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Bidirectional Shared-Switch DC-DC Converter for Electric Vehicle Applications

Michael Kercher, PhD Student

FREEDM Symposium

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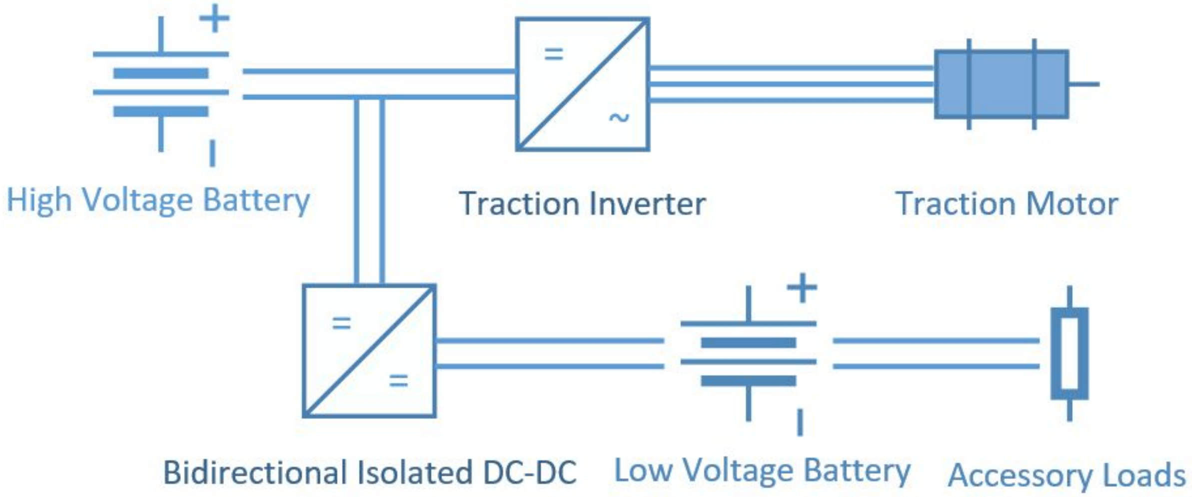
Electric Vehicle Architecture

- Energy from the main battery pack is consumed by:
  - Traction drive system
  - Accessory loads via low voltage subsystem, such as lighting, climate control, radio, etc.
- DC-DC converter connects high and low voltage systems with galvanic isolation
  - Typical size:
    - 2-3 kW (passenger)
    - 5-10 kW + (heavy duty)

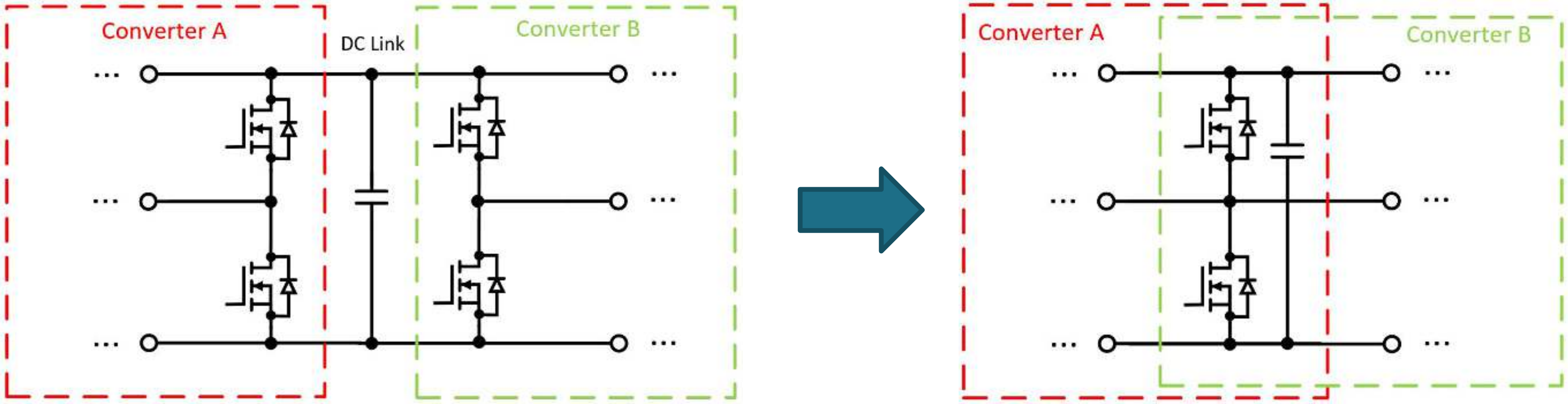


Research Motivation

- Increase efficiency - improves battery life, reduces cooling needs
- Increase density - less mass, easier packaging
- Reduce cost - improved value for manufacturer and consumer

- *The proposed "Shared-Switch Converter" can achieve all 3*
  - One set of switches performs functions for two converter stages
  - Lower parts count means lower size, cost, and losses

Two converter stages

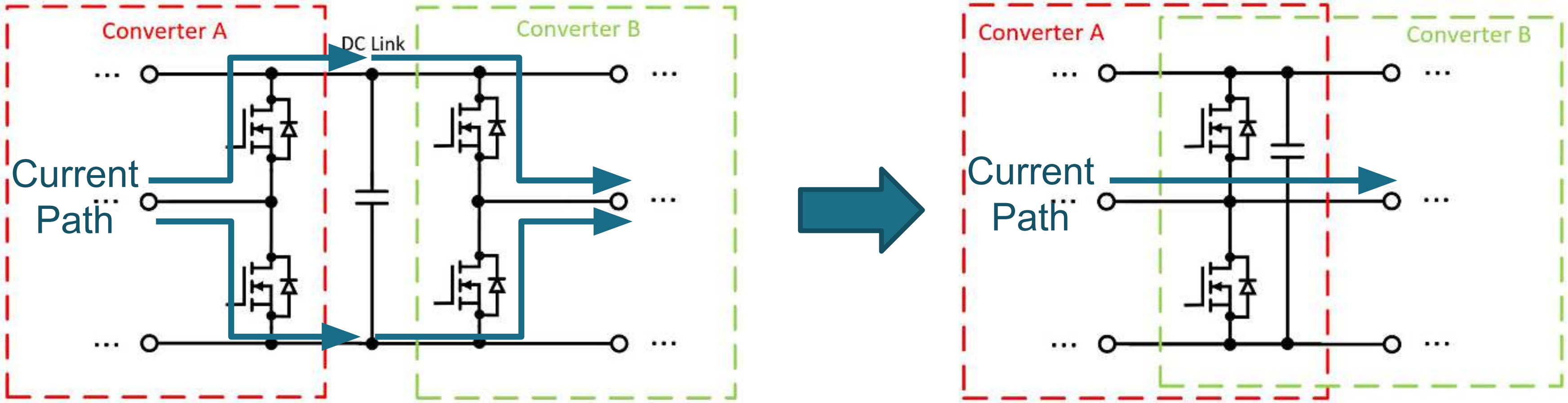


Merged to reduce switch count

Research Motivation

- Benefits:
  - Reduced parts count – smaller, lighter, cheaper
  - Fewer switches to generate switching losses
  - More direct current path reduces conduction loss
- Challenges, gaps in prior art:
  - Gating generation to ensure proper operation of both converters under all conditions – unique to the specific topology
  - Modeling for shared-switch topologys, especially if converters operate in different modes (CCM vs. DCM, etc.)
  - Hardware design: component sizing, minimization of parasitic effects

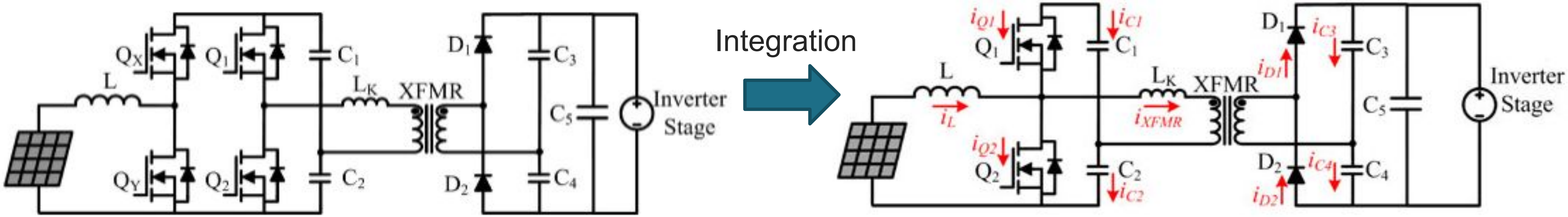
Two converter stages



Merged to reduce switch count

Literature Review

- Numerous examples of integrated topologies in literature
- Boost + Series Resonant Converter:



- Allows resonant stage to operate in efficient DCX mode across varying input voltage from photovoltaic array
- Number of active switches reduced by 50% vs. two stage converter
- Minimum 96.8% efficiency across voltage range vs. 90% for series resonant only

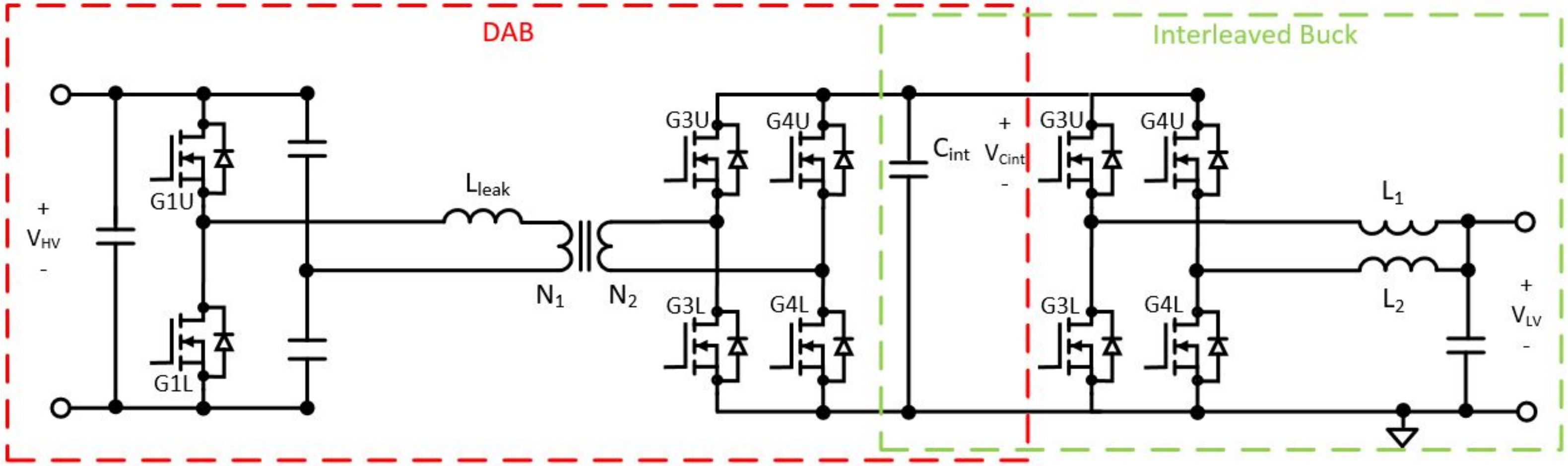
B. York, W. Yu and J. -S. Lai, "An Integrated Boost Resonant Converter for Photovoltaic Applications," in *IEEE Transactions on Power Electronics*, vol. 28, no. 3, pp. 1199-1207, March 2013, doi: 10.1109/TPEL.2012.2207127.

Literature Review

- Examples from literature show:
  - Improved efficiency across varying operating conditions
  - Successful reduction of active switch and filter element requirements
  - Lower cost and higher power density vs. traditional topologies
- Research objectives:
  - Increased power capability for heavy vehicle applications
  - Broader range of voltage conversion ratios to account for changing battery state of charge
  - Ability to maintain high efficiency at conversion ratio extremes
  - Straightforward method for modelling and controller development
  - Simplified control without coupling of controlled variables or nonlinear behavior

Proposed Topology

- EV DC-DC converter requirements:
  - Bidirectional power: LV battery bank can support HV bus under transients
  - Galvanically isolated
  - Wide voltage conversion ratio range 3:1 $(\frac{HV_{max}}{LV_{min}} : \frac{HV_{min}}{LV_{max}})$ due to changing battery state of charge
- Series-connected DAB and Interleaved Buck
  - DAB offers isolation, bidirectional power control
  - Interleaved buck adapts to changing voltage conversion ratio, allowing DAB to maintain ideal ratio for DCX operation[1]



$$(1)\ V_{Cint} = \frac{1}{2} V_{HV} \frac{N_2}{N_1}$$

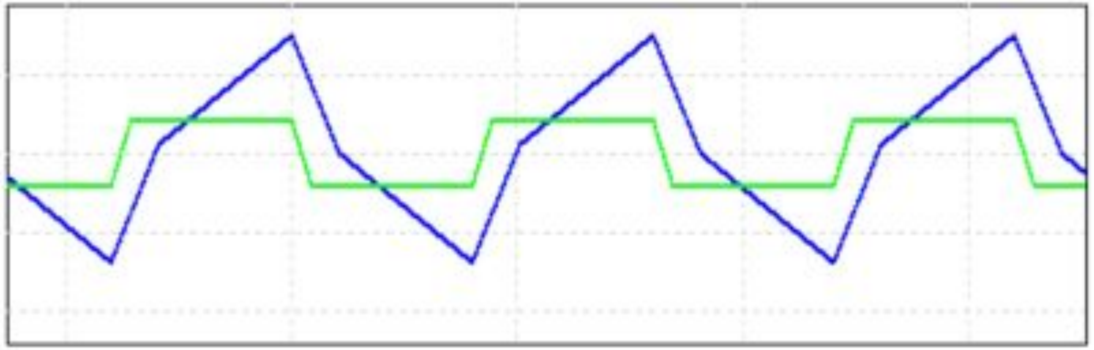
Proposed Topology

- DCX operation of DAB minimizes RMS winding currents, losses

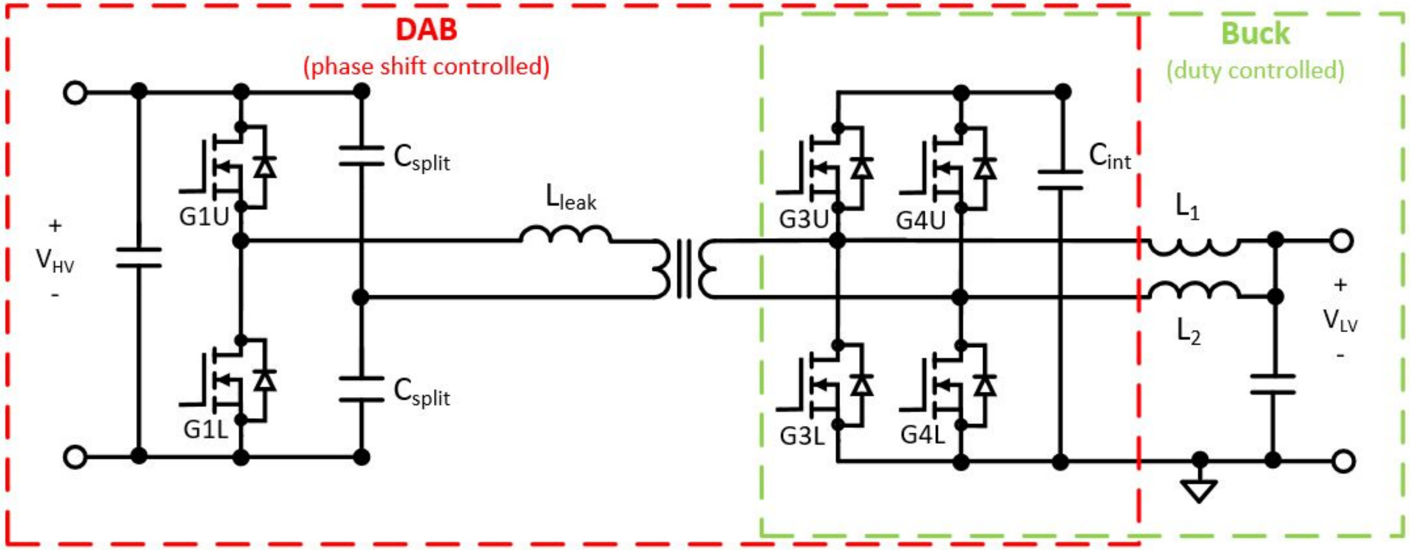
Primary Current for equal power throughput and input voltage:

Sec. voltage matched $V_{Cint} = V_{HV}\frac{N_2}{N_1}$

Sec. voltage mismatch $V_{Cint} \neq V_{HV}\frac{N_2}{N_1}$

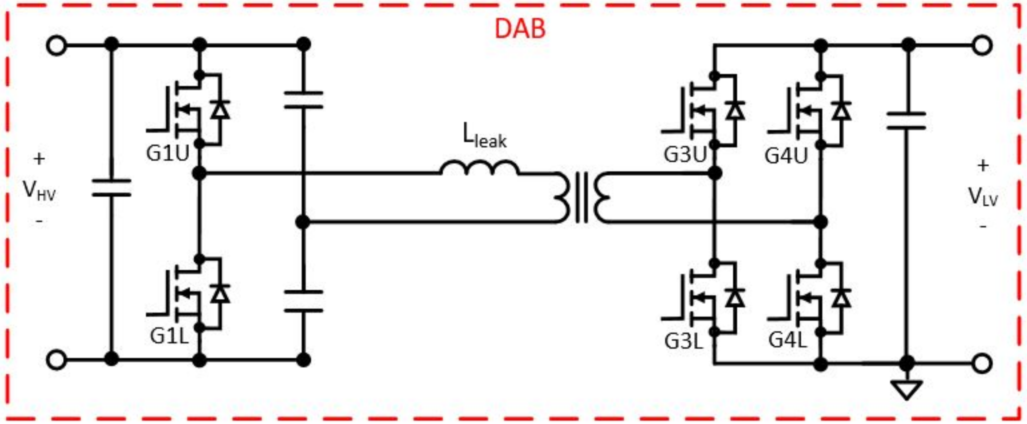


- Applying integration concept reduces switch count 40%, reduces switching and conduction losses

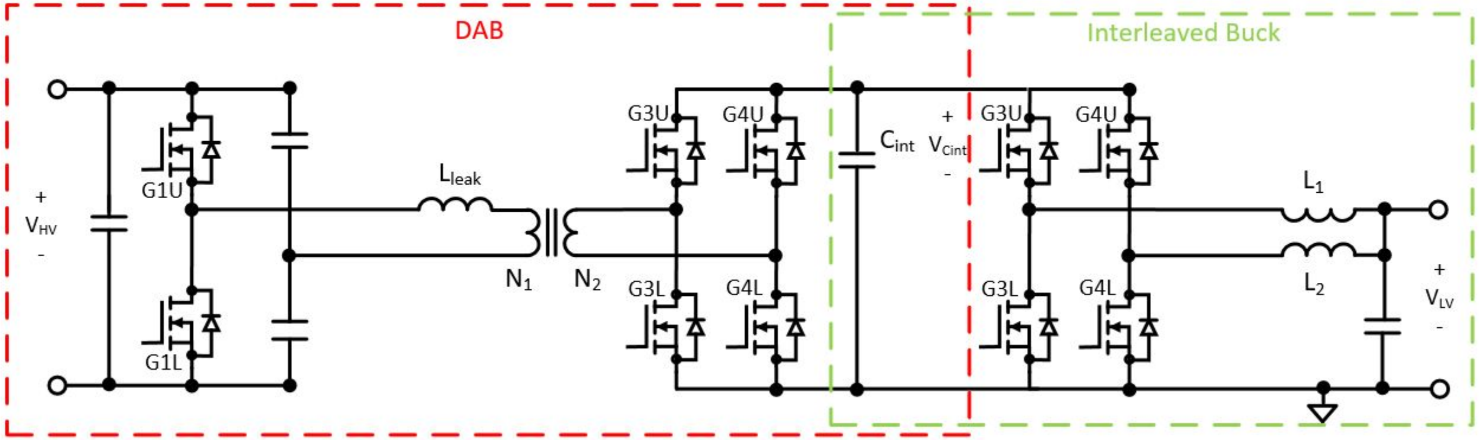


Efficiency Comparison

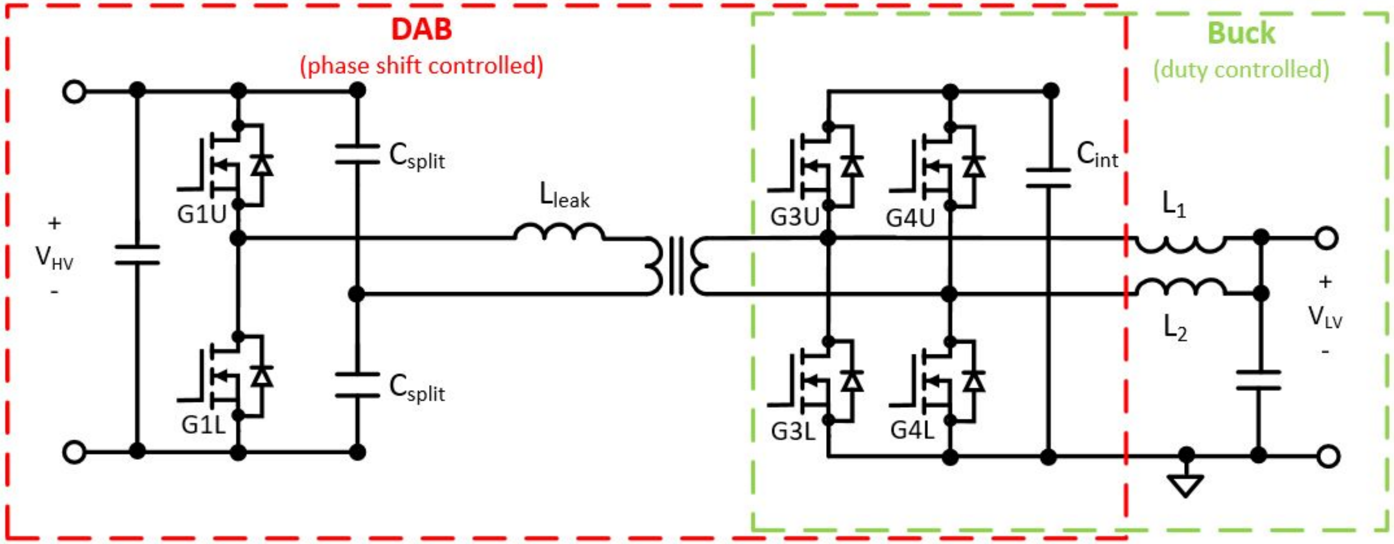
DAB



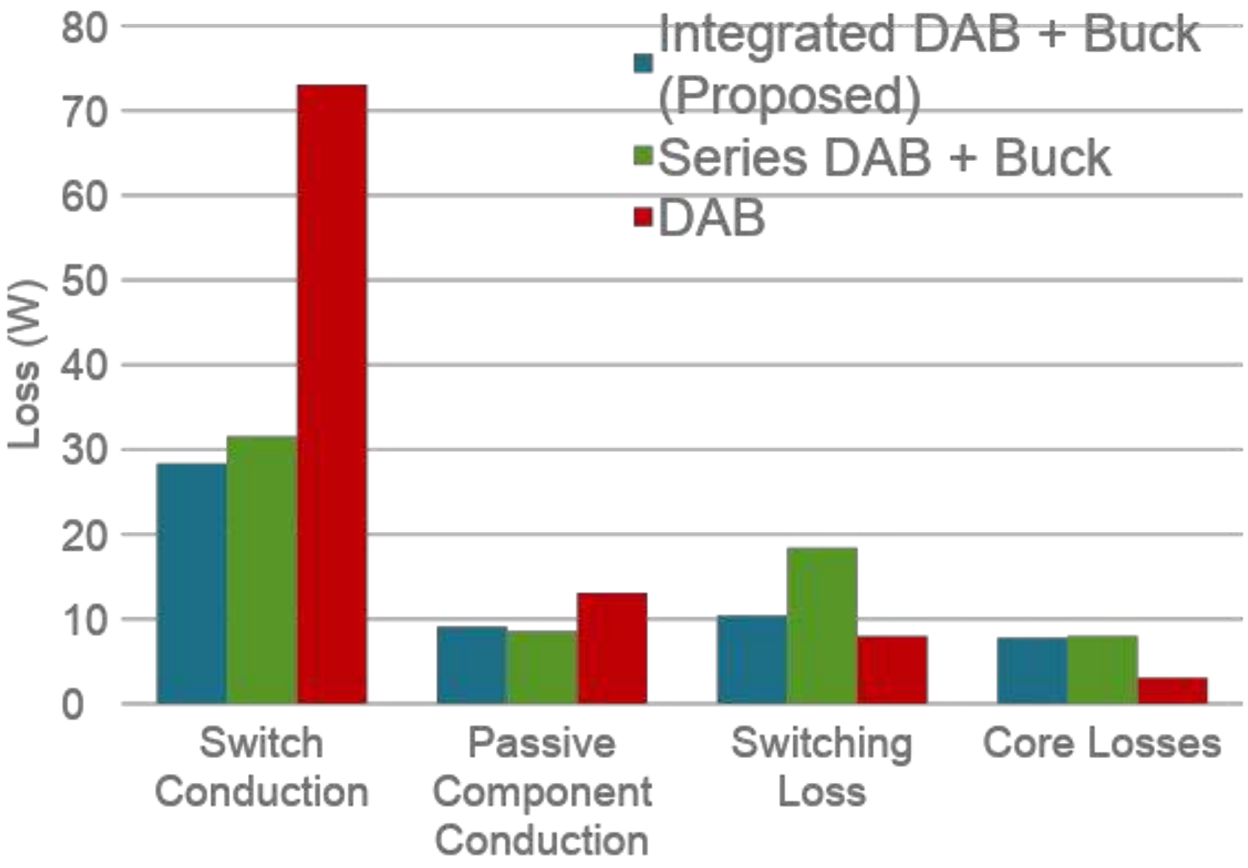
DAB + Buck



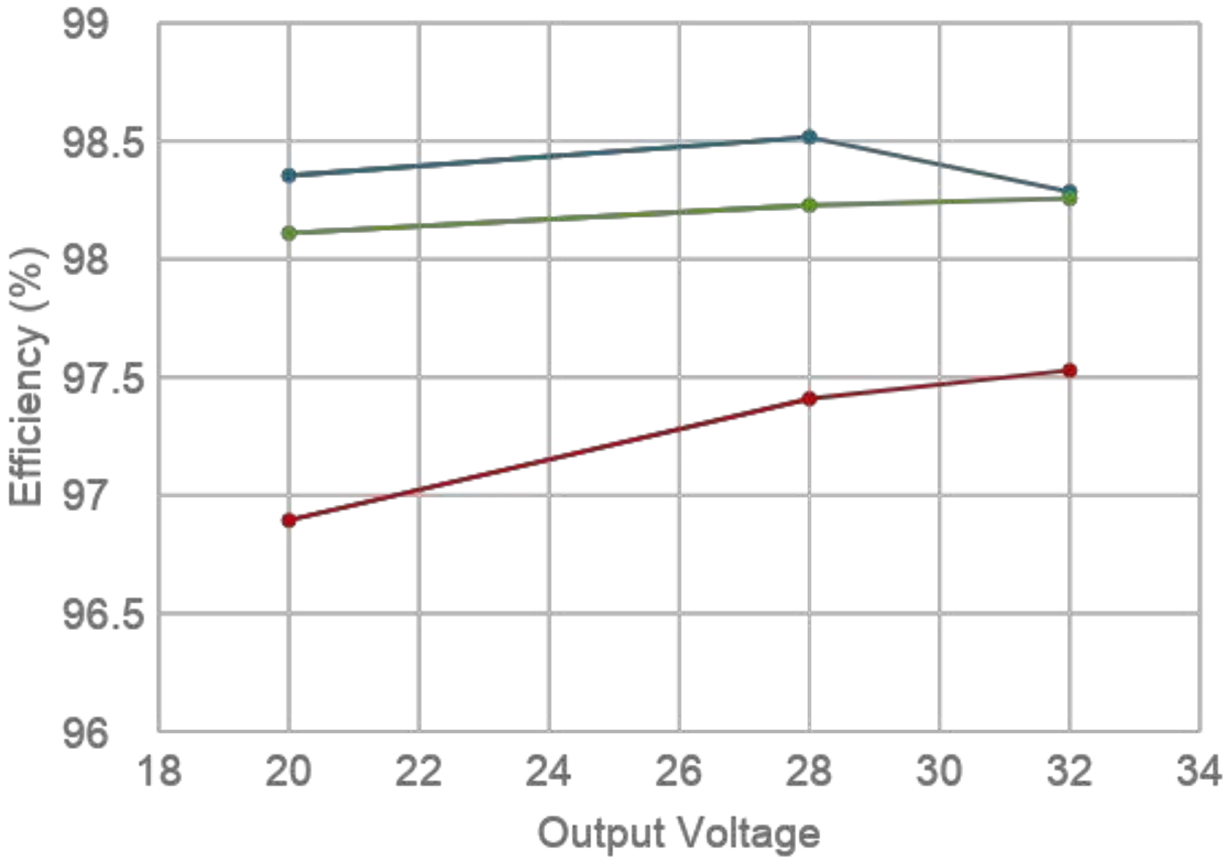
Integrated DAB + Buck



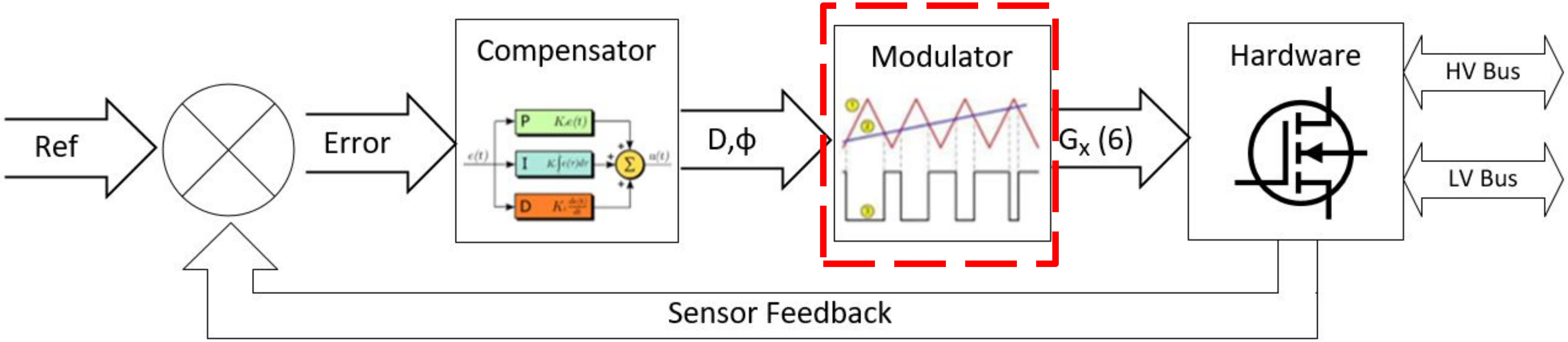
Efficiency Comparison



Loss Breakdown for 600V - 28V, 3.75 kW Operation

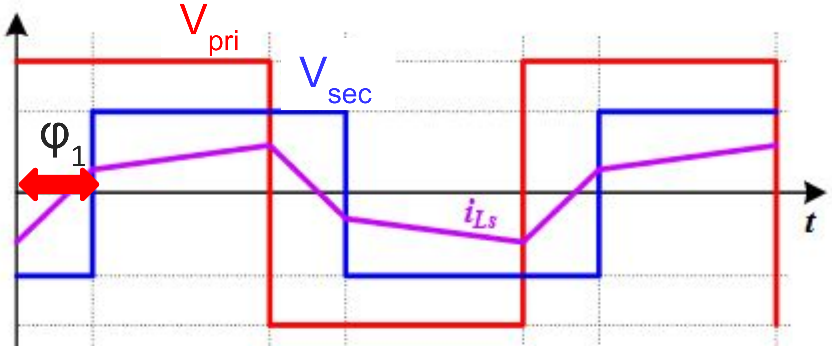


Conventional DAB Modulator

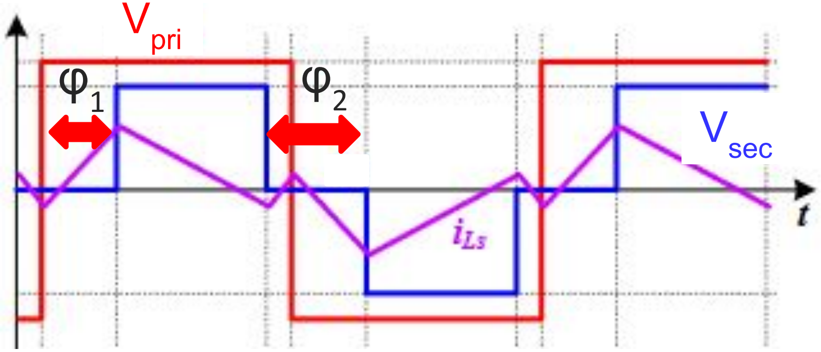


- Conventional DAB modulation: fixed 50% duty, variable phase
  - Single, Double, or Triple Phase Shift used to control power flow
  - HV bridge to LV bridge phase, phase between each full bridge leg

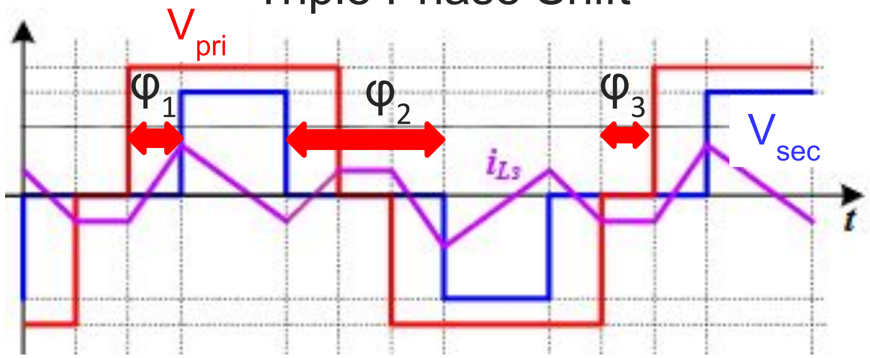
Single Phase Shift



Double Phase Shift

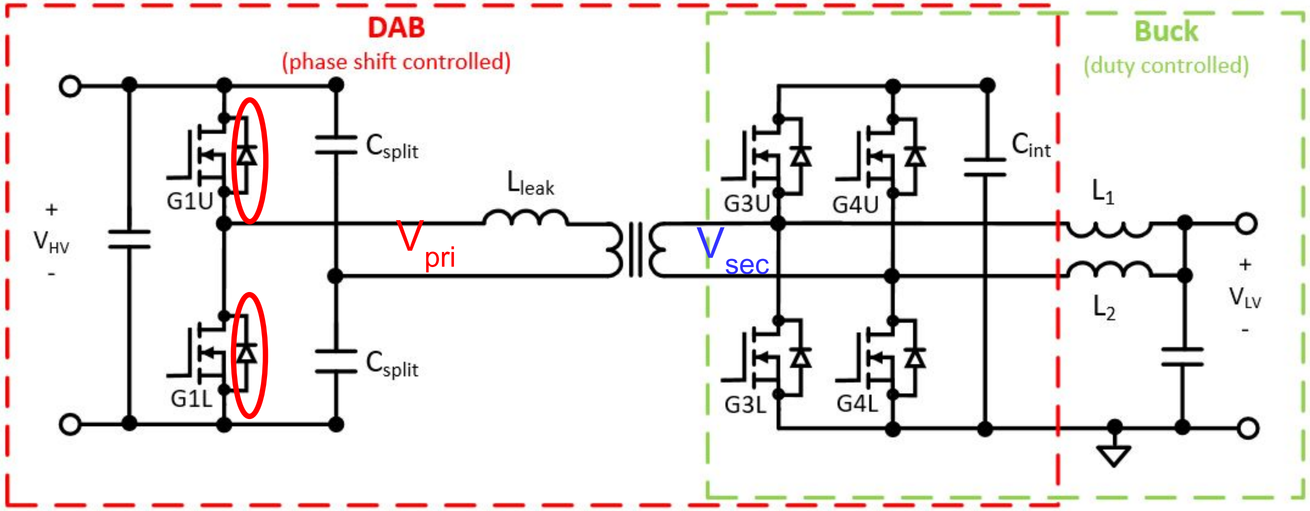


Triple Phase Shift



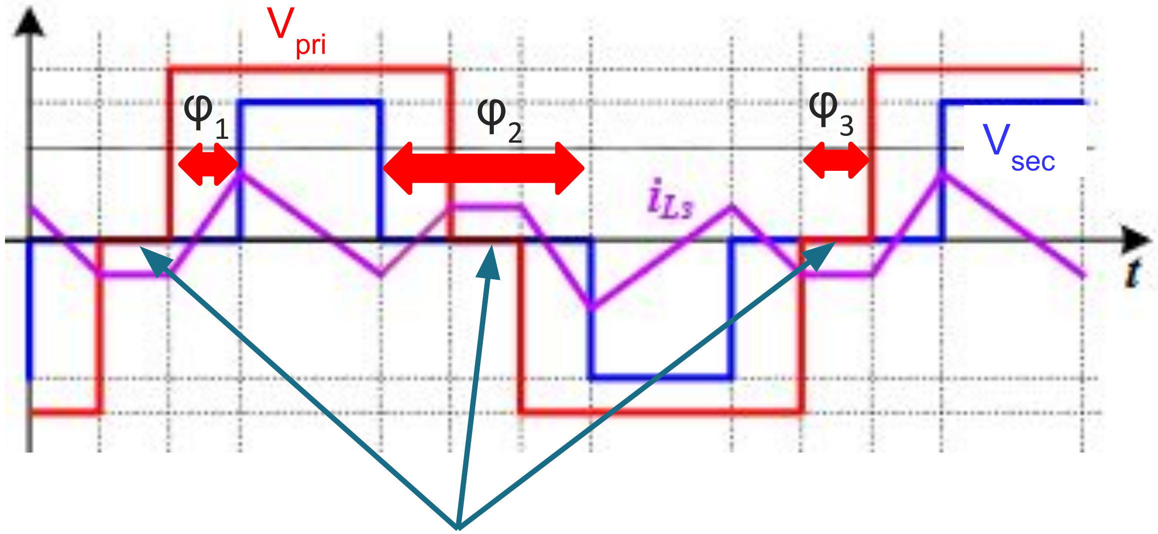
Modulator Challenges

- Fundamental differences for proposed topology vs. traditional DAB:
  - LV Duty ≠ 50% - variable according to buck converter requirements – not DAB
  - HV half bridge cannot enforce $V_{pri} = 0$ when $I_{pri} \neq 0$
- DAB and Buck interaction causes control difficulty



$$D_3 = D_4 = \frac{2\,V_{LV}}{V_{HV}} \frac{N_2}{N_1}$$

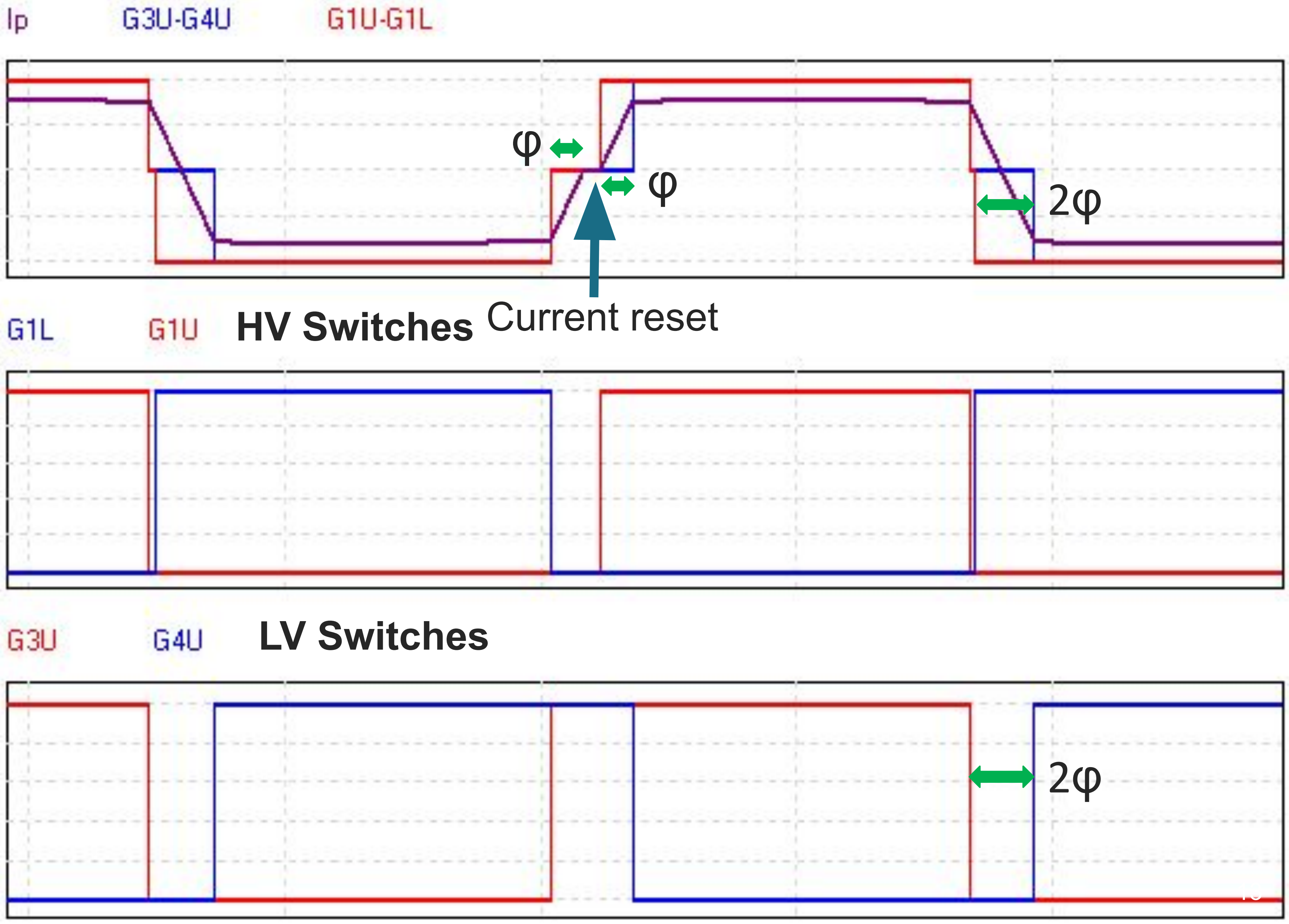
Triple Phase Shift



Not possible due to S1U or S1L body diode conduction

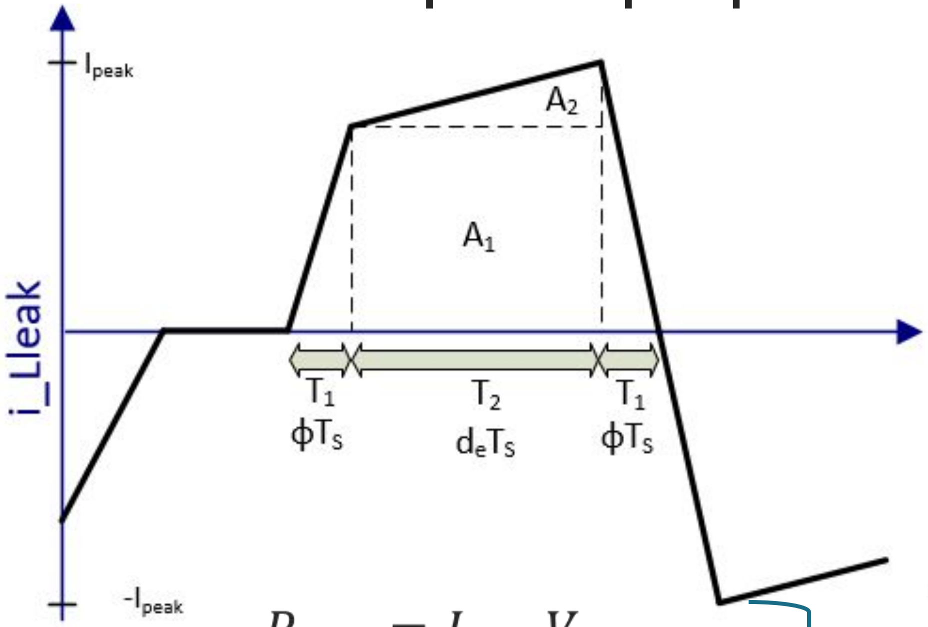
Modulator Solution

- Phase shift between LV legs provides magnetizing current reset once per period for any duty



Decoupled Control

- DAB output is proportional to new control input “Vm”

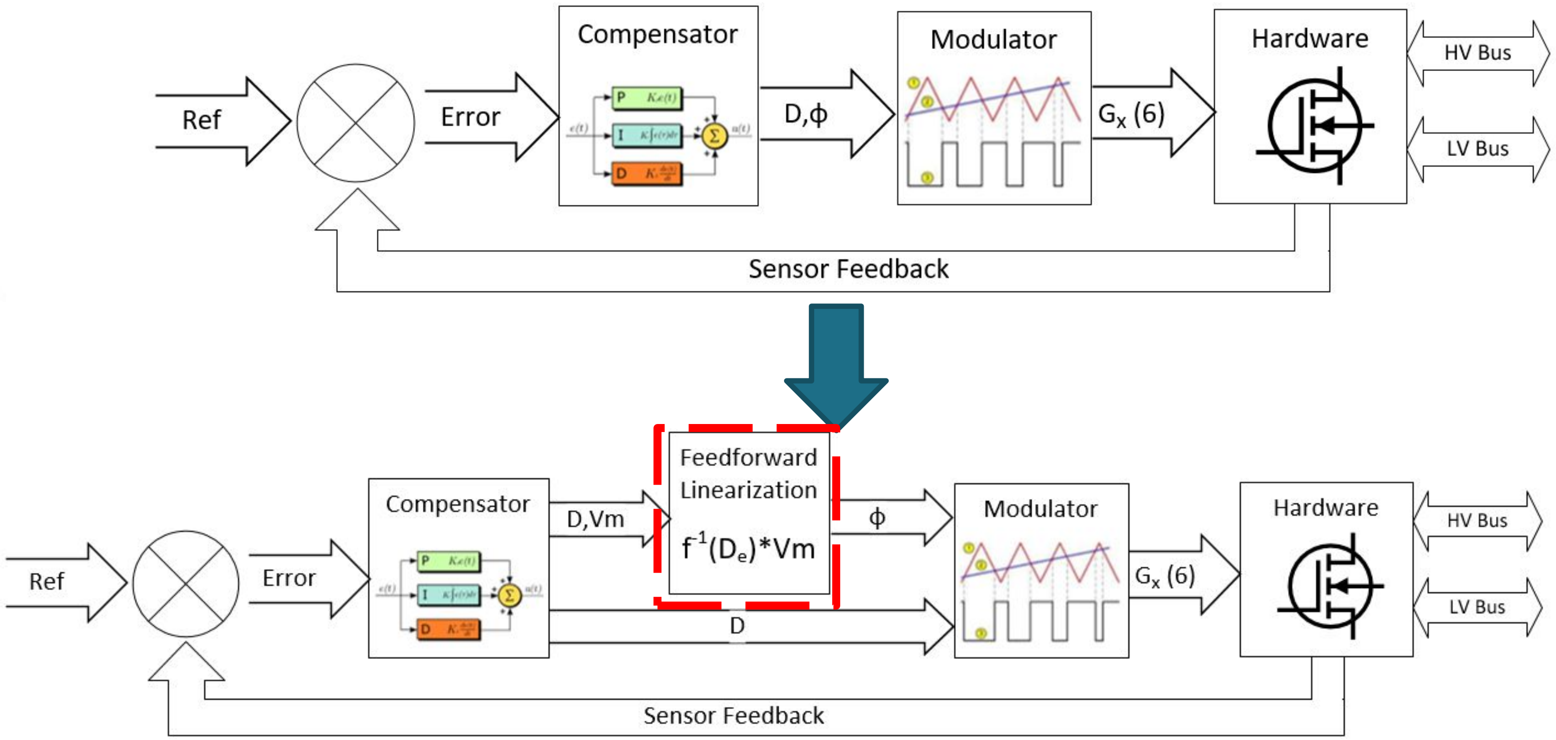


$$P_{DAB} = I_{DAB} V_{LV}$$

$$I_{DAB} = \frac{2 * (A_1 + A_2)}{T_s} \frac{N_1}{N_2}$$

$$A_1 = D_e T_s \frac{\varphi T_s V_{HV}}{2 L_{leak}}$$

$$A_2 = 0 \; for \; V_{Cint} = \frac{1}{2} V_{HV} \frac{N_2}{N_1}$$



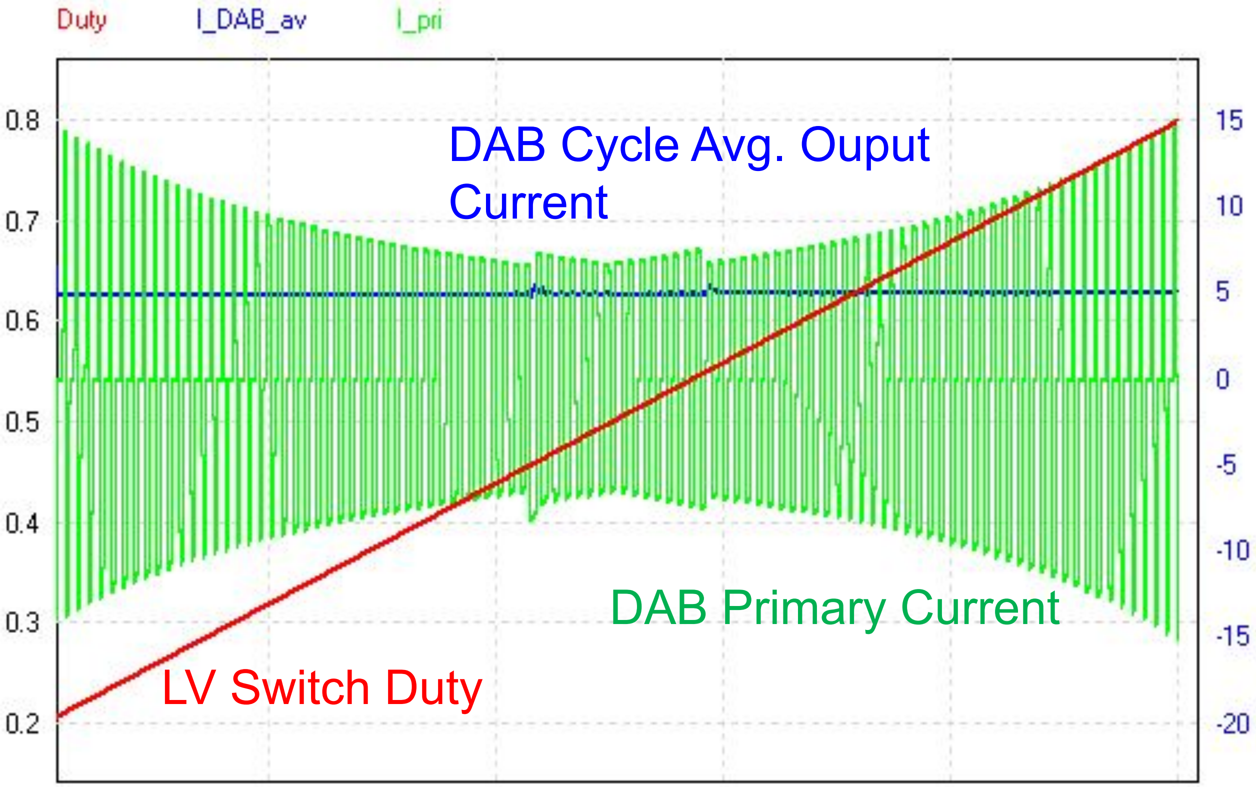
$$P_{DAB} \propto f(D_e) * \varphi$$

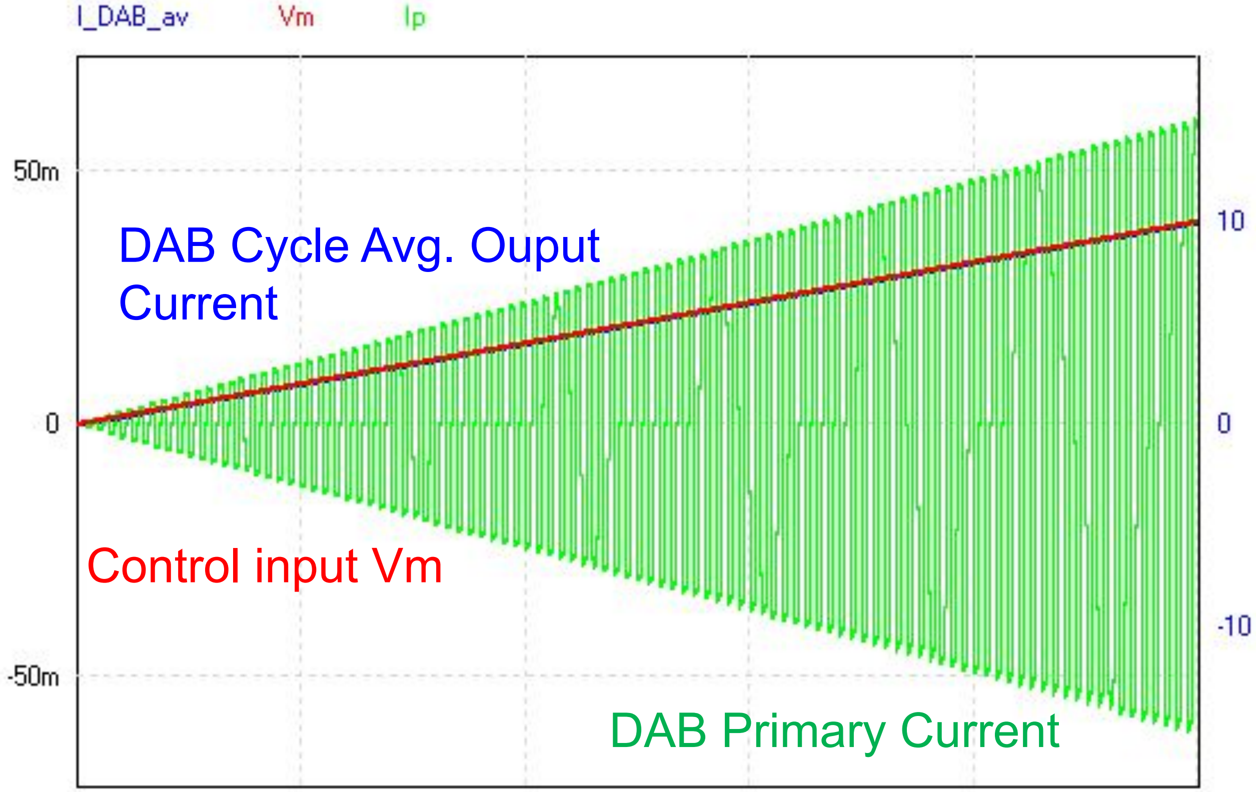
Define: $\boxed{\varphi = f^{-1}(D_e) * Vm}$

Result: $P_{DAB} \propto Vm$ ★

Decoupled Control

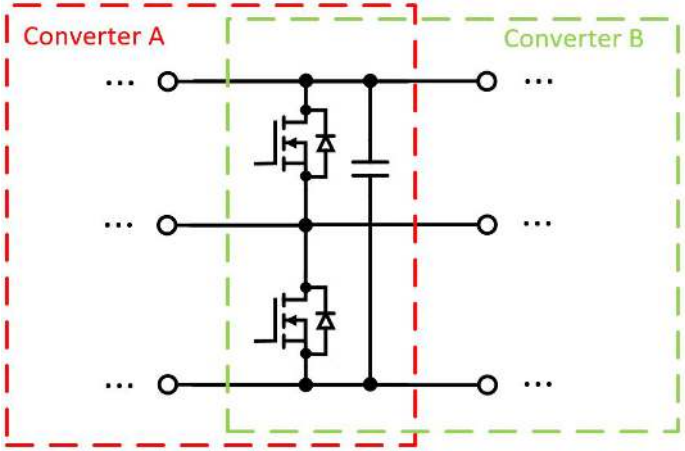
- DAB output current is fully decoupled from LV Duty
- DAB output current is directly proportional to control input Vm



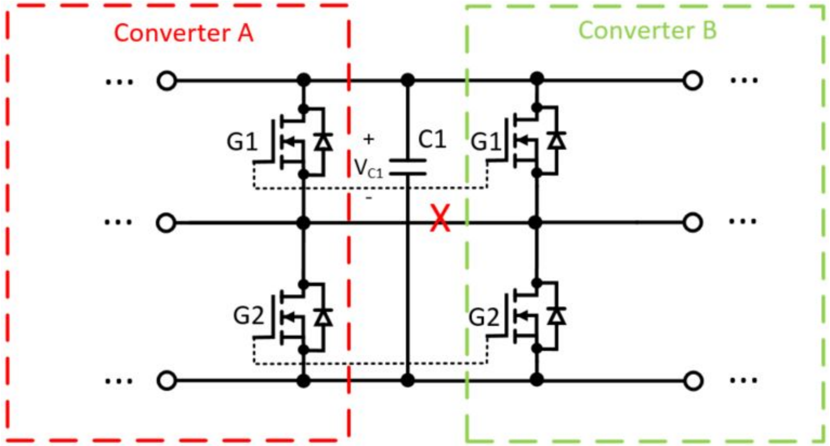


Virtual Converter Model

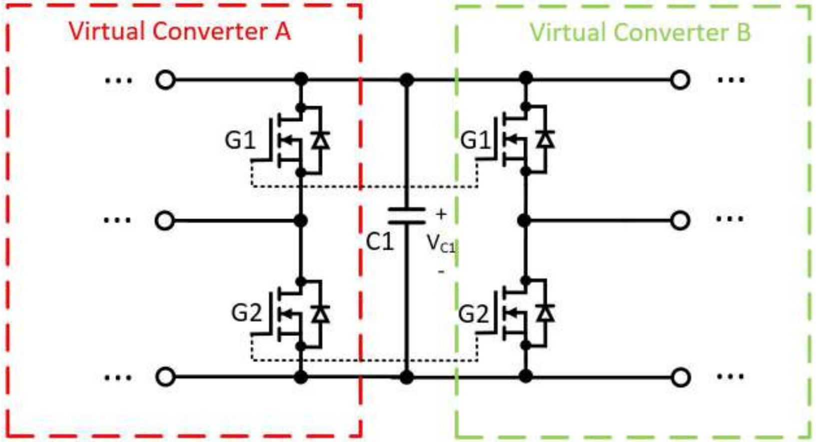
- Integrated converter analysis can be difficult due to interaction between stages at the shared components
- Virtual Converter Modeling (VCM) splits an integrated converter in to separate “virtual converters” which can be analyzed by traditional methods



Integrated Converter



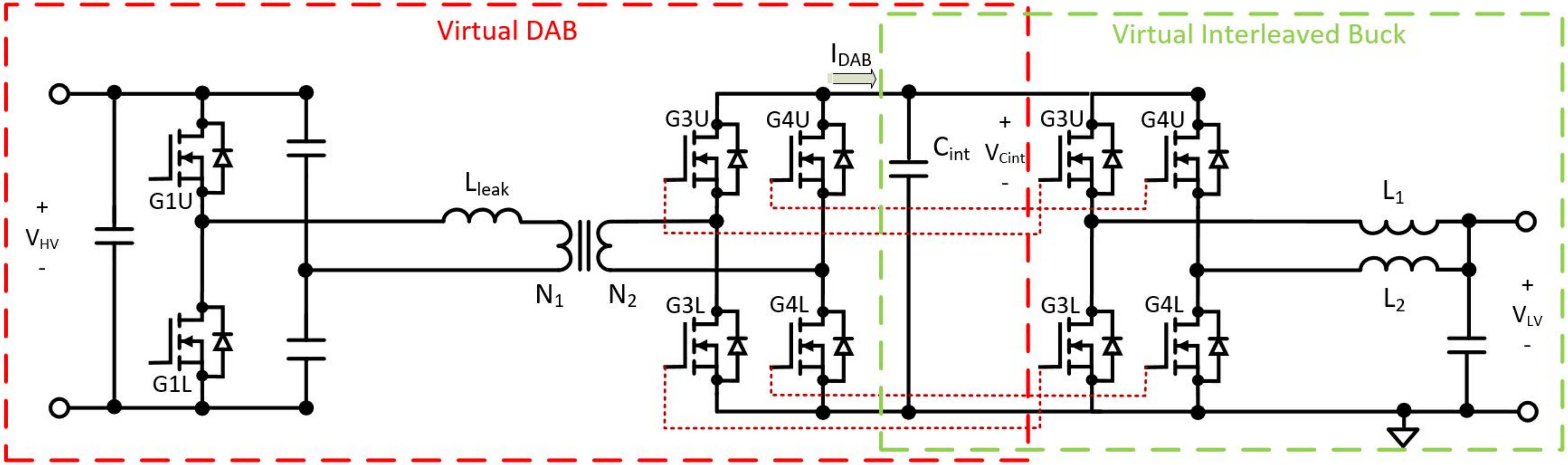
Switches duplicated, gates connected



Virtual Converter equivalent circuit

Application of VCM

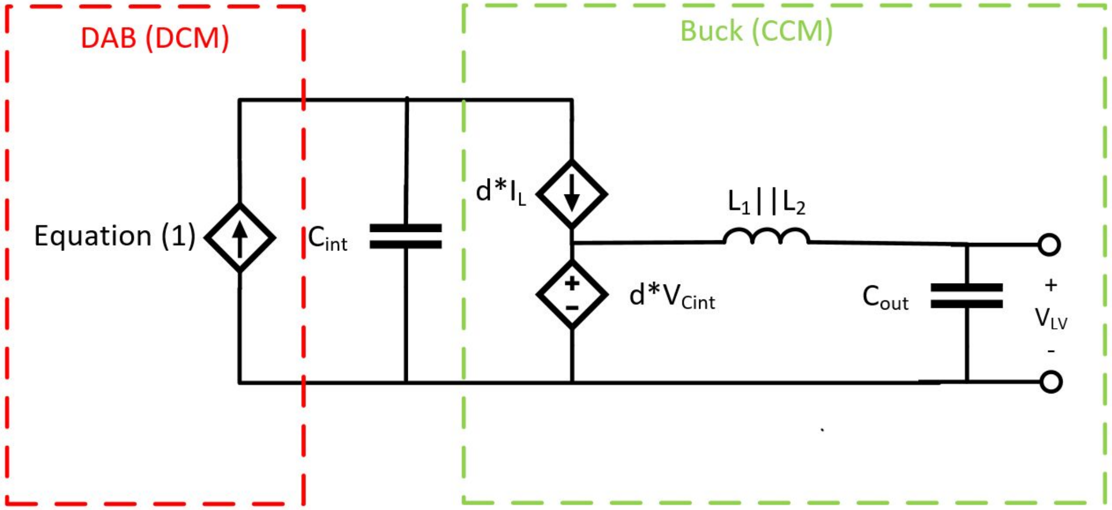
- Bidirectional Shared-Switch DC-DC Converter is modelled as separate DAB and Interleaved Buck
  - Additional constraint: LV bridge gates are driven in unison



Model Derivation

- Large signal model is combination of standard DAB and buck models
  - DAB model derived by integrating transformer current (1)
  - Different operating modes (DCM vs. CCM) not an issue

$$I_{DAB} = \frac{2 * (A_1 + A_2)}{T_s} \frac{N_1}{N_2} \quad (1)$$



$$\begin{bmatrix} \dot{V}_{Cint} \\ \dot{i}_{out} \end{bmatrix} = \begin{bmatrix} \frac{I_{DAB}}{C_{int}} & -\frac{di_{out}}{C_{int}} \\ \frac{2dV_{Cint}}{L_{buck}} & -\frac{2V_{LV}}{L_{buck}} \end{bmatrix}$$

Large signal model and corresponding state space equations

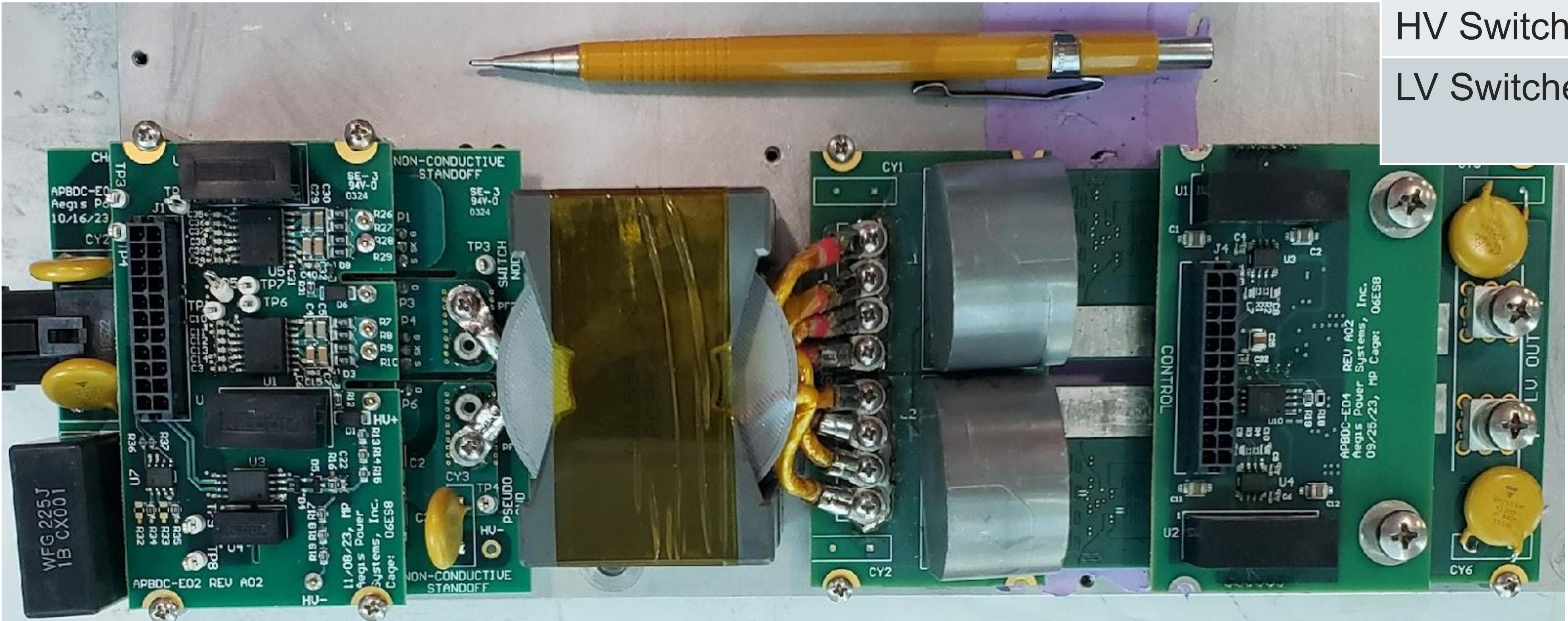
- Small signal model can be derived from large signal state space equations

$$\begin{bmatrix} \dot{\tilde{V}}_{Cint} \\ \dot{\tilde{i}}_{out} \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial V_{Cint}} \frac{I_{DAB}}{C_{int}} & -\frac{d}{C_{int}} \\ \frac{2d}{L_{buck}} & 0 \end{bmatrix} \begin{bmatrix} \tilde{V}_{Cint} \\ \tilde{i}_{out} \end{bmatrix} + \begin{bmatrix} \frac{\partial}{\partial \phi} \frac{I_{DAB}}{C_{int}} & \frac{\partial}{\partial d} \frac{I_{DAB}}{C_{int}} - \frac{i_{out}}{C_{int}} \\ 0 & \frac{2V_{LV}}{L_{buck}} \end{bmatrix} \begin{bmatrix} \tilde{\phi} \\ \tilde{d} \end{bmatrix}$$

Hardware Design

- 600V to 28V DC-DC for military vehicles
- 4x parallel converters per module, 15kW total

Parameter	Value
Rated Power	3750 W
V_{HV}	565 – 635 V
V_{LV}	20 – 32 V
Switching Freq.	200 kHz
N_1:N_2	11:2
HV Switches	SiC, 1200 V, 31 A
LV Switches	GaN, 100 V, 101 A (2p top, 4p bottom)



Summary

- Shared-Switch converter topologies offer the benefits of a multi-stage converter with a reduced switch count
  - Lowered size, cost, and losses vs. independent stages
- A series connected DAB and Buck converter is well suited for heavy-duty electric vehicle applications
  - DAB provides isolation and bidirectional power control
  - Buck ensures DAB operates at maximum efficiency for all conditions
  - Proposed shared-switch configuration reduces switch count by 40%
- An innovative modulation method ensures linear power control and decoupling between stages
- Virtual Converter Modeling alleviates the difficulty of analyzing a shared-switch converter as a single circuit by superimposing simpler converter models

Thank you!