Evaluation of common-mode leakage current of Aalborg-type transformerless PV inverters

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1. Introduction to Aalborg-type transformerless PV inverters
2. Background on common-mode (CM) leakage current generation
3. Mechanism and expressions for CM current in the Aalborg inverter
4. Proposed filter modification
5. Simulation results
6. Comparison and Discussion

Transformerless PV inverters with voltage step-up

- Transformerless photovoltaic (PV) inverters
  - High efficiency (H5, HERIC, NPC, …)
  - Lower volume, weight, cost
- Normally combined with a voltage step-up (Boost) stage
  - Ensures that the DC-link voltage is adequate to inject power to the grid
  - Performs Maximum Power Point Tracking (MPPT)
- Step-up stage traditionally separate from the inverter stage
- Topologies that combine them – **dual-mode time-sharing** topologies
- Different DC-link voltage waveforms – **rectified sine wave**

Dual-mode time-sharing topologies

- Operate in Buck or Boost mode for portions of each half-cycle
- In full-bridge versions, the DC-link voltage waveform has the form of a rectified sine wave
- An H-bridge "unfolds" it to supply it to the grid
- PF ≈ 1

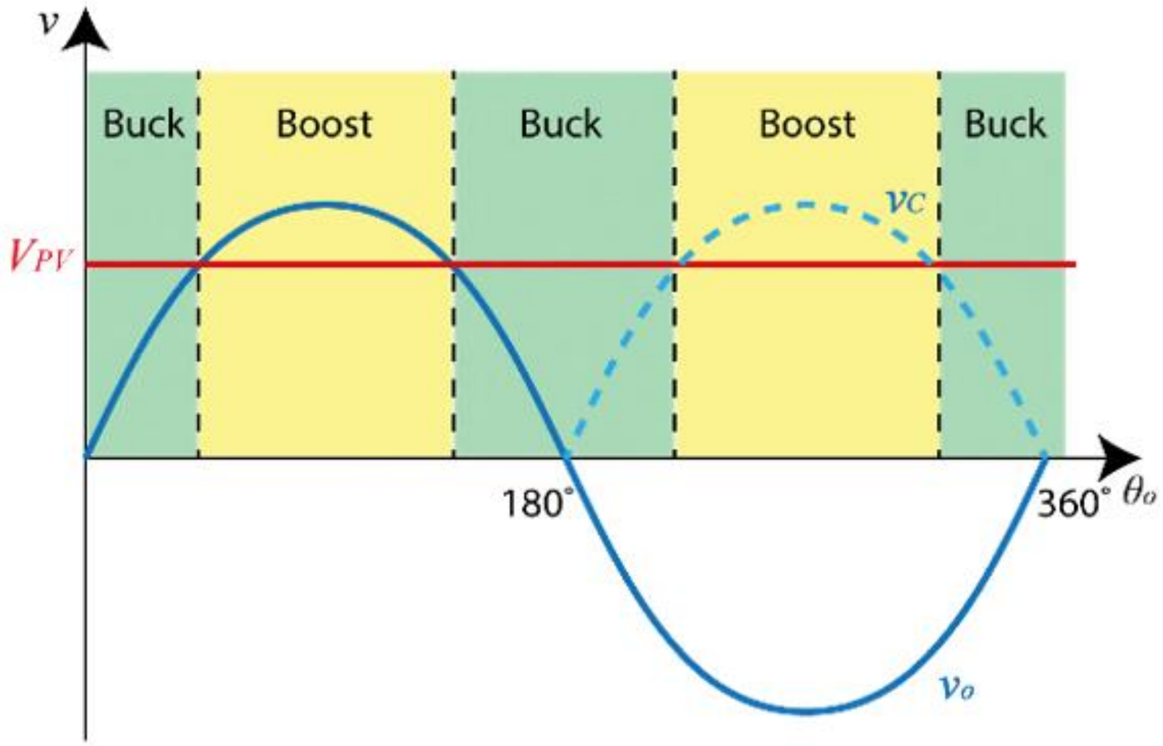


Fig. 1: Waveforms and modes of operation of full-bridge dual mode time-sharing inverters.

Full-bridge Aalborg inverter

- Elimination of one inductor, as compared to other topologies of the same family
- Operation of only one power switch at high frequency
  - S6 for Buck mode
  - S5 for Boost mode

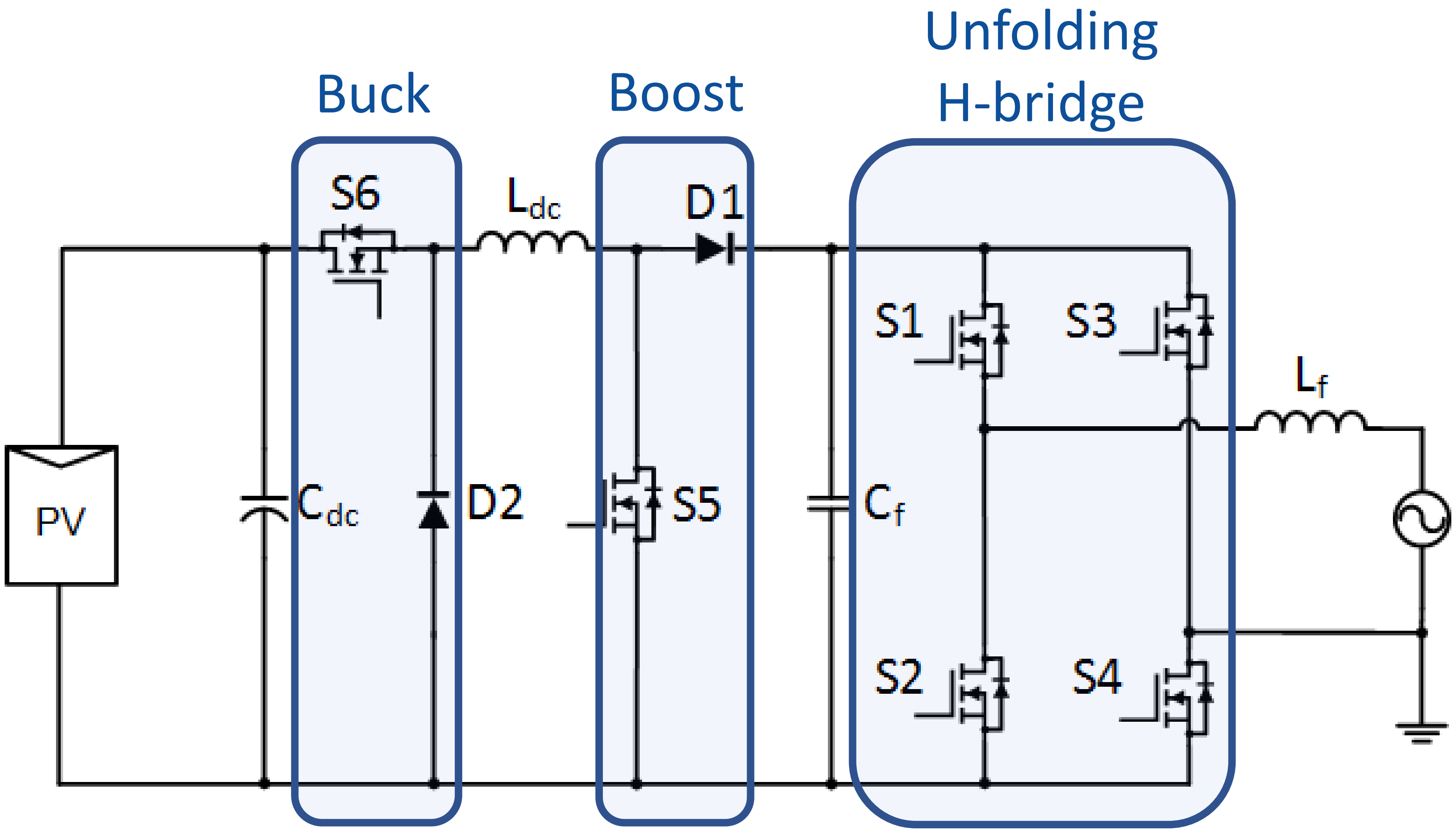


Fig. 2: Full-bridge Aalborg inverter topology.

Common-mode leakage current generation

- CM ground leakage current circulation path
  - Inverter PWM operation
  - Parasitic capacitances between the solar cells and the ground
  - Grounded neutral of the grid
- Not systematically analysed for topologies with rectified sine wave DC-link voltage

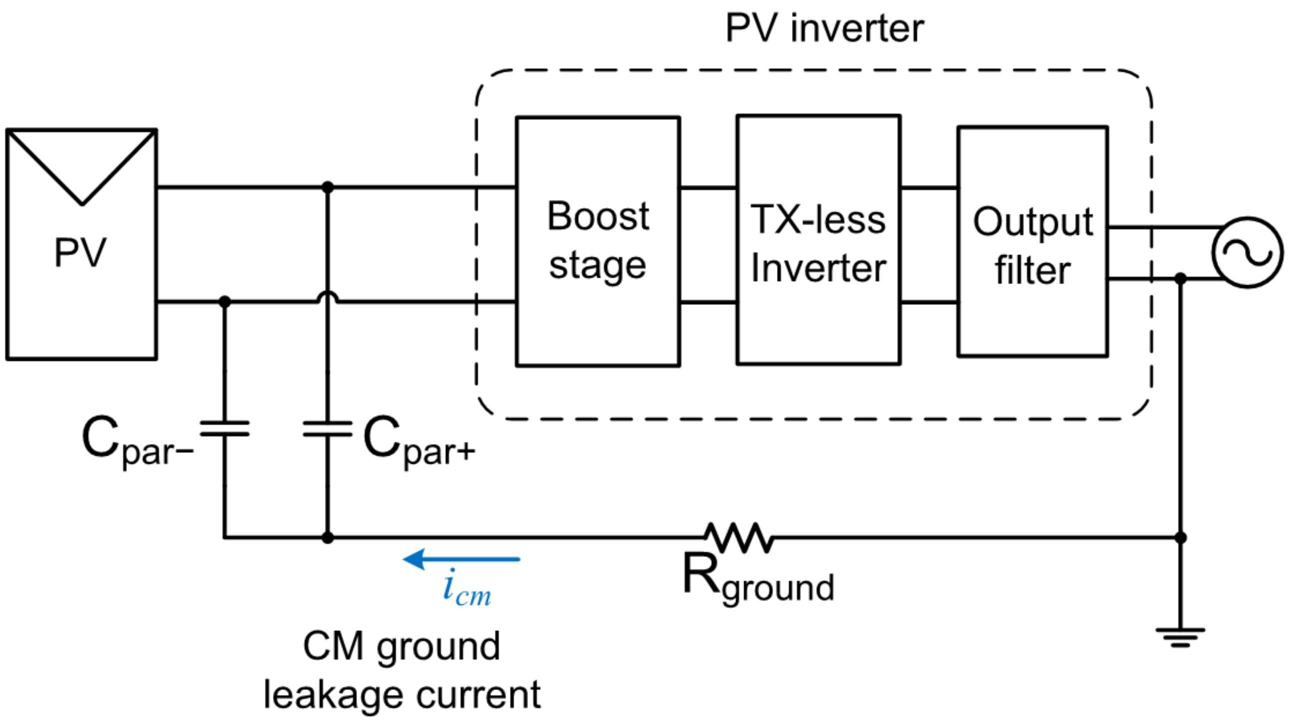


Fig. 3: CM ground leakage current circulation path.

Contribution

1. CM leakage current generation **mechanism** for the Aalborg inverter
2. Output filter **modification** for the reduction of CM leakage current
3. Equivalent **circuits** and analytical **expressions** for the RMS value of the CM currents
4. Effect of inverter **operating conditions**
5. Effect of **filter parameters**

Fundamentals of the CM voltage waveform

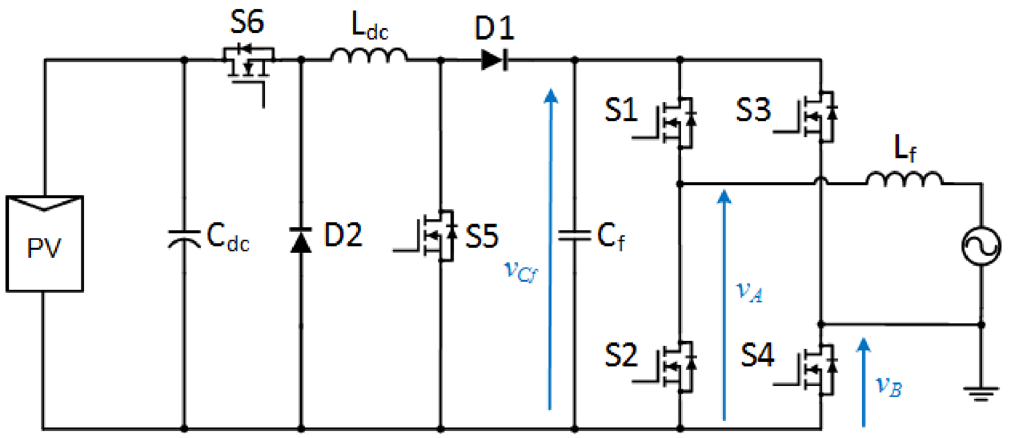
- CM voltage:

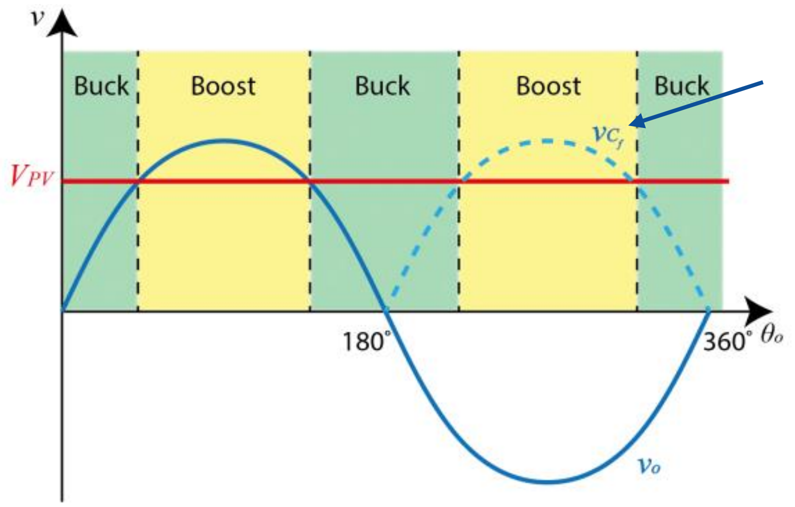
$$v_{cm} = \frac{v_A + v_B}{2}$$

- Fast variation of v_{cm} gives rise to CM current
- H-bridge (S1 to S4) switches at the grid frequency

$$v_{cm} = \frac{v_{Cf}}{2}$$

- Rectified sine wave – Not pulsating – Low CM current expected
- But v_{Cf} contains different types of distortion
- Will be discussed for Buck / Boost mode





Distortions on the CM voltage waveform Buck mode

I. Voltage ripple:

- LC filter capacitor for the Buck converter
- ≈ 1% of the peak grid voltage

II. Distortion at zero-crossings:

- Operation only with PF = 1
- Phase lag introduced to the output current by the filter inductors
- C_f voltage does not exactly follow a rectified sine wave in the area of zero crossings of the grid voltage
- Fast voltage transients appear because the capacitor current changes direction before the capacitor voltage reaches zero

Distortions on the CM voltage waveform
Boost mode

III. Increased voltage ripple:
- Output capacitor for the Boost converter
- ≈ 15% of the peak grid voltage

IV. Distortion at the transitions between the two modes:
- Characteristics depend on the inverter control strategy and method applied to ensure a smooth transition
- Not appearing with control method proposed in previous work

Equivalent circuits for CM current generation

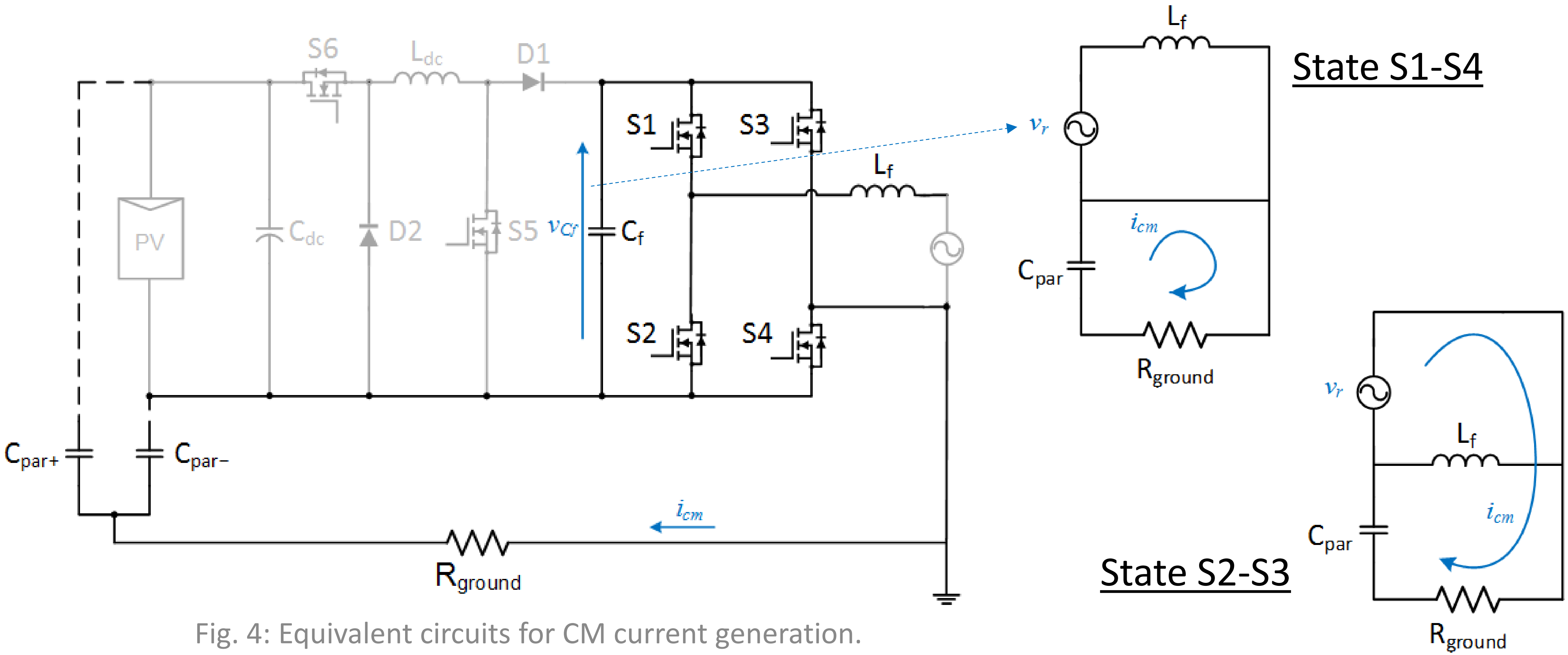


Fig. 4: Equivalent circuits for CM current generation.

Equations for CM current RMS value

A) Due to switching-frequency ripple on v_{Cf} (v_r, $V_{r,RMS}$)

- State S1–S4 (positive half-cycle)

$$I_{cm,r,RMS,1-4} = 0,$$

- State S2–S3 (negative half-cycle)

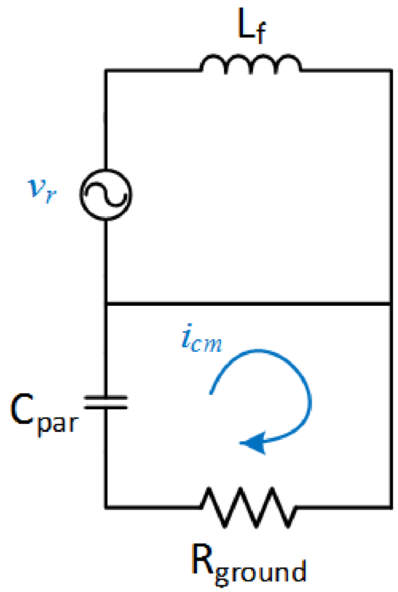
$$I_{cm,r,RMS,2-3} = V_{r,RMS} \Big/ \sqrt{R_{ground}^2 + 1/(\omega_s C_{par})^2}$$

- Total

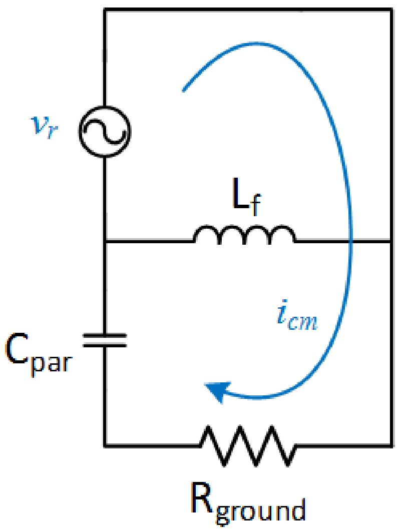
$$I_{cm,r,RMS} = V_{r,RMS} \Big/ \sqrt{2\left[R_{ground}^2 + 1/(\omega_s C_{par})^2\right]}$$

B) Due to fundamental-frequency ripple on v_{Cf} ($V_{g,RMS}$)

$$I_{cm,f,RMS} \approx V_{g,RMS}\, \omega_g C_{par} / \sqrt{2}$$



State S1-S4



State S2-S3

Proposed output filter modification

- Output filter inductor (L_f) split to two
- Suppresses the CM currents peaks at the zero-crossings of the grid voltage
- Neutral of the grid no longer connected to the negative DC-link terminal during state S1-S4
- CM current flows during both grid voltage half-cycles

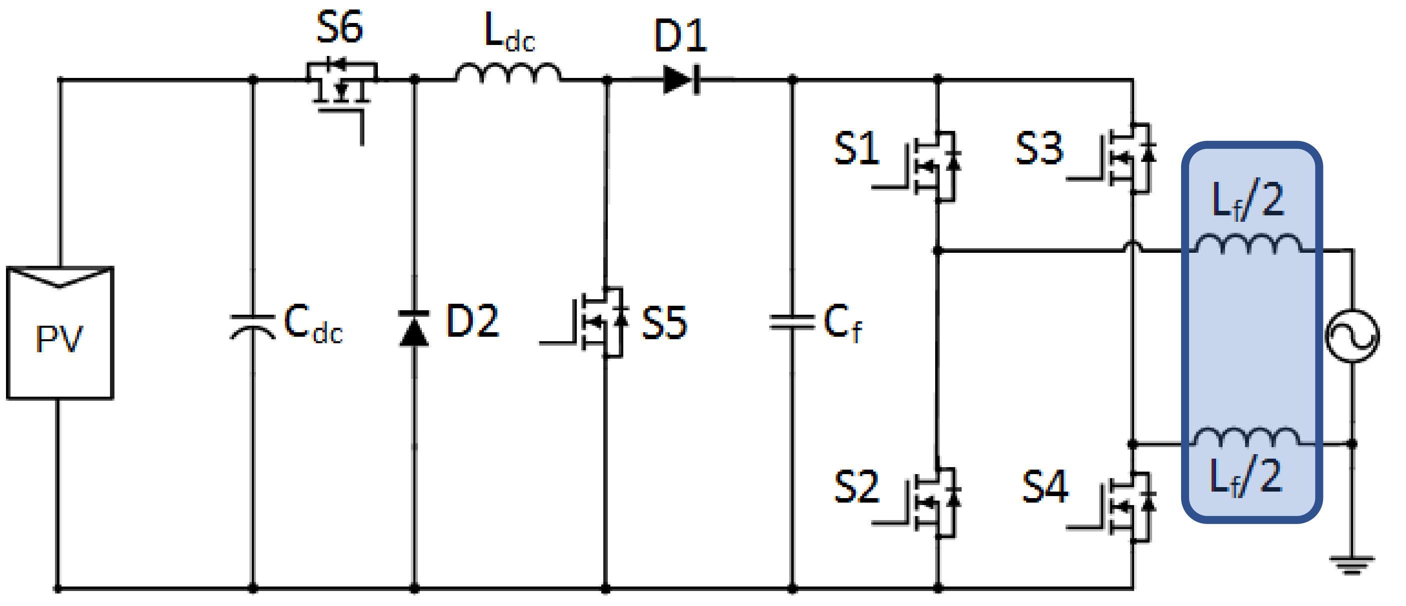


Fig. 5: Full-bridge Aalborg inverter topology with modified output filter.

Equivalent circuit for CM current generation

- Equivalent circuit of Fig. 6 holds for both inverter states
- Same values of $V_{r,RMS}$ and $V_{g,RMS}$ as before
- CM current RMS value due to switching-frequency ripple

$$I'_{cm,r,RMS} = V_{r,RMS} \cdot 2\omega_s C_{par} / \left|4 - \omega_s^2 L_f C_{par}\right|$$

- Resonance at

$$L_{f,res} = \frac{4}{\omega_s^2 C_{par}}$$

- **Ratio** and **minimum L_f** for CM current reduction

$$\frac{I'_{cm,r,RMS}}{I_{cm,r,RMS}} = \frac{2\sqrt{2}}{\left|4 - \omega_s^2 L_f C_{par}\right|}, \qquad L_{f,min} = \frac{4 + 2\sqrt{2}}{\omega_s^2 C_{par}}$$

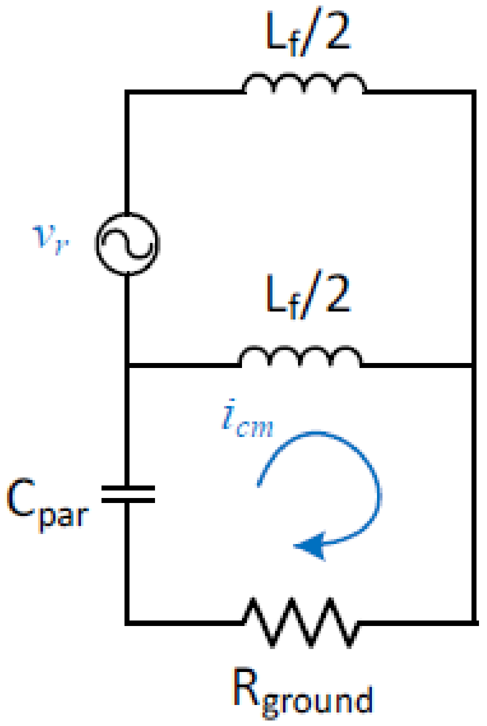
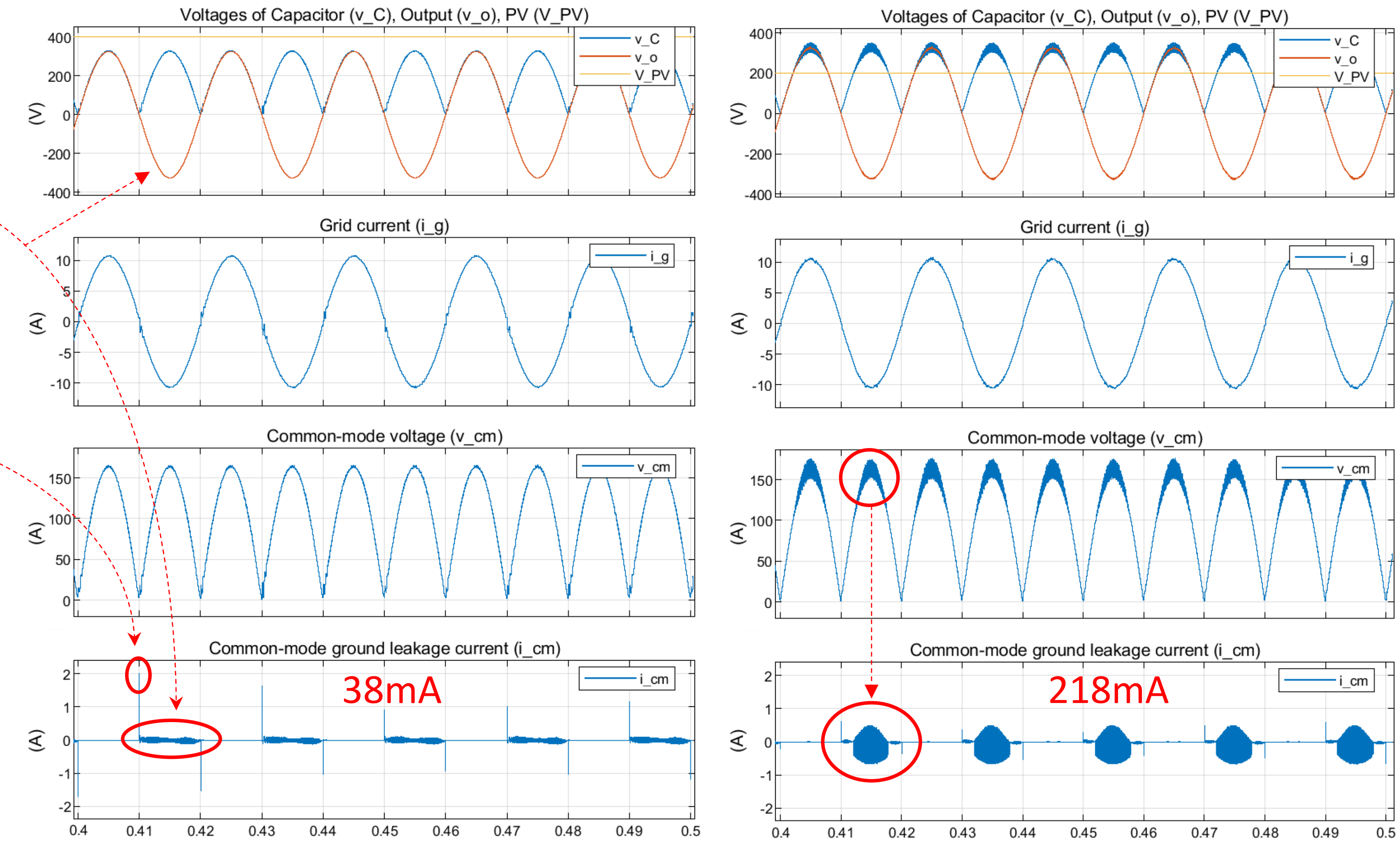


Fig. 6: Equivalent circuit for CM current generation with modified filter.

Simulation results – Original filter

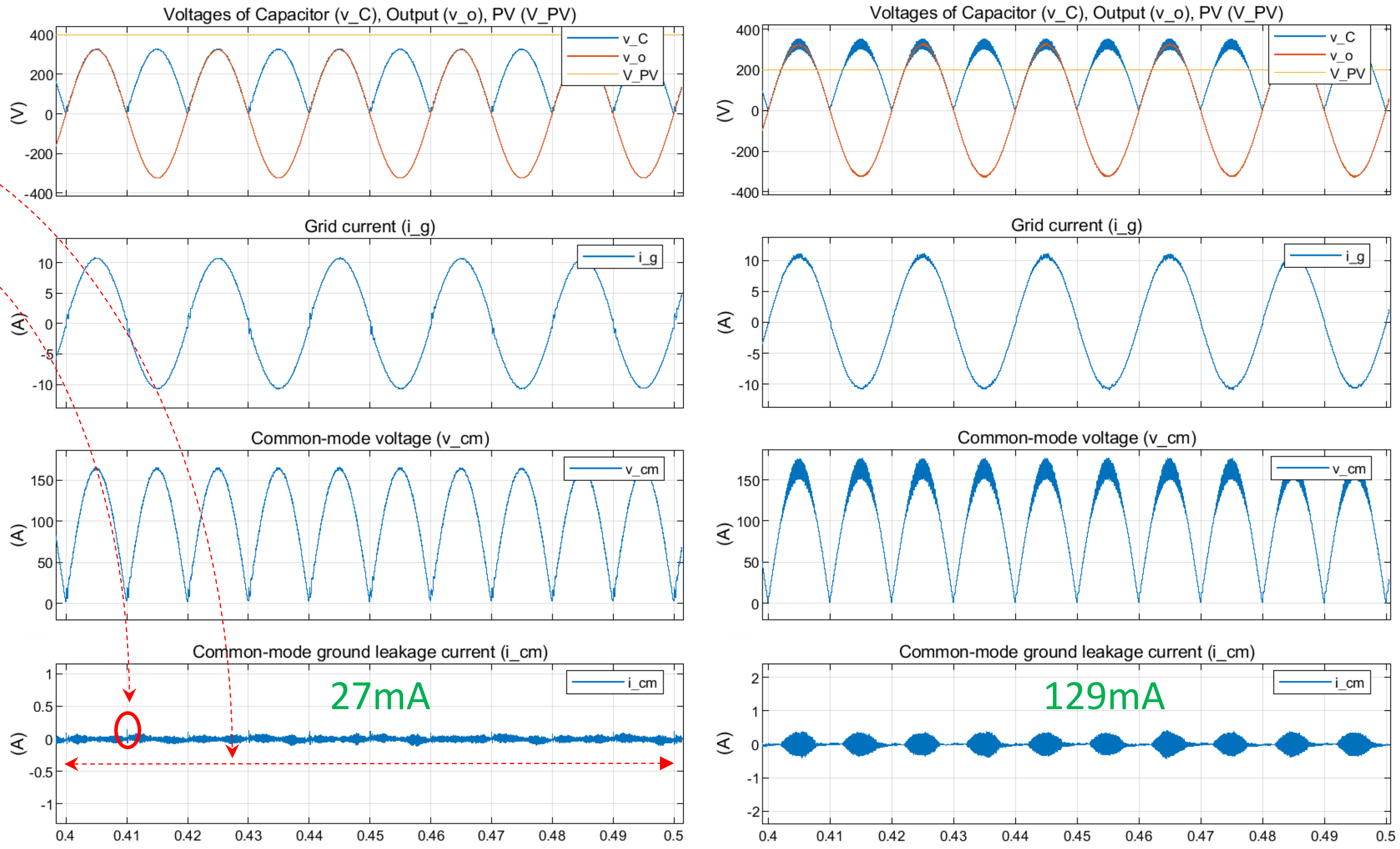
- Buck only / Buck-Boost mode
- CM current flows only during the negative half-cycles
- High peak values of CM current at the zero crossings of the grid voltage
- RMS values:
  - 38mA for the Buck only mode
  - 218mA for the Buck-Boost mode, due to higher voltage ripple
- Peak values: 0.5 – 2A



Simulation results – Modified filter

- CM current flows during both half-cycles
- Low peak values of CM current at the zero crossings
- RMS values:
  - 27mA for the Buck only mode
  - 129mA for the Buck-Boost mode
- Ratio (vs original filter): 0.62

$$\frac{I'_{cm,r,RMS}}{I_{cm,r,RMS}} = \frac{2\sqrt{2}}{\left|4 - \omega_s^2 L_f C_{par}\right|}$$



Ratio for different operating conditions

- Same values of ω_s , L_f, C_{par}
- PV voltage:
  - 200V – Buck-Boost mode
  - 400V – Buck only mode
- PV power: 250 – 2000W
- Within –5/+8% of 0.62
- HERIC inverter with boost stage and LCL filter generates approximately 100mA

Table I: CM current RMS value ratio for the original and modified filter, under different operating conditions.

PV voltage [V]	PV power [W]	Original [mA]	Modified [mA]	Ratio
200	2000	247.8	142.6	0.58
	1000	124.6	71.3	0.57
	500	64.2	37.7	0.59
	250	36.7	21.8	0.60
400	2000	37.7	22.9	0.61
	1000	35.6	22.9	0.64
	500	34.6	22.9	0.66
	250	34.6	22.9	0.66

≈ 0.62

Ratio for different filter parameters

- CM current is inversely proportional to L_{dc} and C_f
- L_f from $L_{f,min}$ to $2L_{f,min}$
- PV voltage: 200V / 400V
- PV power: 2000W
- Ratio for $2L_{f,min}$: 0.3

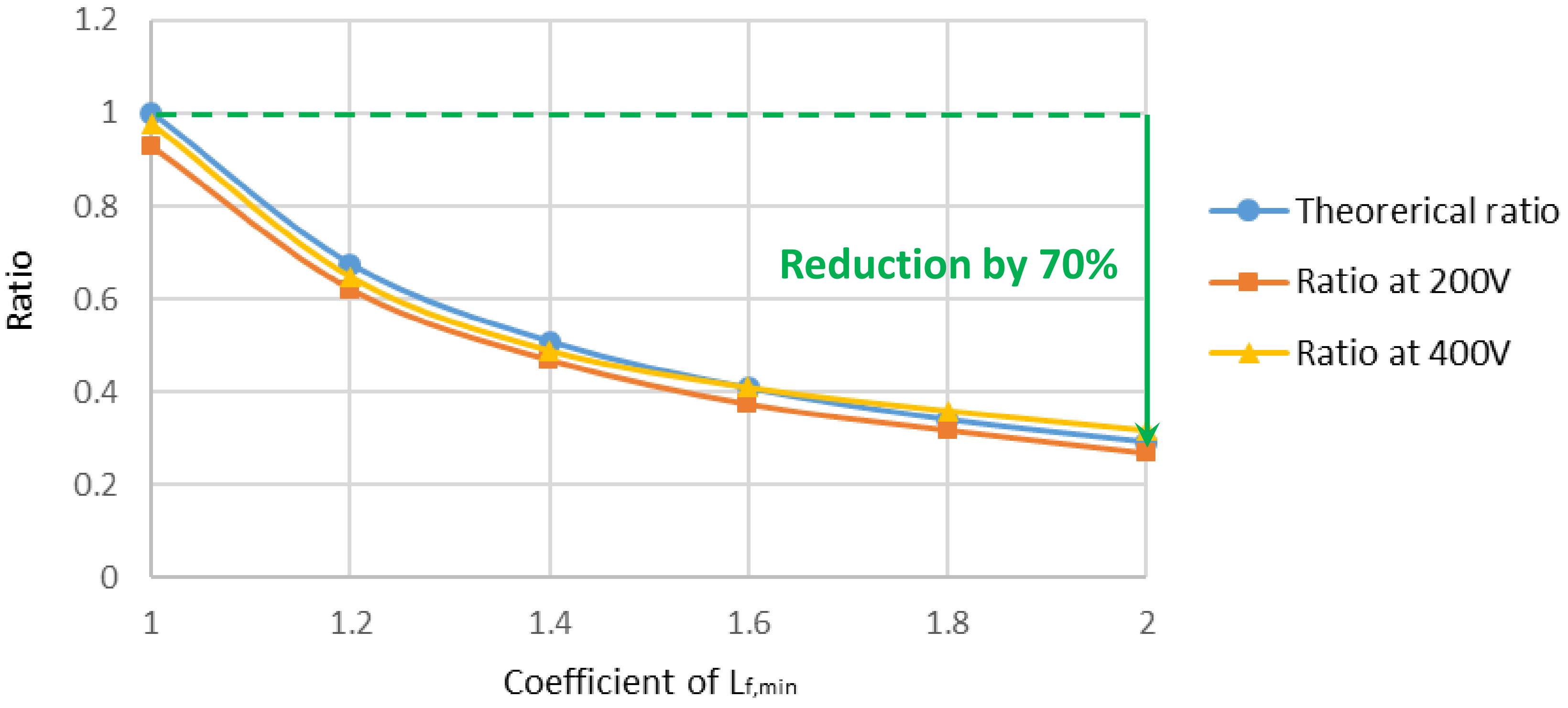


Fig. 7: CM current RMS value ratio for different values of L_f.

Comparison of alternatives for reducing the CM current

- Increasing C_f
  - grid current distortion at the zero-crossings
  - imposes a limit on the size of C_f
- Increasing L_{dc}
  - rated at higher current (2 – 3×) than L_f
  - lower effect on CM current
  - subject to higher copper and core losses
  - wound on a low-loss (e.g. ferrite) core
- Given the switching frequency and the value of C_f, increment of L_f is preferable
- Requires approximate knowledge of C_{par}

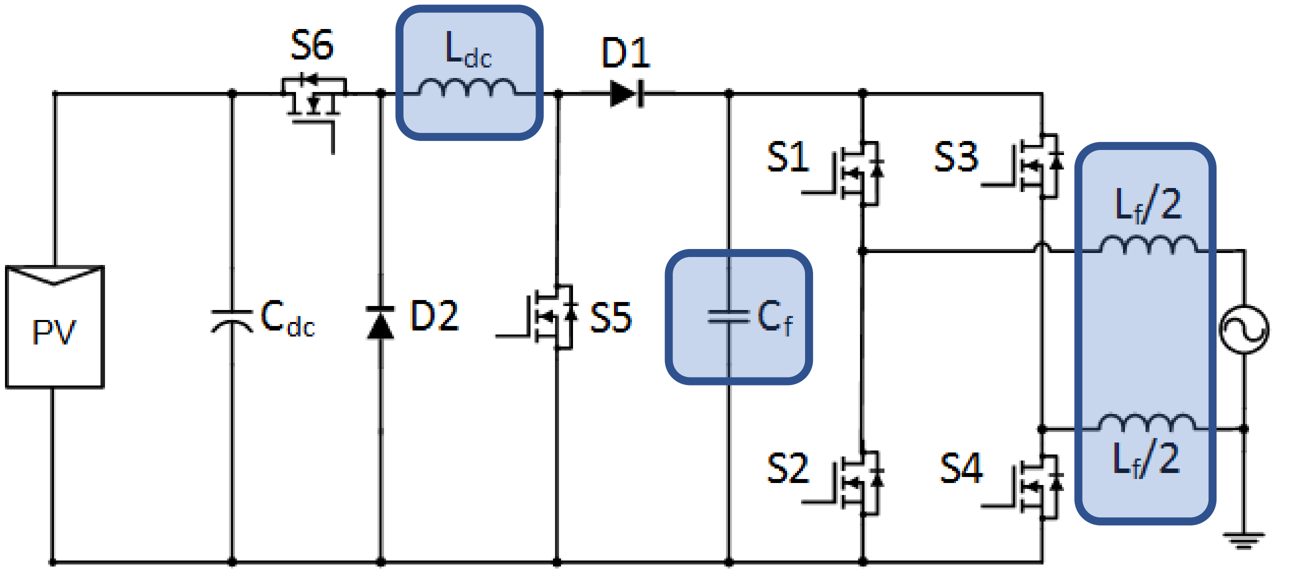


Fig. 8: Full-bridge Aalborg inverter topology with modified output filter, highlighting the components considered for CM current reduction.

Conclusion

- CM leakage current generation mechanism – analytical expressions
- Output filter modification for up to 70% reduction of CM current
- Investigation under different operating conditions
- Effect of LCL filter parameters
- Applicable to other topologies with rectified sine wave DC-link voltage (!)

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THANK YOU!