge (HB) requires higher rating switches and produces distorted output current with high EMI and switching loss.



NPC Topology



Half-bridge can inhibit leakage current through parasitic capacitance of the module

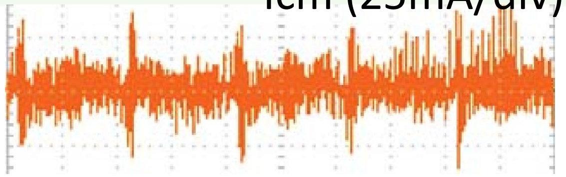
→ we have NPC topology

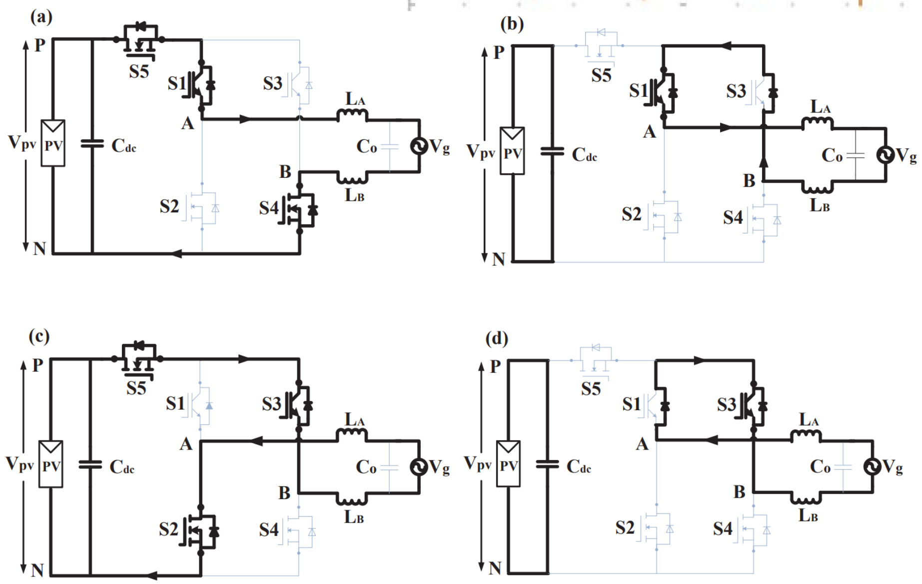
Latest Solution

Islam, M. et al. (2014), An Improved Transformerless Grid Connected Photovoltaic Inverter with Common Mode Leakage Current Elimination
Li, H. et al. (2018), An Improved H5 Topology with Low Common Mode Current for Transformerless PV Grid-Connected Inverter

- H5 Topology

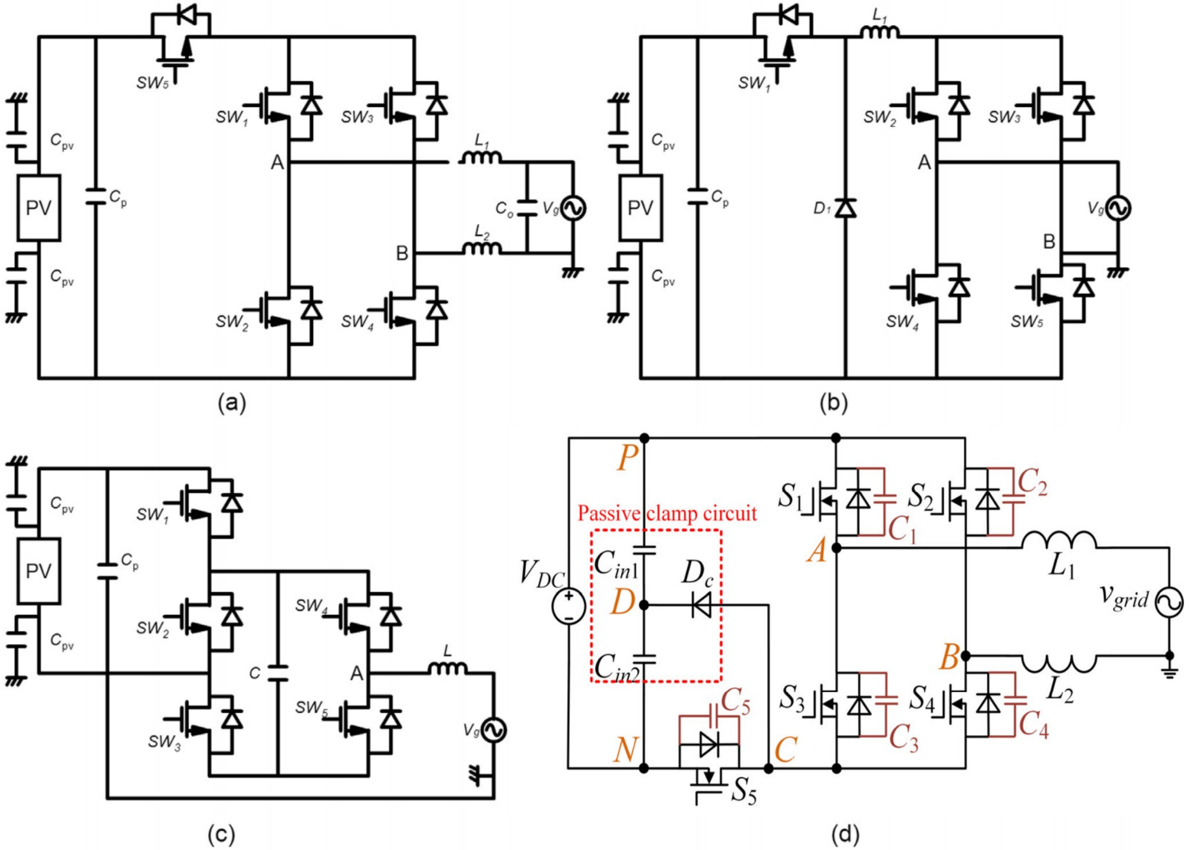
Icm (25mA/div)





Constant common mode voltage during switching

Slope of Vcm depends on **Junction Capacitance** especially in **free-wheeling mode**

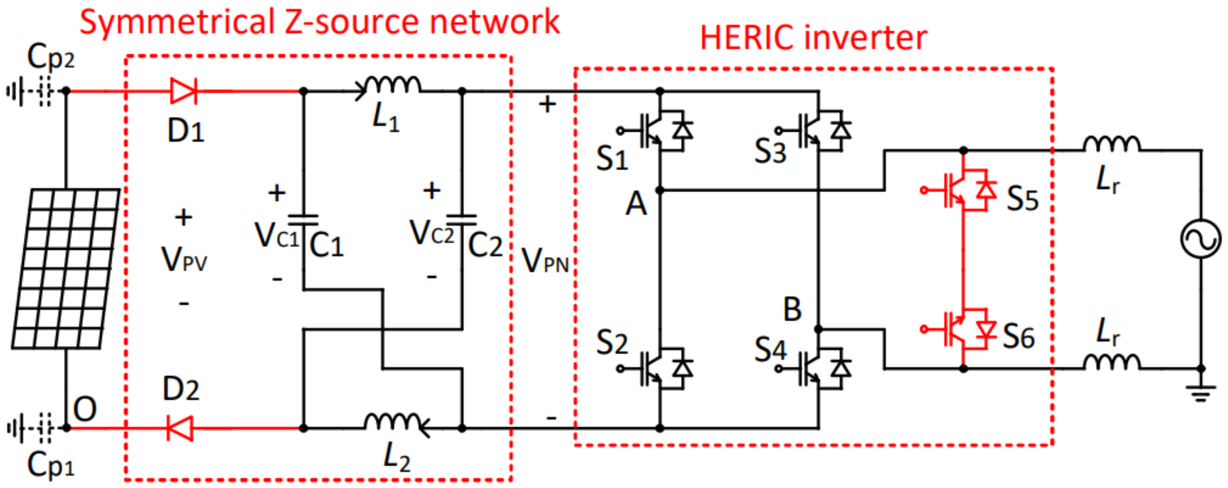


Different Types of H5 Inverter

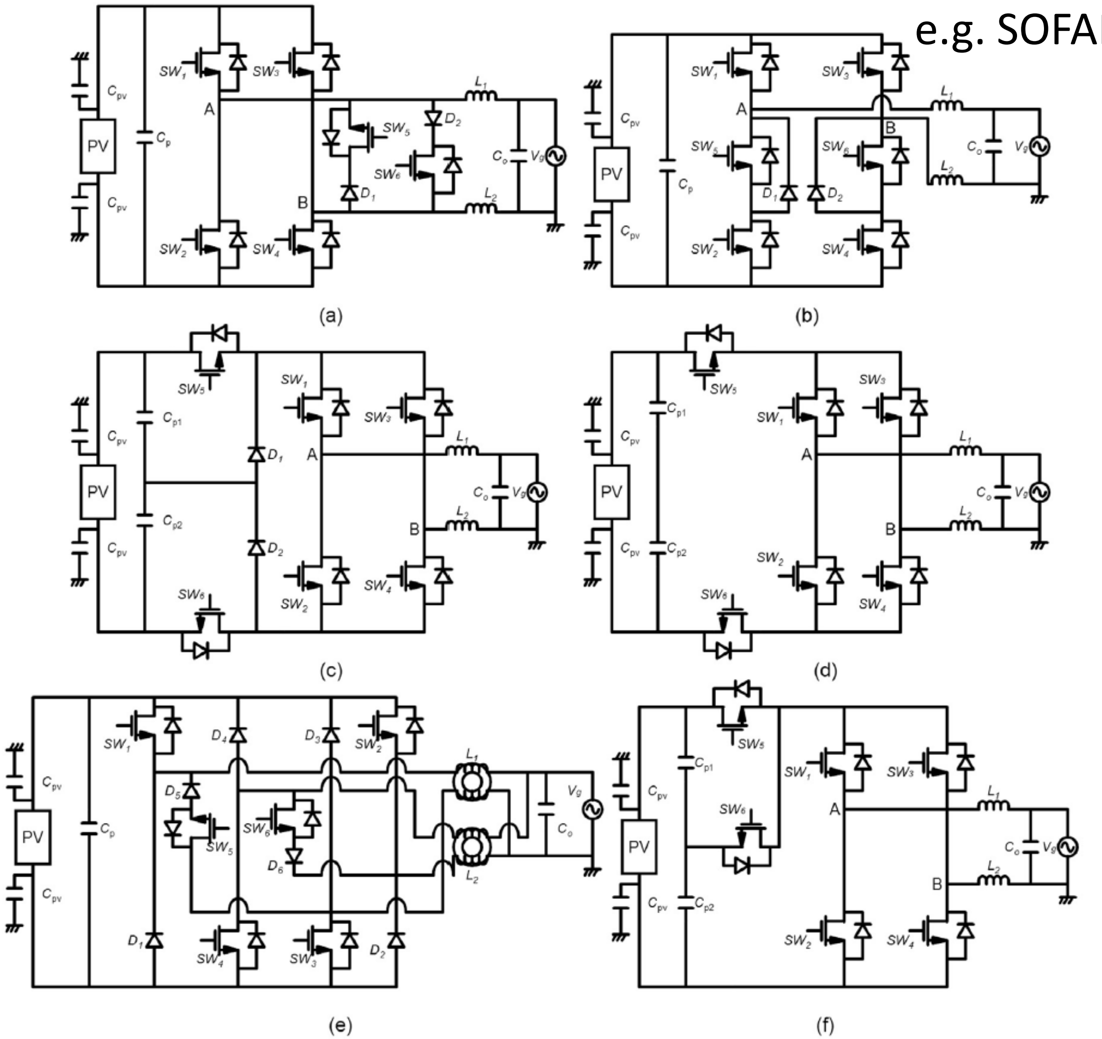
Latest Solution

Hasanzadeh A. (2012), Reduced Switch NPC-based Transfromerless PV Inverter by Developed Switching Pattern

- HERIC Topology:
  - Common in commercial inverter (e.g. Sunway)
  - Avoid occurrence of leakage current
  - Three level output voltage
  - High efficiency & Unipolar PWM

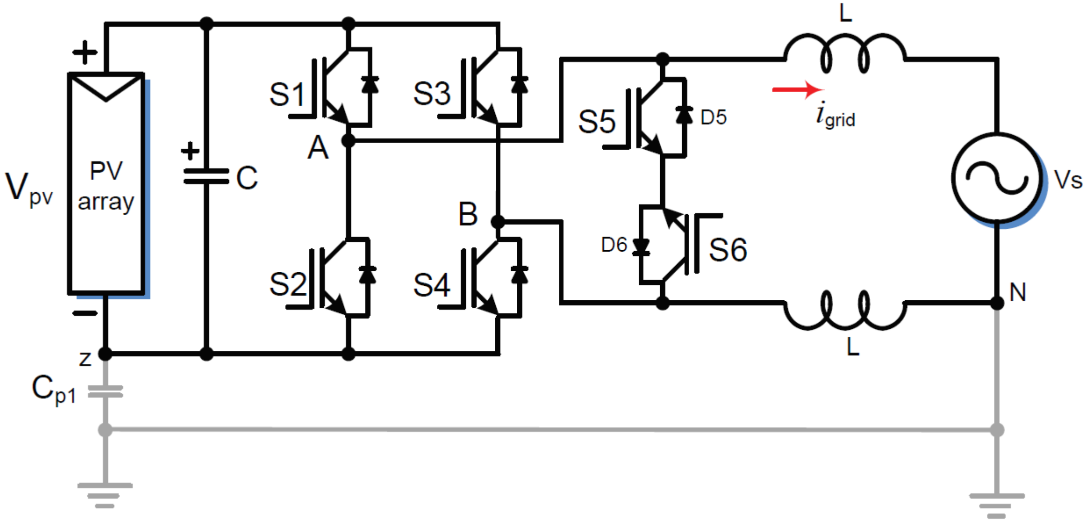


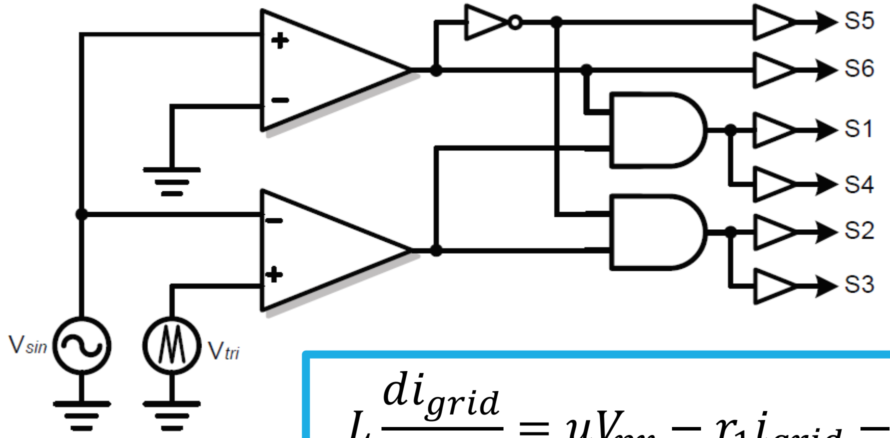
e.g. SOFAR



Khan, A. (2017) Review and Simulation of Leakage Current in Transformerless Microinverter for PV Application

HERIC switching





$$L\frac{di_{grid}}{dt} = uV_{pv} - r_1 i_{grid} - v_s$$

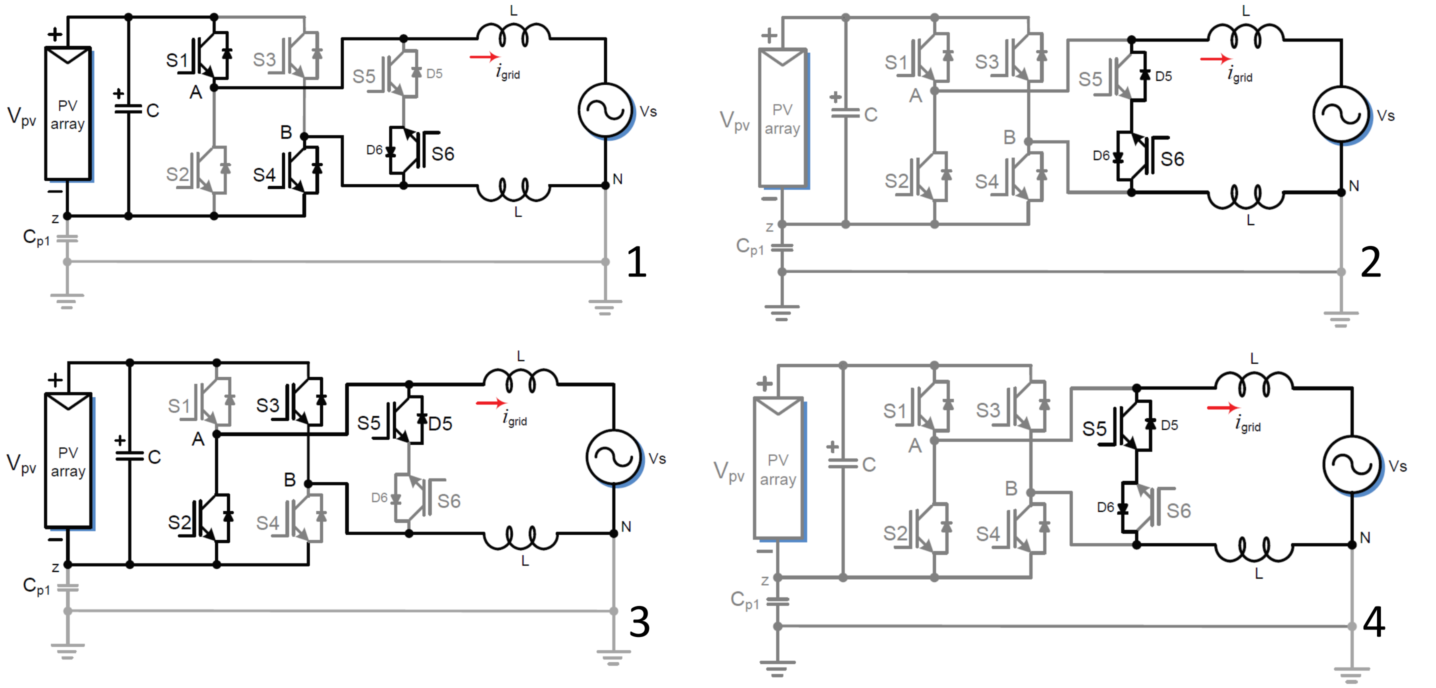
Constant voltage in CM

Positive: $$V_{cm} = \frac{V_{AZ} + V_{BZ}}{2} = \frac{V_{DC} + 0}{2} = \frac{V_{DC}}{2}$$

Zero: $$V_{cm} = \frac{V_{AZ} + V_{BZ}}{2} = \frac{\frac{V_{DC}}{2} + \frac{V_{DC}}{2}}{2} = \frac{V_{DC}}{2}$$

Negative: $$V_{cm} = \frac{V_{AZ} + V_{BZ}}{2} = \frac{0 + V_{DC}}{2} = \frac{V_{DC}}{2}$$

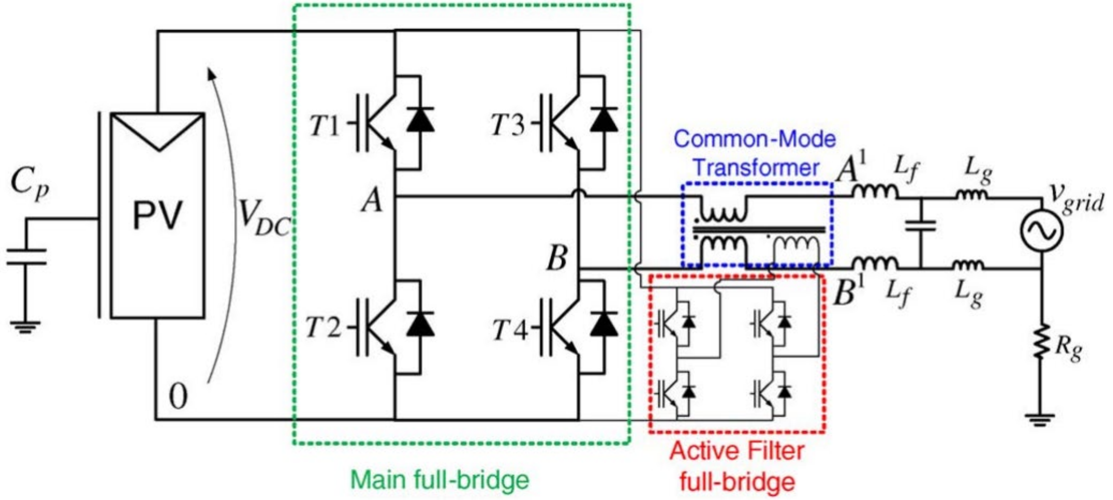
Switching Topology



Barater D. et al. (2014), Active CM Filter for Ground Leakage Current Reduction in Grid Connected PV Converters
Doerry, N & Amy J.V. (2017), MVDC Grounding and Common Mode Current Control
Chen, F. et al. (2018), A Bidirectional High-Efficiency Transformerless Converter with Common Mode Decoupling for the Interconnection of AC and DC Grid
Bortis, D. et al (2016), np-Pareto Optimization and Comparative Evaluation of Inverter Concepts considered for the Google Little Box Challenge

Latest Solution

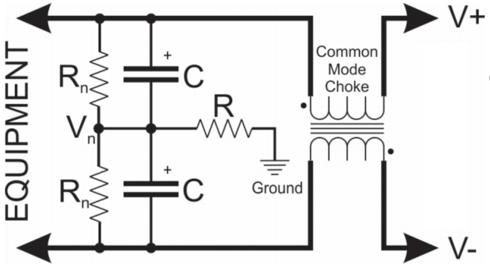
- Passive Filter (e.g. CM Choke)

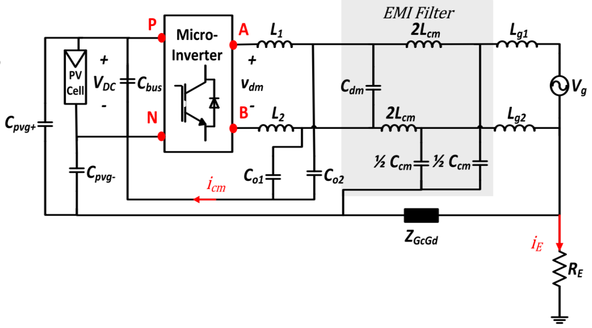


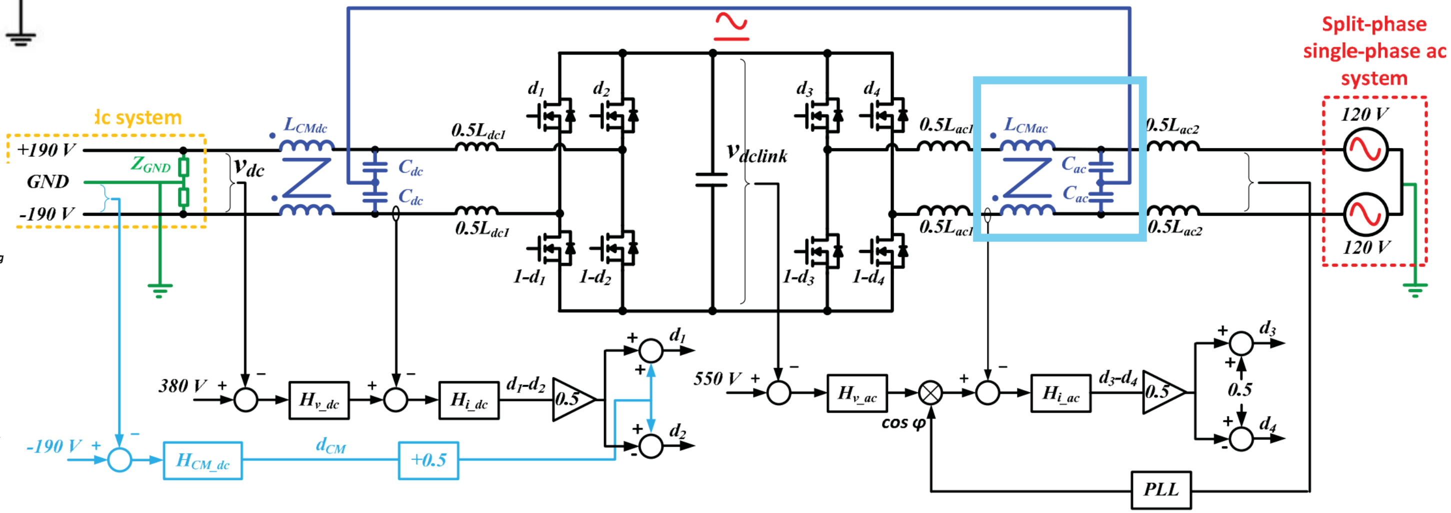
To prevent **resonant** and **DC injection**, L-C filter/ chokes should be properly sized.

Resistor is added in to increase **high freq. Impedance**

Connection between capacitor legs are to **stabilize** common mode voltage







In Conclusion:

- DC Injection mainly comes from (common mode) stray capacitance between ground and PV panels, (differential mode) ADC errors, current sensing errors and sampling circuit errors, (main injection) inverter asymmetric gate signal
- Foreign countries mainly improves control method (e.g. virtual capacitor, synchronous frame), topology (e.g. half-bridge converter, electrolytic capacitor, filter added), or sensing accuracy (e.g. demodulation)
- Back to the question: what if inverter is malfunctioning?
  - any control error/component malfunction will trigger OFR/UFR, OVR/OFR, HR (relays to detach PV from grid/ islanding)
  - some topology has inverter to block the DC components