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Fly-buck Converter Parametric Analysis and ZVS Operation for Multiple Outputs

Lee Gill†, Matthew McDonough, Timothy Donnelly, and Jason Neely
Sandia National Laboratories
†lgill@sandia.gov

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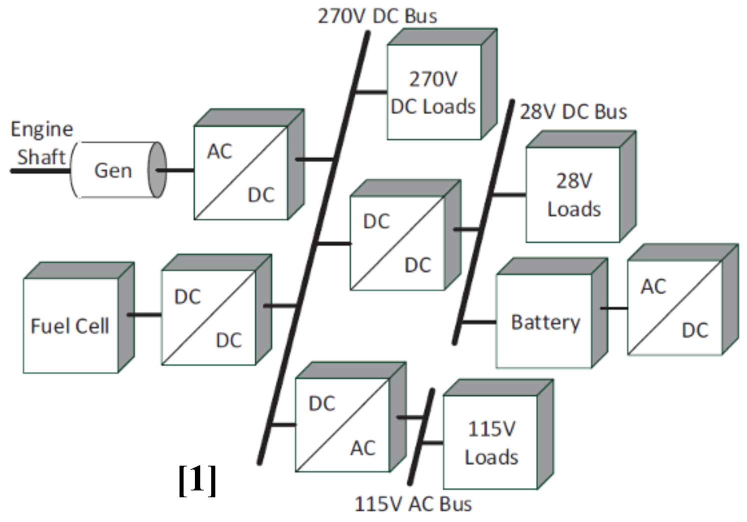
Presentation Outline

- Introduction and Theory of Operation
- Fly-buck Zero-Voltage-Switching (ZVS) Analysis
- ZVS Operation Validation
- Conclusions and Future Work

Background Information

Power Distribution Systems have a Diversity of Voltage and Power Needs

- Several systems that rely on power electronic power delivery and conversion demand multiple voltage rails.
  - Satellite and Spacecraft power systems
  - All and More-electric aircraft power systems
  - Data Centers
  - Distributed sensing
- To meet voltage and power needs, large systems may contain many power conversion circuits.
- Designs are driven by requirements on cost, power density or specific power, reliability, and efficiency.
- Various DC-DC converter topologies (isolated and non-isolated) are available to enable multi-output voltage rails.



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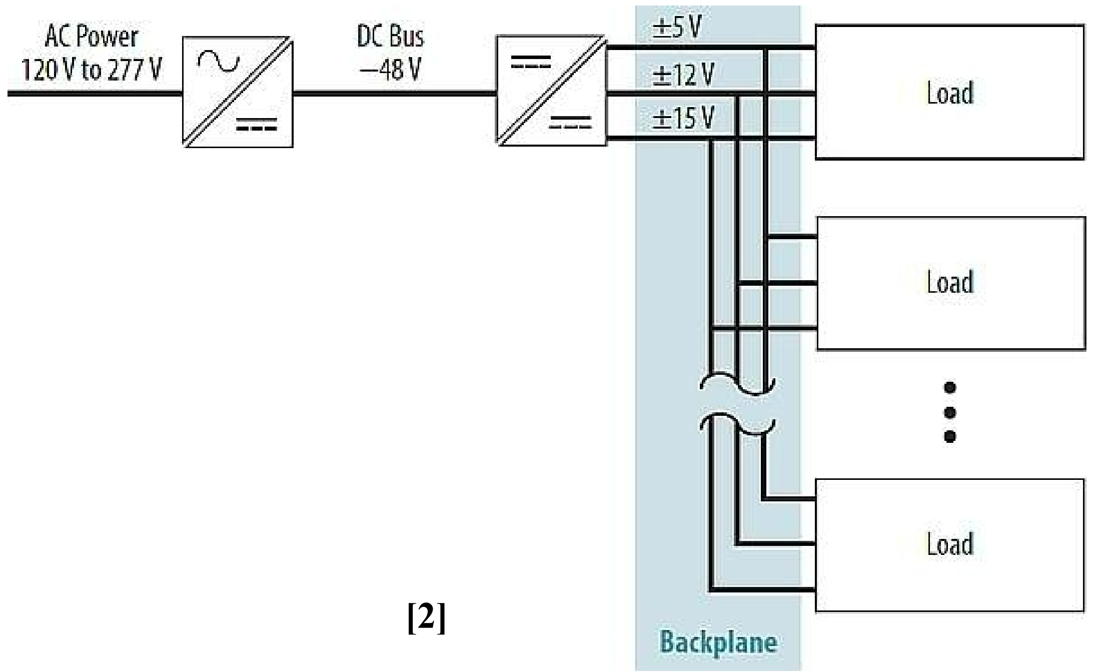

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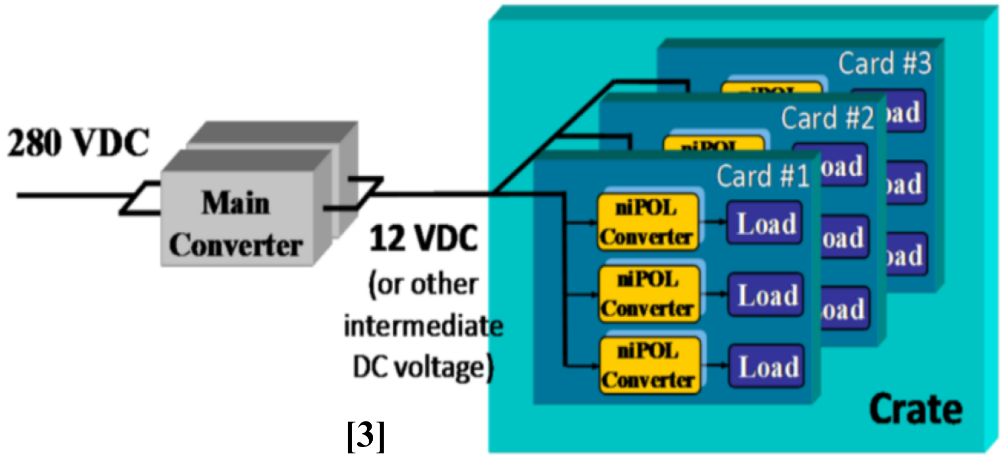

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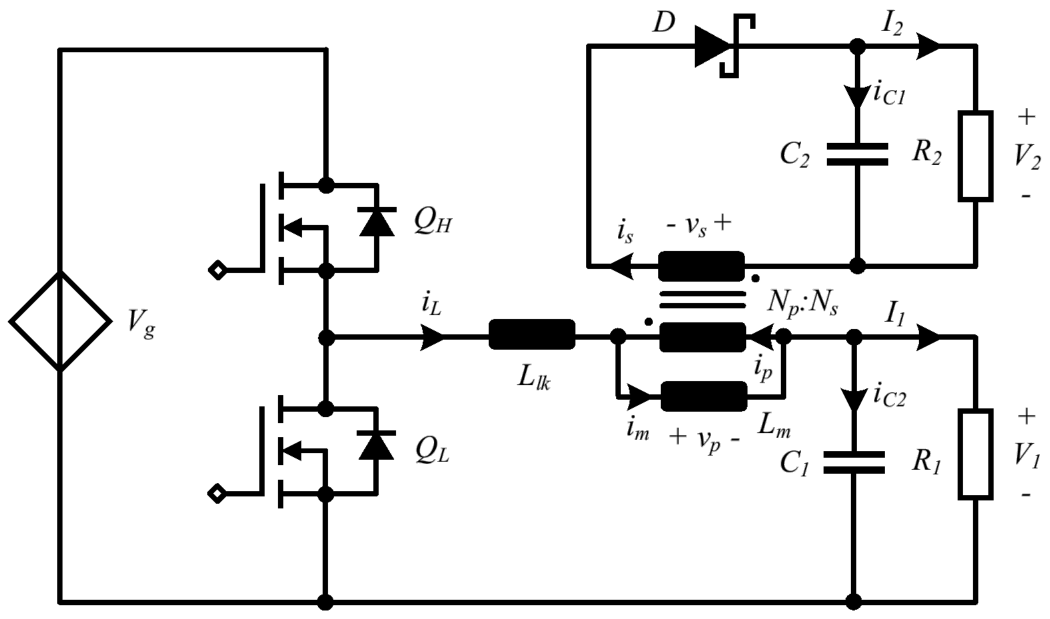
[1] Xin Zhao, J. M. Guerrero and Xiaohua Wu, "Review of aircraft electric power systems and architectures," *2014 IEEE International Energy Conference (ENERGYCON)*, Cavtat, 2014, pp. 949-953.

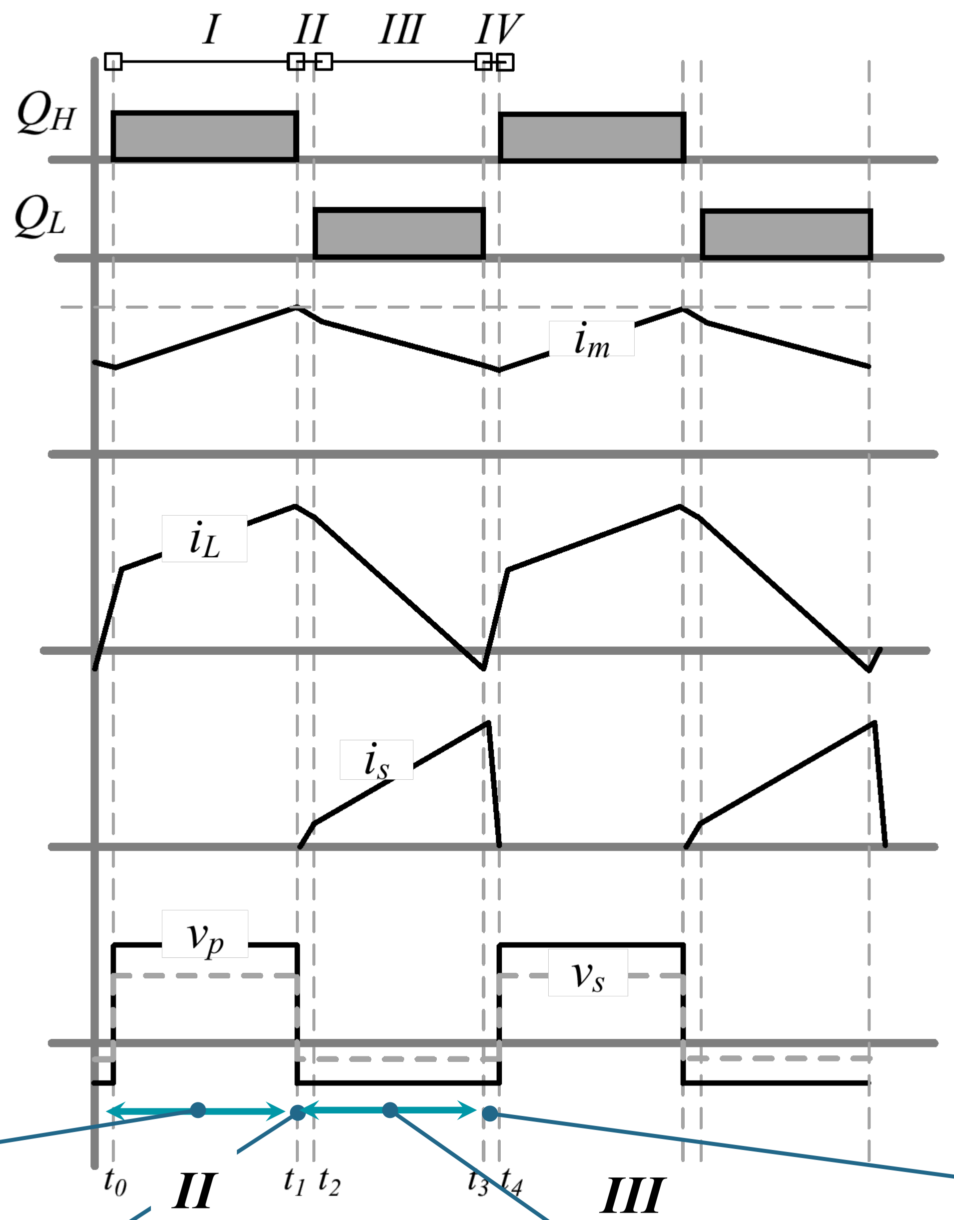
[2] David Reusch and John Glaser; DC-DC Converter Handbook: A Supplement to GaN Transistors for Efficient Power Conversion; Hong Kong; 2015.

[3] Tenti, P., G. Spiazzi, S. Buso, M. Riva, P. Maranesi, F. Belloni, P. Cova et al. "Power supply distribution system for calorimeters at the LHC beyond the nominal luminosity." Journal of Instrumentation 6, no. 06 (2011): P06005.

Fly-Buck Converter Theory of Operation



- The Fly-Buck converter is a buck converter with a coupled inductor
- It provides isolated multi-output voltage rails.
- Simple control feedback, small footprint, no isolation requirement for control signal.

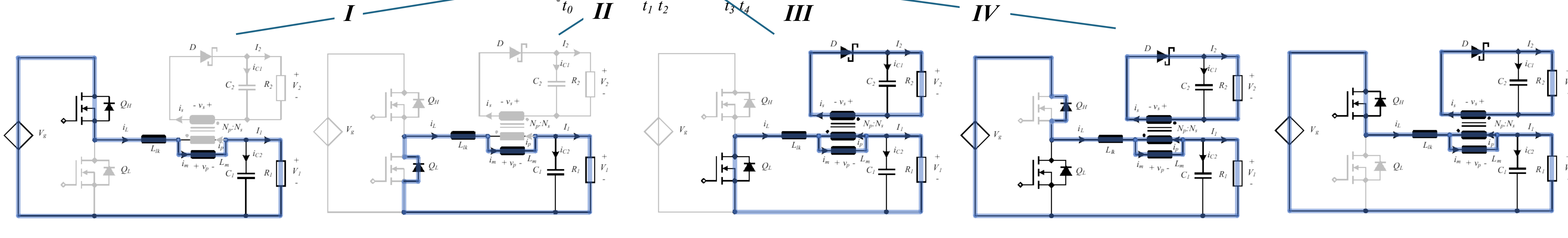


Interval I (t_1-t_0): when HS switch, Q_H is ON and LS switch, Q_L is OFF; same as the buck converter.

Interval II (t_2-t_1): when both Q_H and Q_L are OFF, inductor current resonates between the output capacitances, C_{oss}, C_1, and $L_m + L_{lk}$.

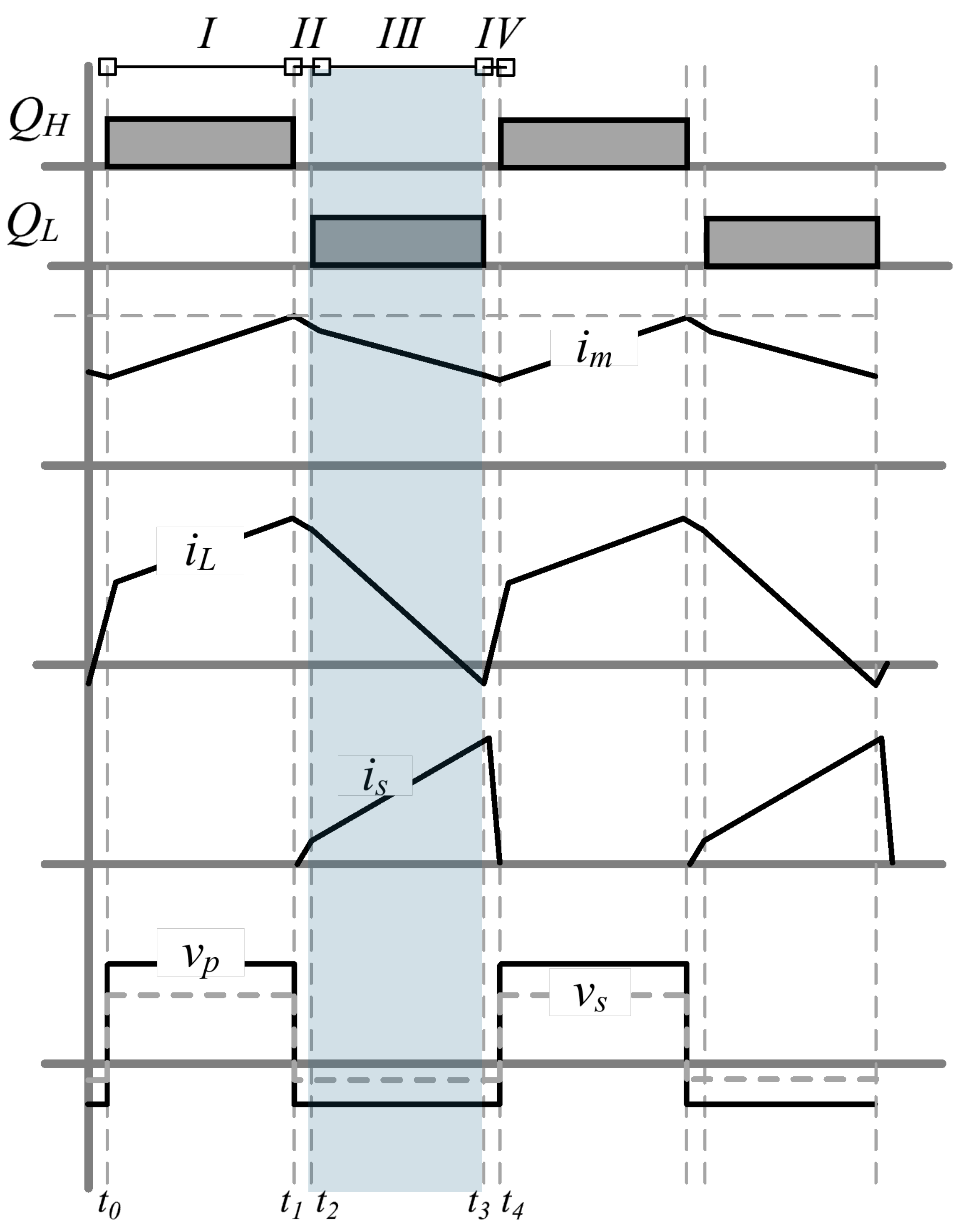
Interval III (t_3-t_2): Q_L is ON and Q_H switch is OFF and D is forward biased; current resonates between C_1, C_2 and L_{lk}.

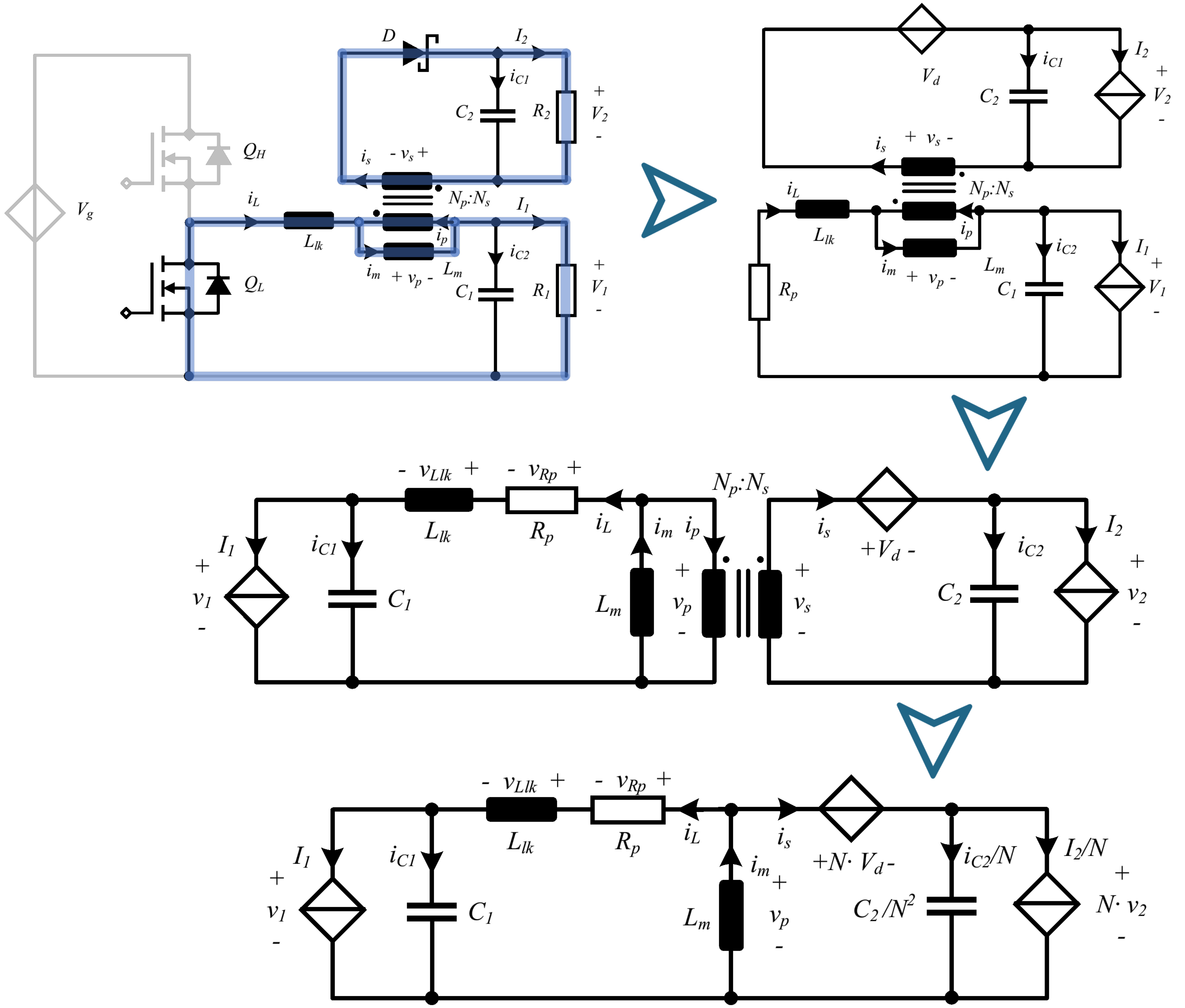
Interval IV (t_4-t_3): Q_H and Q_L are OFF. If inductor current is negative **zero-voltage-switching (ZVS) can be achieved on Q_H**.



Fly-buck Equivalent Circuit Analysis

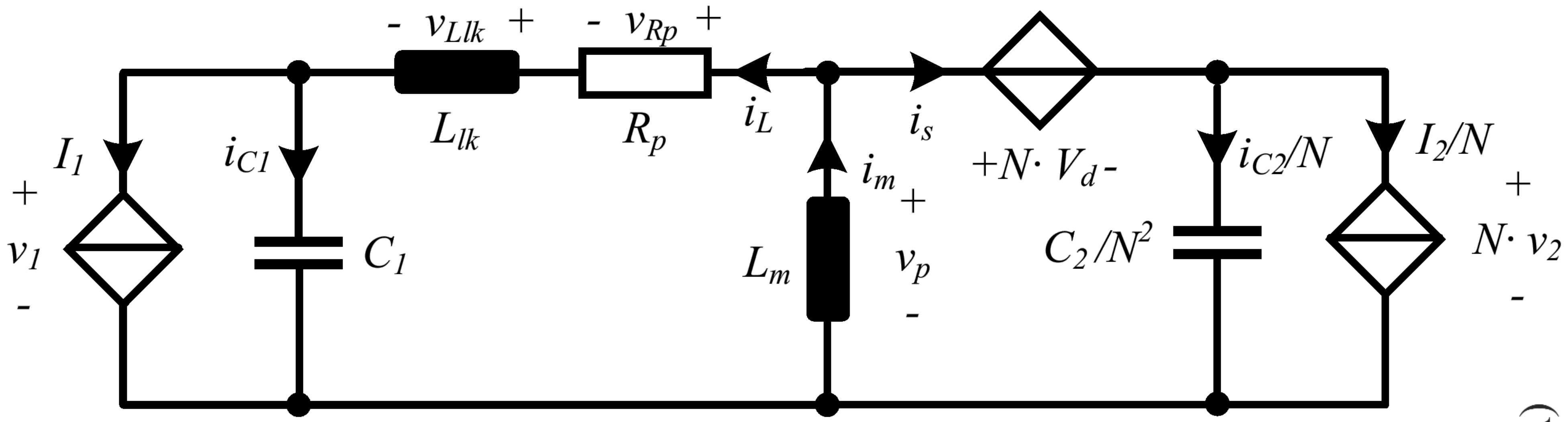
- To analyze ZVS on $Q_{H,}$ derive proper equations for the current through Q_H during Interval III (OFF time).





Fly-buck Equivalent Circuit Equation

- Primary side current through the inductor can be derived by solving the following equivalent circuit.
- The equation is in terms of **leakage inductance and output currents** given that other parameters are fixed.



$$i_L = e^{-\frac{\alpha t}{2}}\left(\cosh\left(\frac{t\cdot r}{2}\right)(\gamma+\delta)+\sinh\left(\frac{t\cdot r}{2}\right)\frac{(\gamma\cdot\alpha+2\varepsilon+\alpha\cdot\delta)}{r}\right)-\gamma$$

$$\alpha = \frac{R_p}{L_{lk}}, \beta = \frac{1}{L_{lk}C_{eq}}, \gamma = \left(I_1 - \frac{I_2}{N}\right)$$

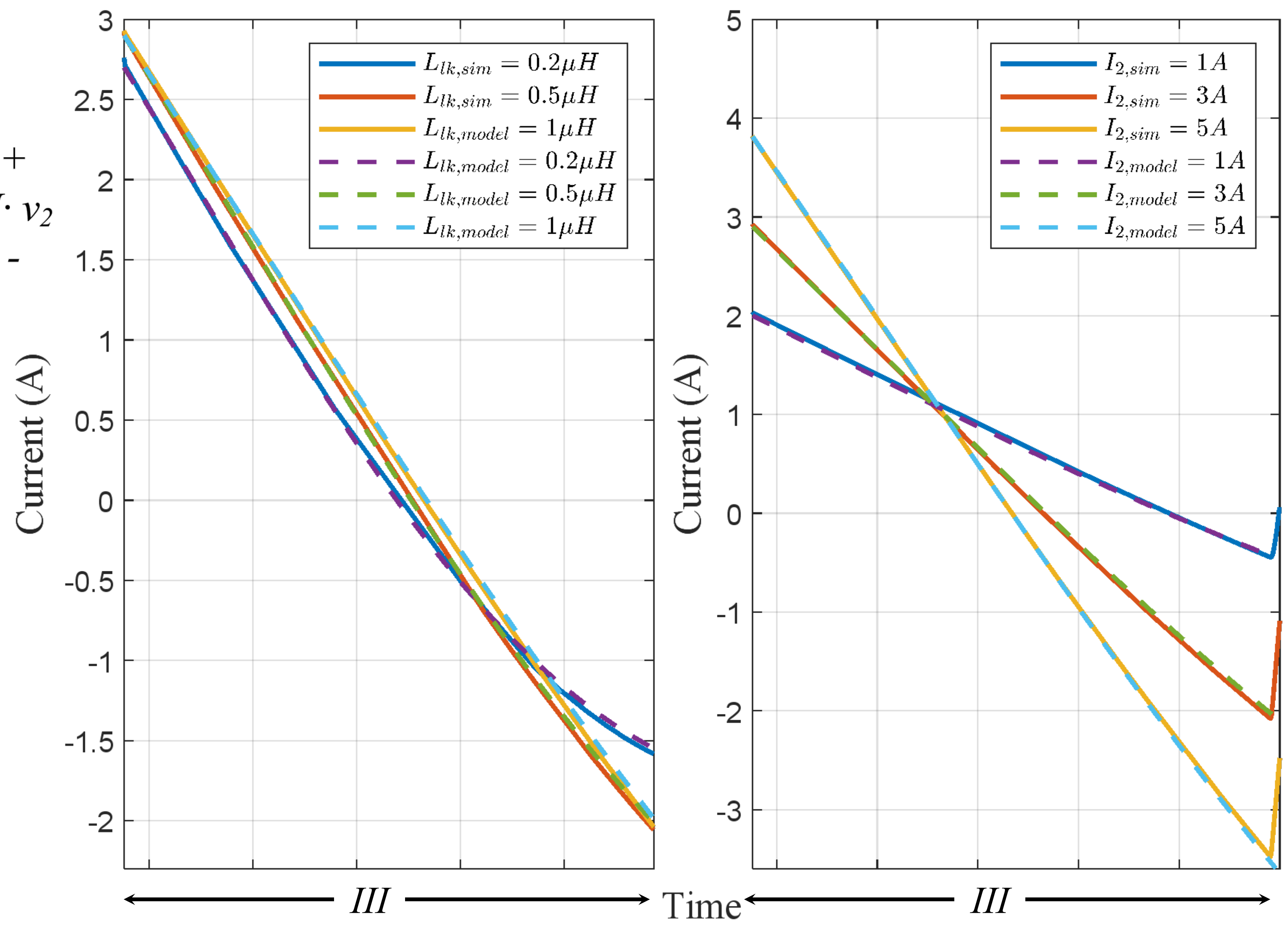
$$\delta = I_1 + \frac{I_2}{N} + \frac{V_1(V_g - V_1)}{2\cdot V_g\cdot f_{sw}\cdot L_m} = i(t_2)$$

$$\varepsilon = \frac{N\cdot V_2 + N\cdot V_d - V_1 - \delta\cdot R_p}{L_{lk}} = i_L'(t_2)$$

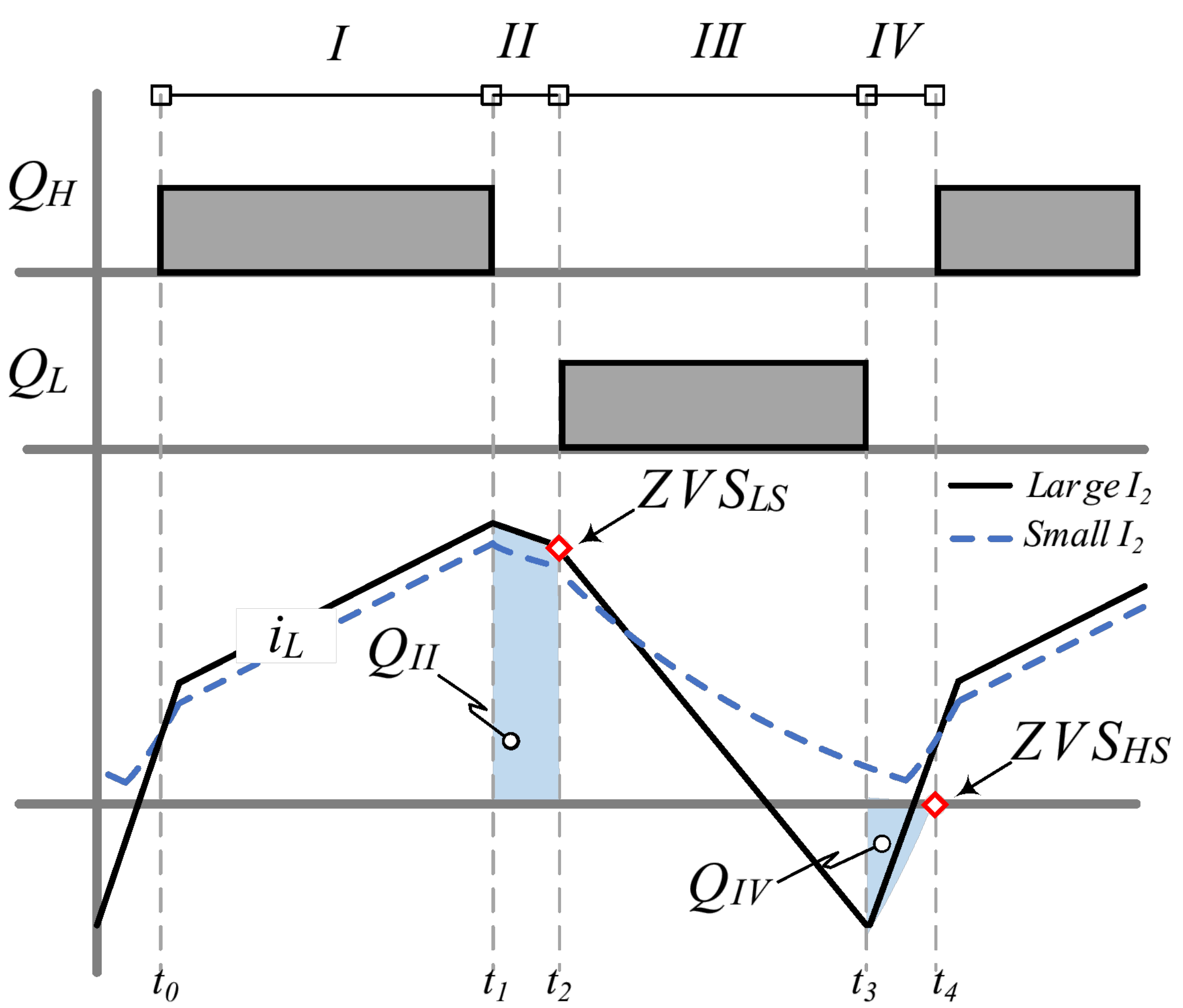
$$r = \sqrt{\alpha^2 - 4\beta}$$

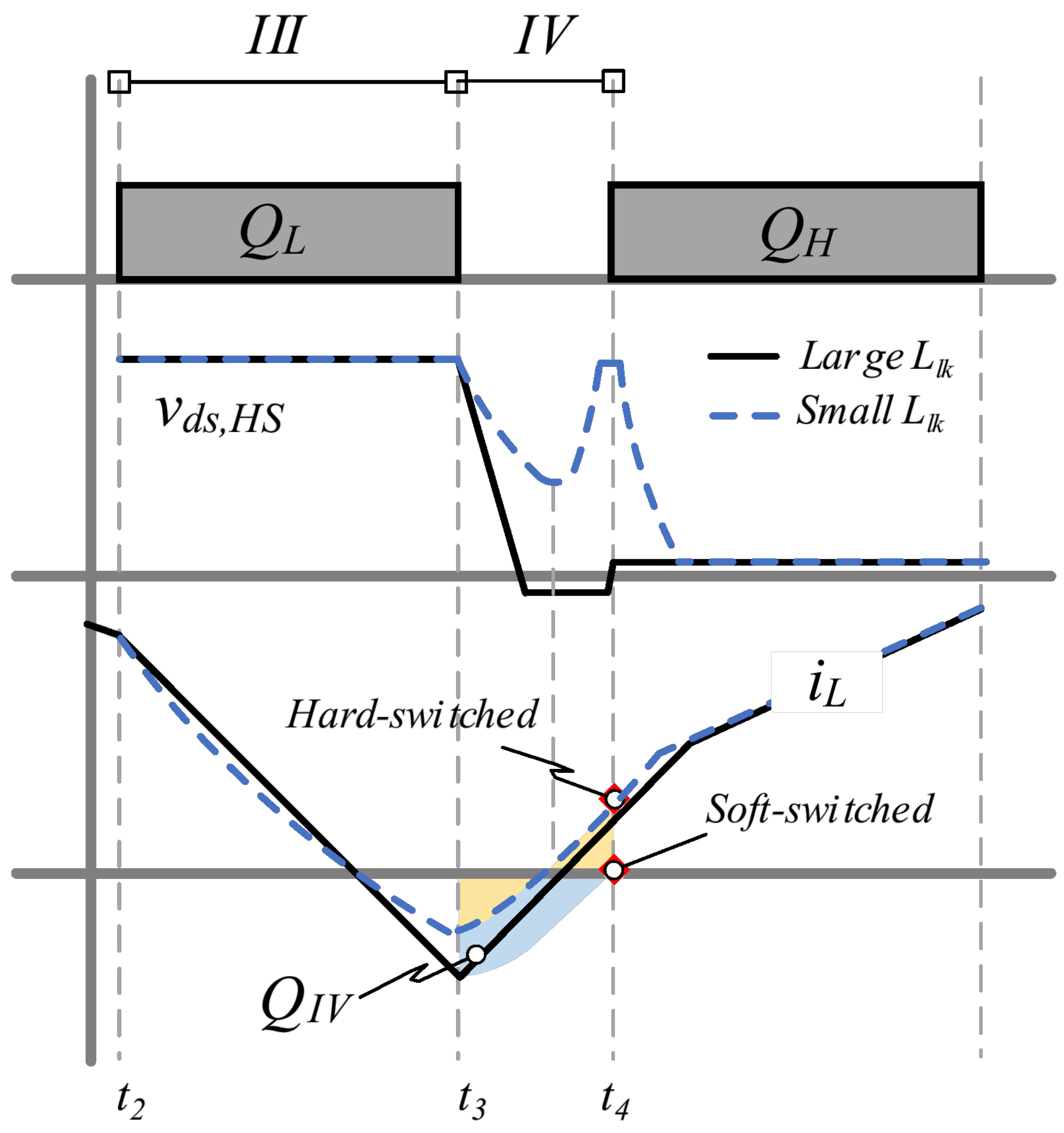
- The derived equation validated through LTSpice simulation comparison at **different leakage inductance** and **secondary output current**.

Primary Inductor Current During OFF Time



Fly-buck ZVS Operation Conditions





- The total charge, Q_{IV} needs greater than or equal to the output capacitances, eqn (1)-(2).
- Small I_2 affect current magnitude, affecting ZVS operation
- The current slope during IV can be approximated by eqn (3)

$$Q_{IV} > \int_0^{V_g} 2C_{oss}(v)d(v) = 2Q_{oss} \quad (1)$$

$$Q_{IV_{min}} = \int_{t_3}^{t} i_L(\tau)\,d\tau = 2Q_{oss} \quad (2)$$

$$\frac{di_L(t_3)}{t_{IV}} = \frac{V_g - NV_d}{L_{lk}} \quad (3)$$

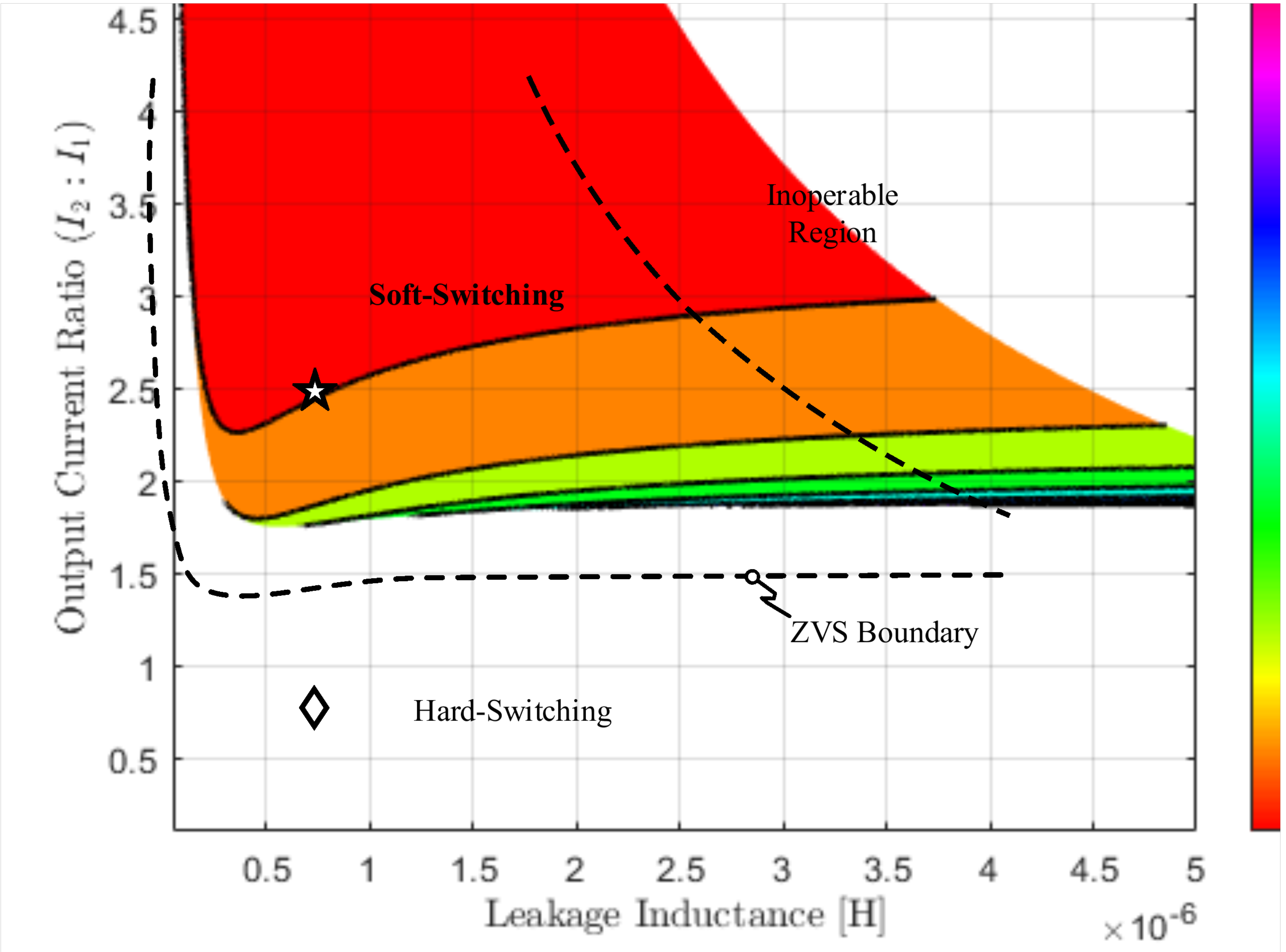
- Small L_{lk} may not have enough energy to discharge the output capacitance.
- I_L current direction during t_{IV} is critical for ZVS.

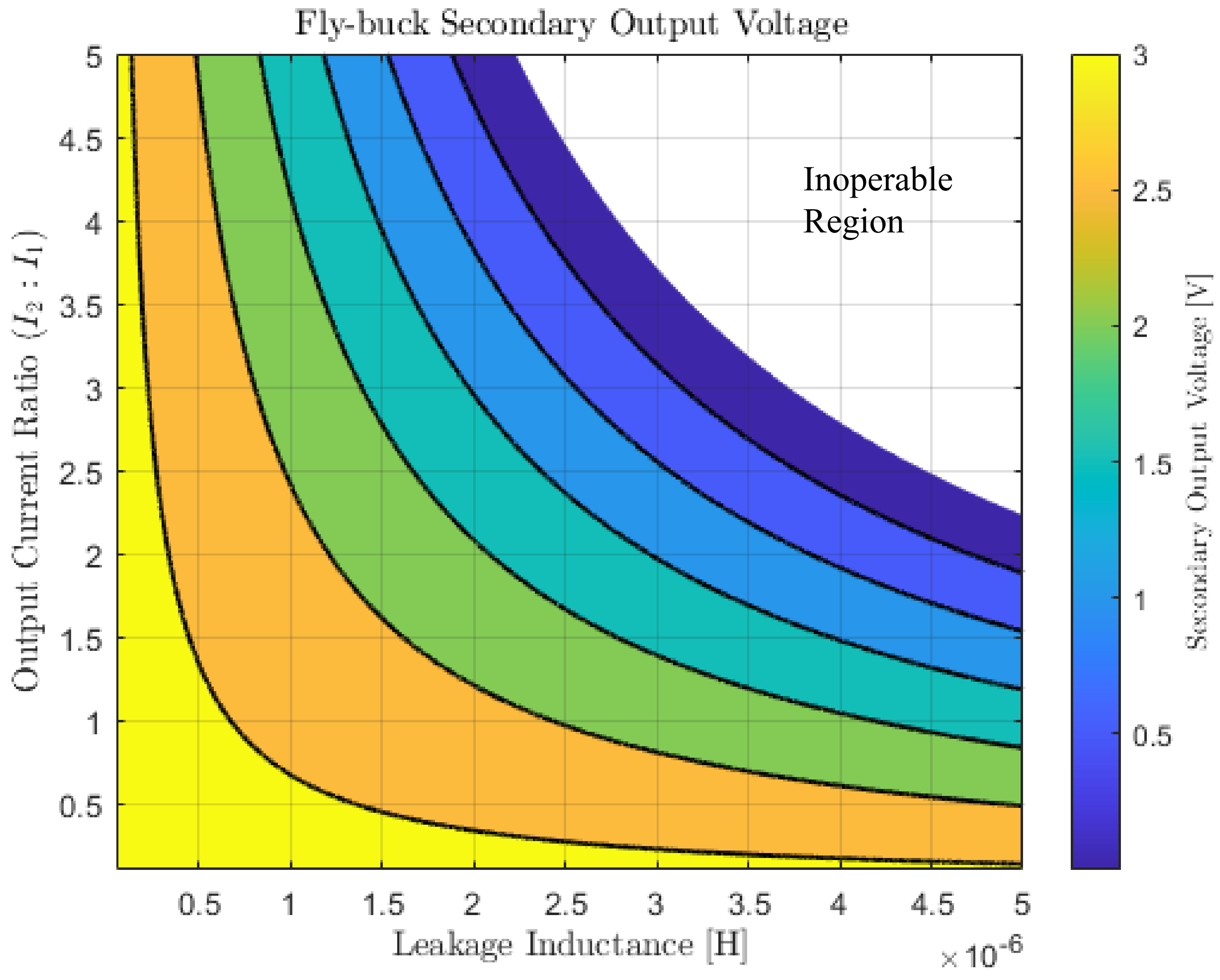
$$i_L(t - t_4) = \frac{V_g - NV_d}{L_{lk}}(t - t_4) - i_L(t_3) \quad (4)$$

$$\frac{V_g - NV_d}{2L_{lk}}(t - t_4)^2 - i_L(t_3)t - 2Q_{oss} = 0 \quad (5)$$

$$t_{IV_{min}}(L_{lk}, I_2{:}I_1)$$

Fly-buck ZVS Region and Output Voltage

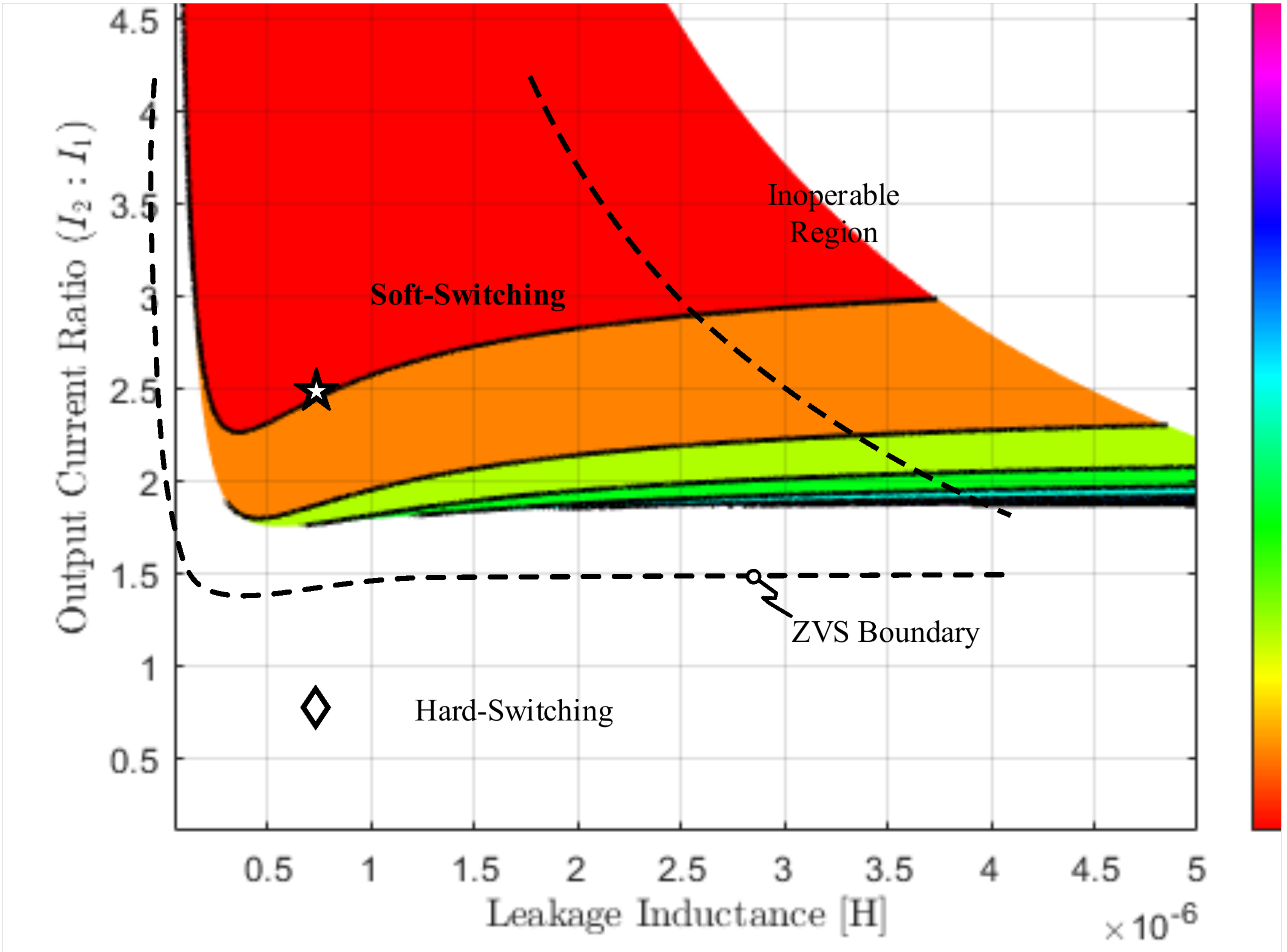




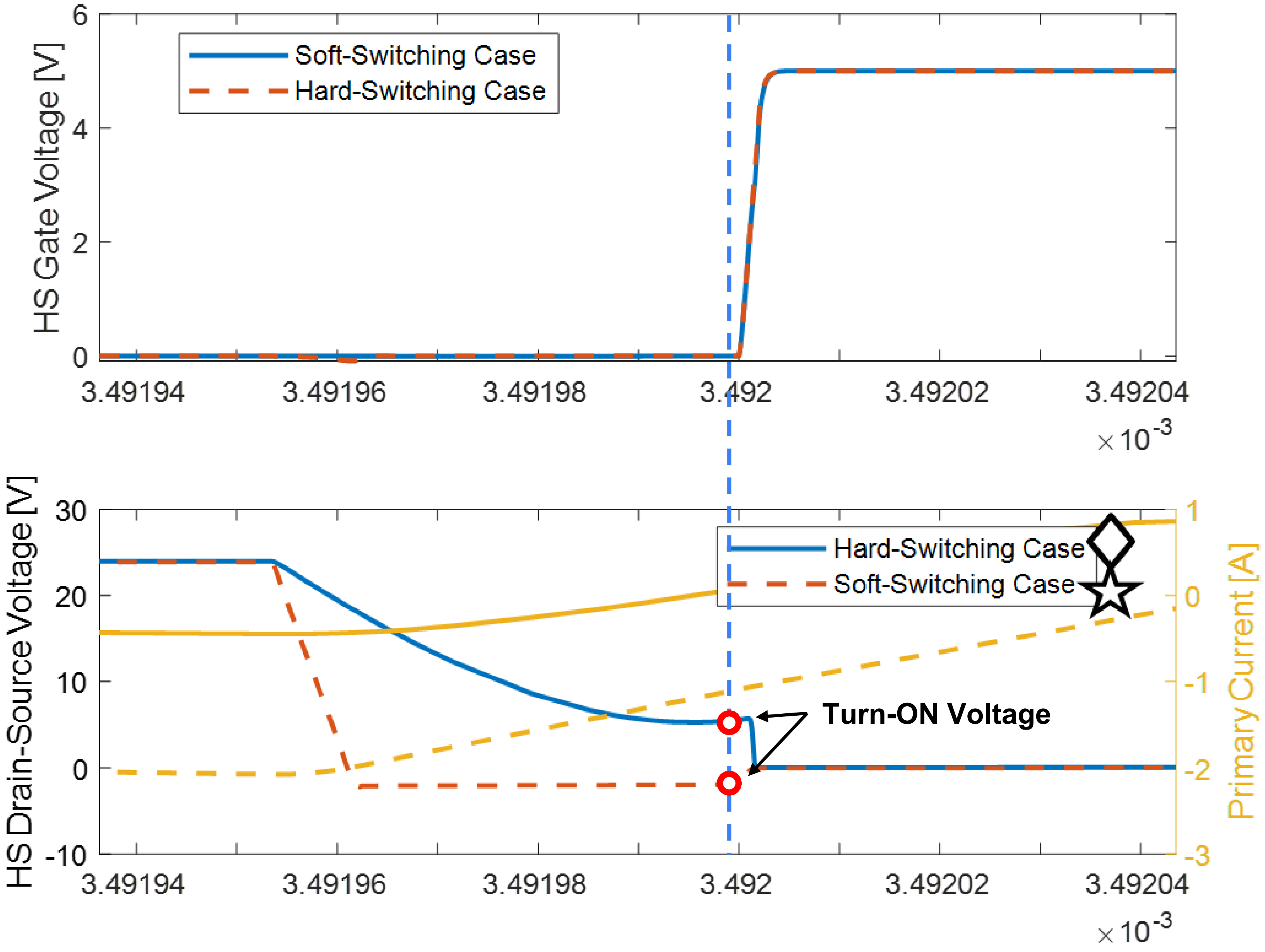
- Whether Q_H can turn-on at ZVS depends on leakage inductance and output current ratio.
- Thus, very high coupling coefficient can inhibit ZVS operation even at large current ratio.
- The inoperable region is determined by the secondary side voltage drop.

- The secondary side voltage drop also depends on the leakage inductance and output current ratio.
- The inoperable region is when the secondary side voltage is zero.

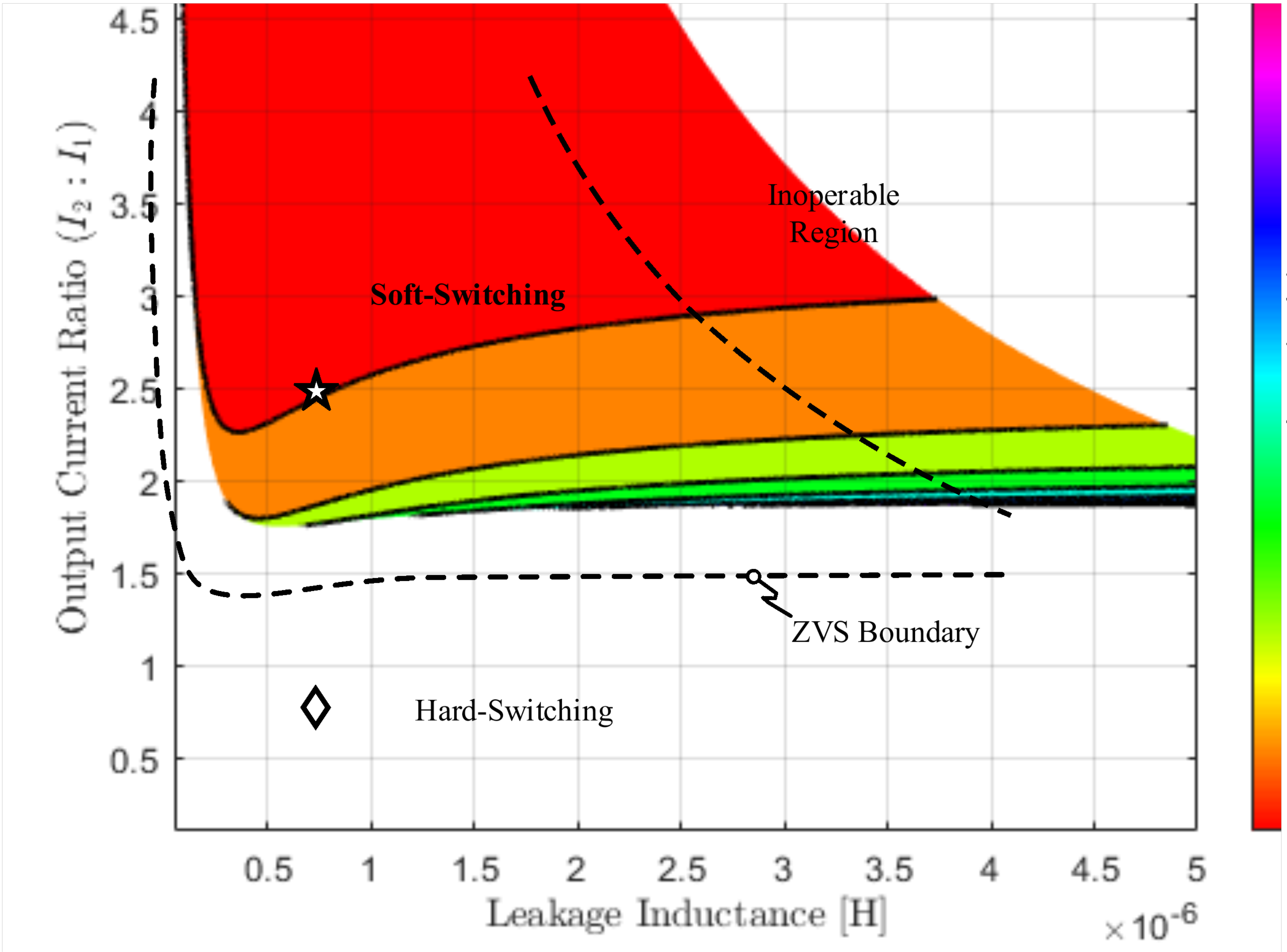
Simulation Validation of ZVS Operation



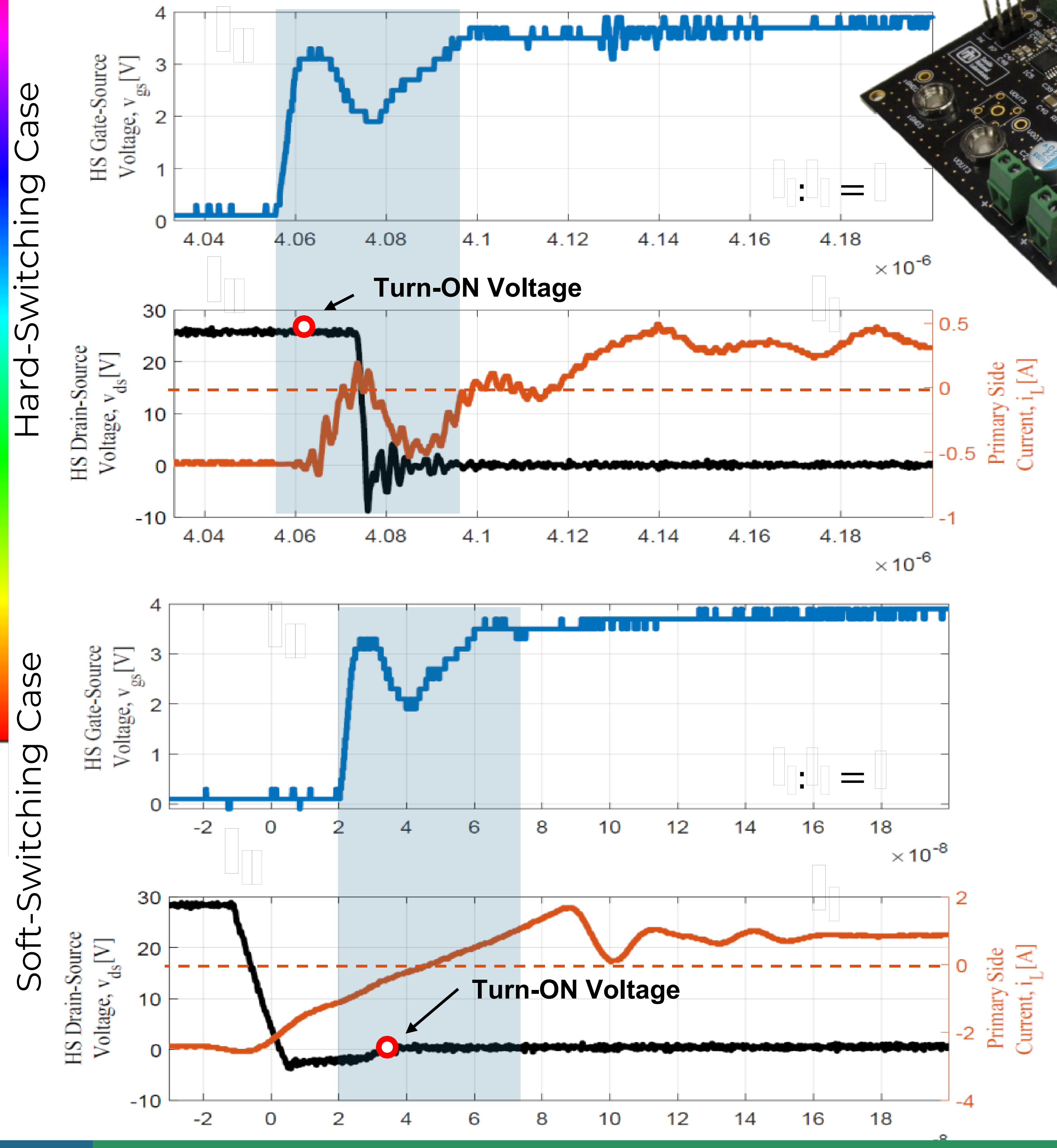
LTSpice Simulation Validation Results

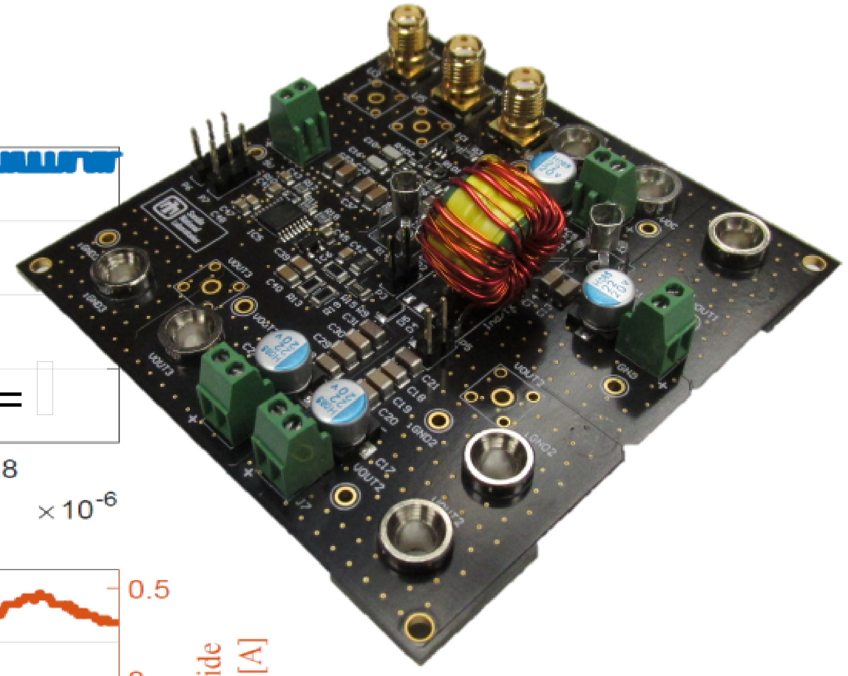


Experiment Validation of ZVS Operation



Experimental Validation Results





Summary and Future Work

- Fly-buck converter is an attractive solution for multi-output voltage rails
- Both LS and HS switches can turn-on at zero voltage and highly dependent on the leakage inductance and current ratio.
- The ZVS boundary is also determined by the secondary side voltage drop.
- High coupling coefficient inhibit ZVS while small coupling coefficient increases the secondary voltage drop.
- ZVS operation has been validated and evaluated through simulation and experiments.
- Future work includes multi-dimensional ZVS analysis with more than 2 output voltages

Acknowledgement

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