A 5 – 115V Efficiency-Enhanced Synchronous LED Driver with Adaptive Resonant Timing Control

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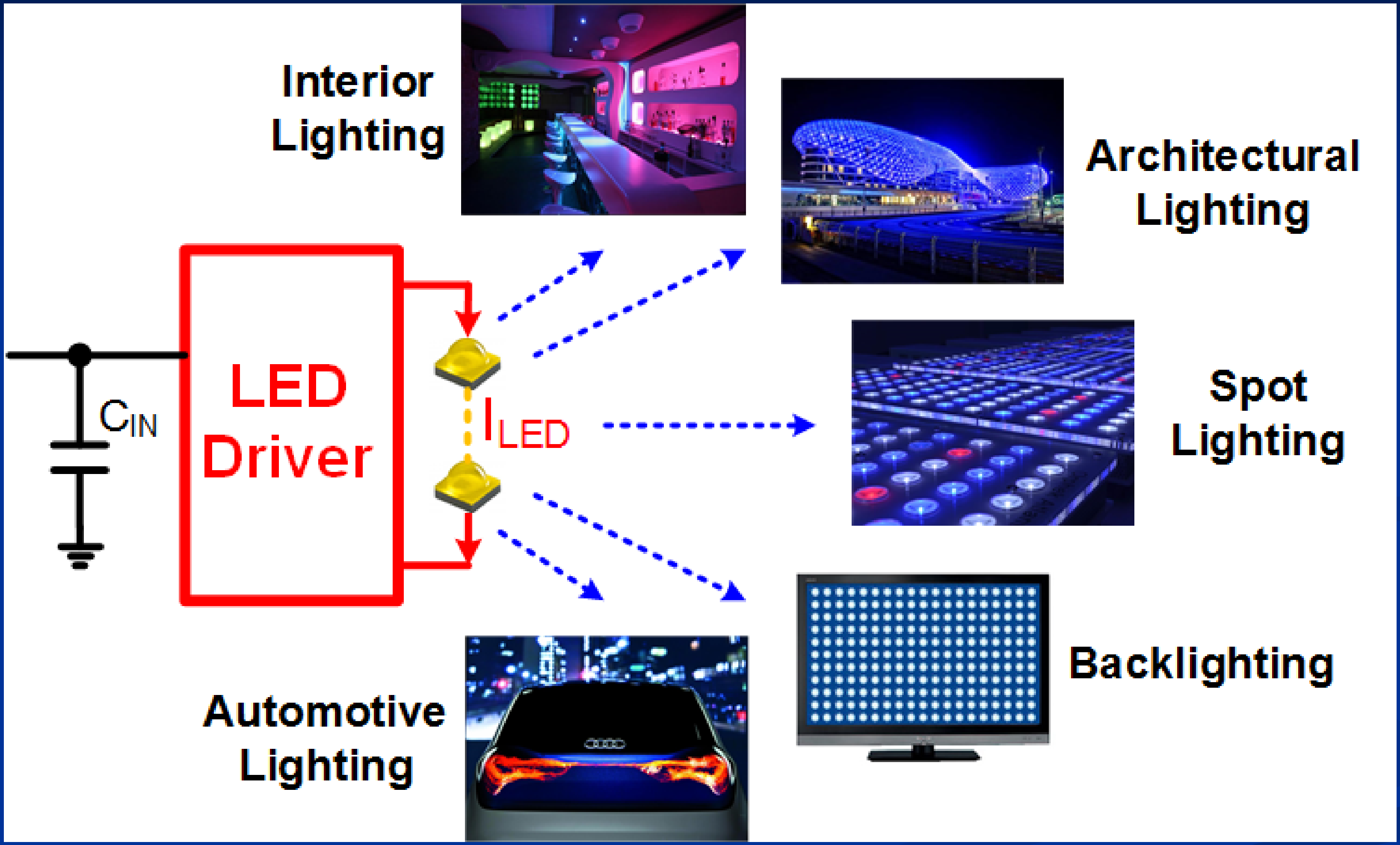
Outline

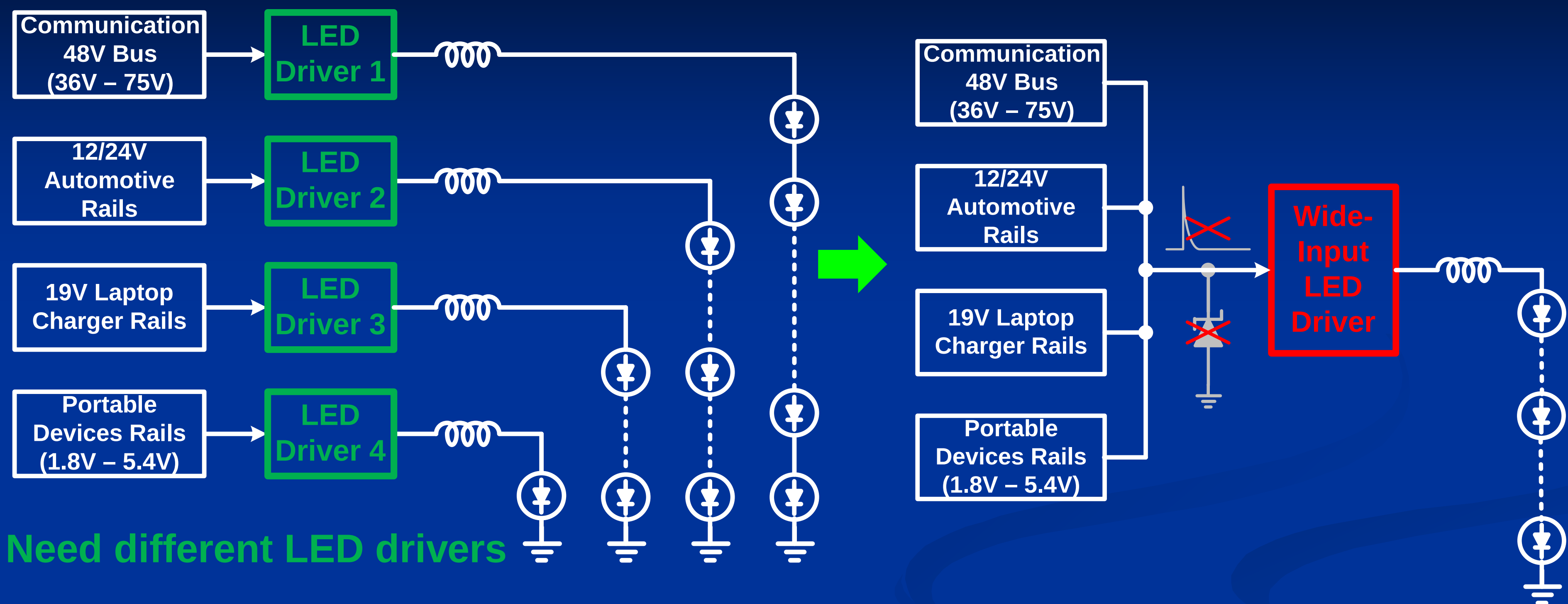
- Introduction and Background
- Proposed Wide-Input-Range LED Driver
  - System Architecture
    - Auto-Configurable Switching Scheme & Adaptive Resonant Timing Control
  - Circuit Implementations
    - Adaptive Resonant Time Emulator and HV Body-Diode Based Zero-Voltage-Switching Detectors
  - Measurement Results
- Conclusions

High-Brightness LED Lighting



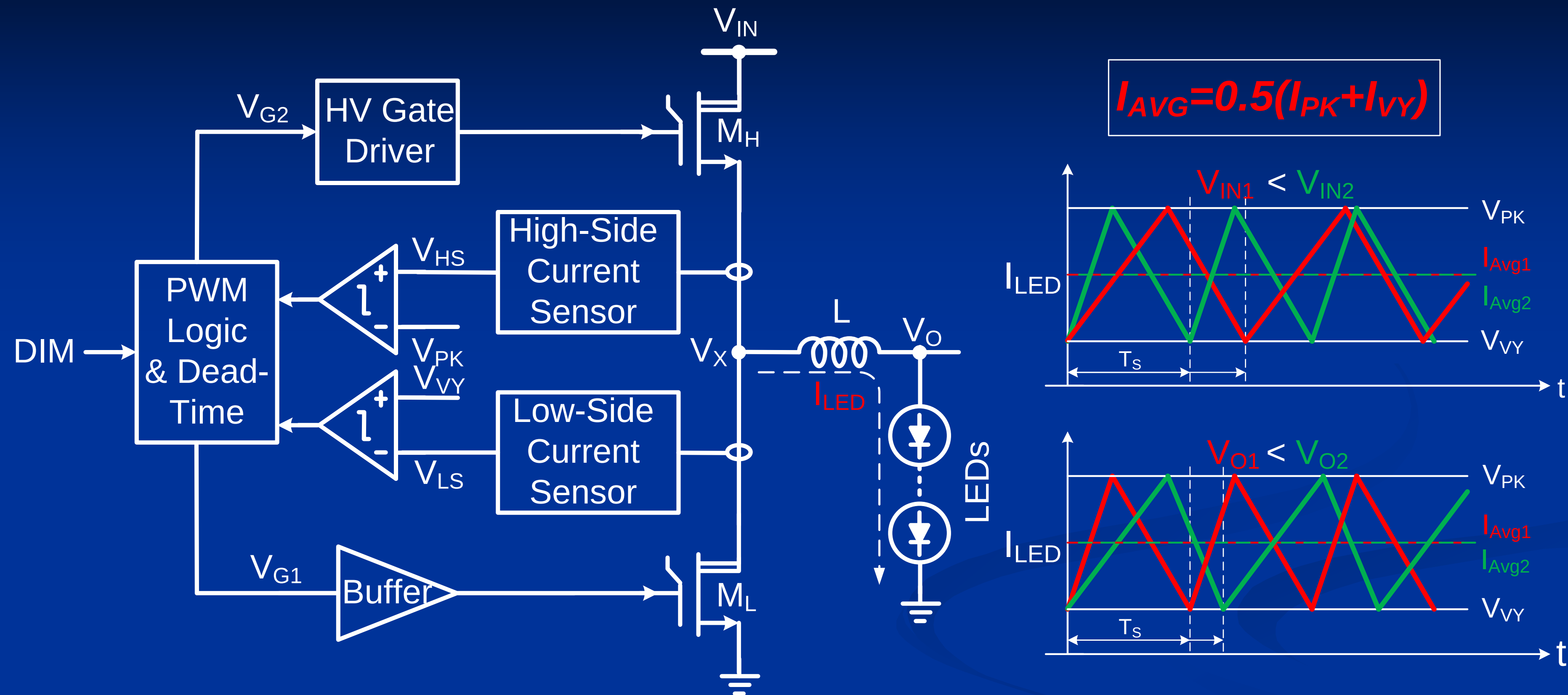
- High efficacy, long lifetime, and environmental friendliness

Why Wide-Input-Range LED Driver?



- Wide-input-range LED driver is able to
  - handle a variety of inputs including HV spikes;
  - remove the additional protective clamp circuit;
  - simplify system design, reduce bill-of-material cost, and enhance reliability.

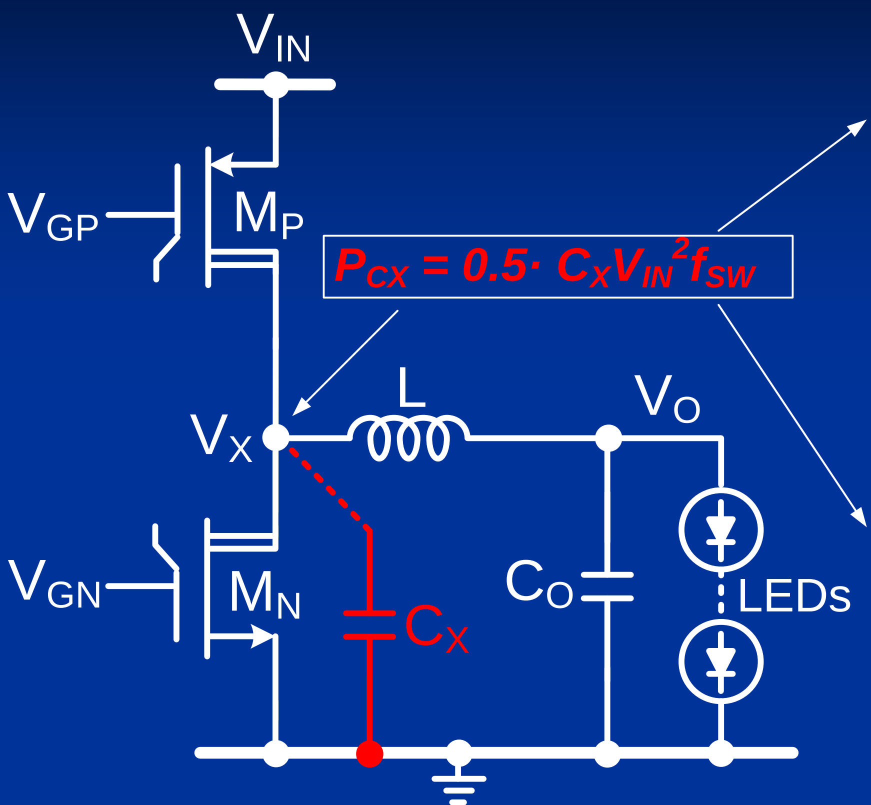
State-of-the-Art DC-DC Based LED Driver

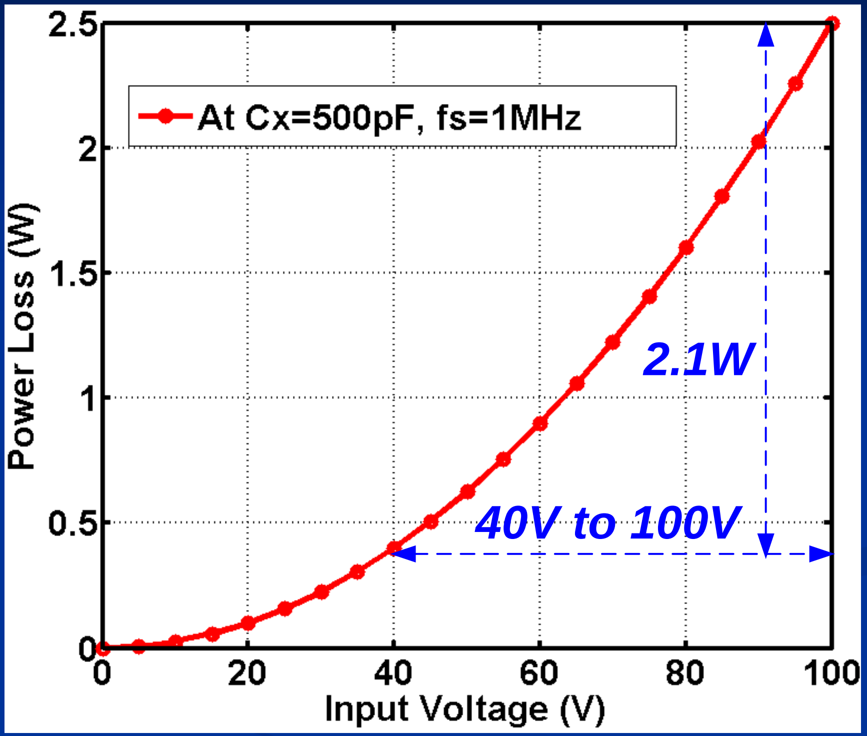


* Z. Liu et. al., *IEEE JSSC*, Sep. 2015

- ✓ **Synchronous current control offers good regulation of the average LED current under different input/output conditions.**
- ✘ **The LED driver can only support a limited input voltage range with the maximum input voltage of 45V.**

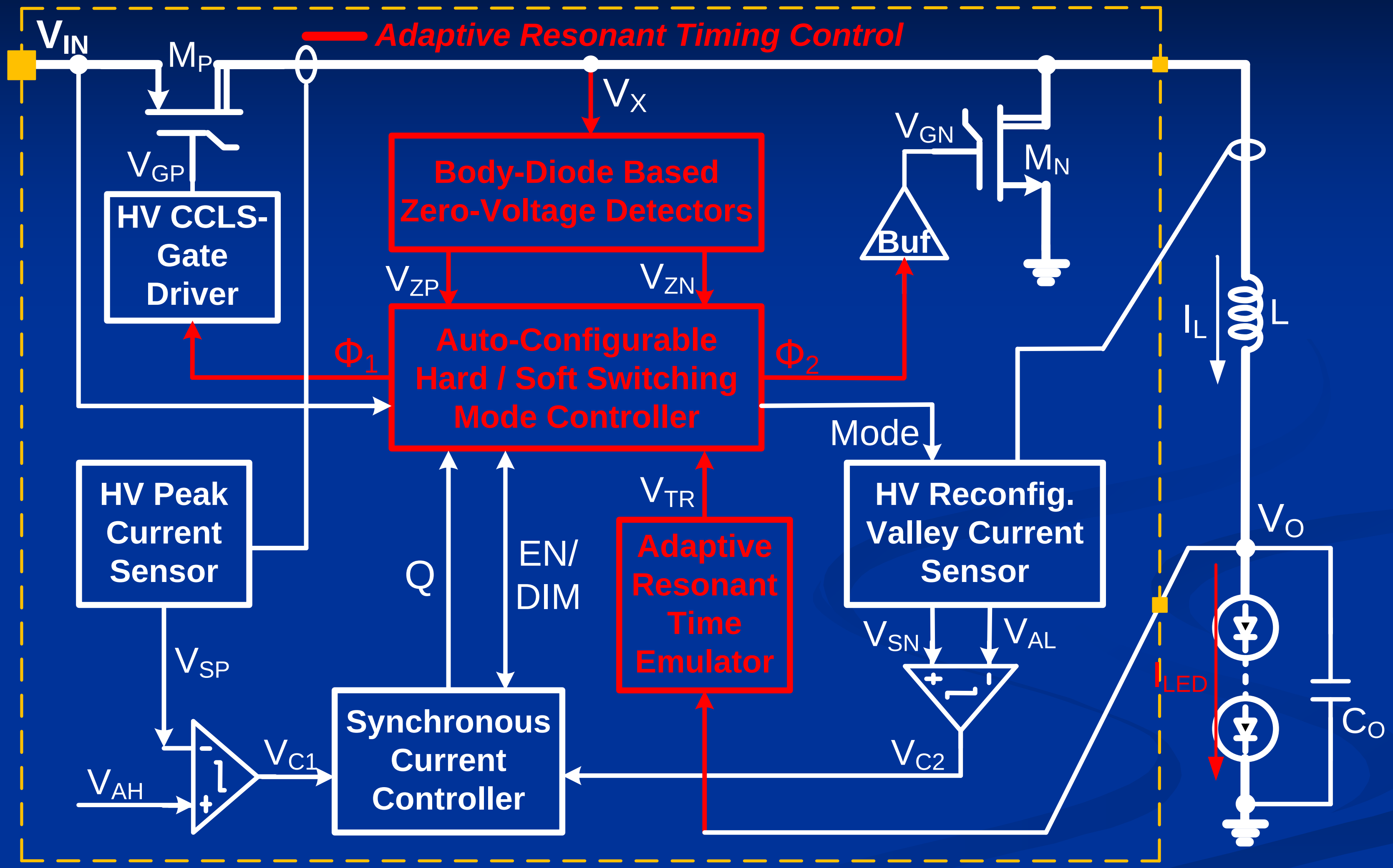
Switching Power Loss in HV LED Drivers





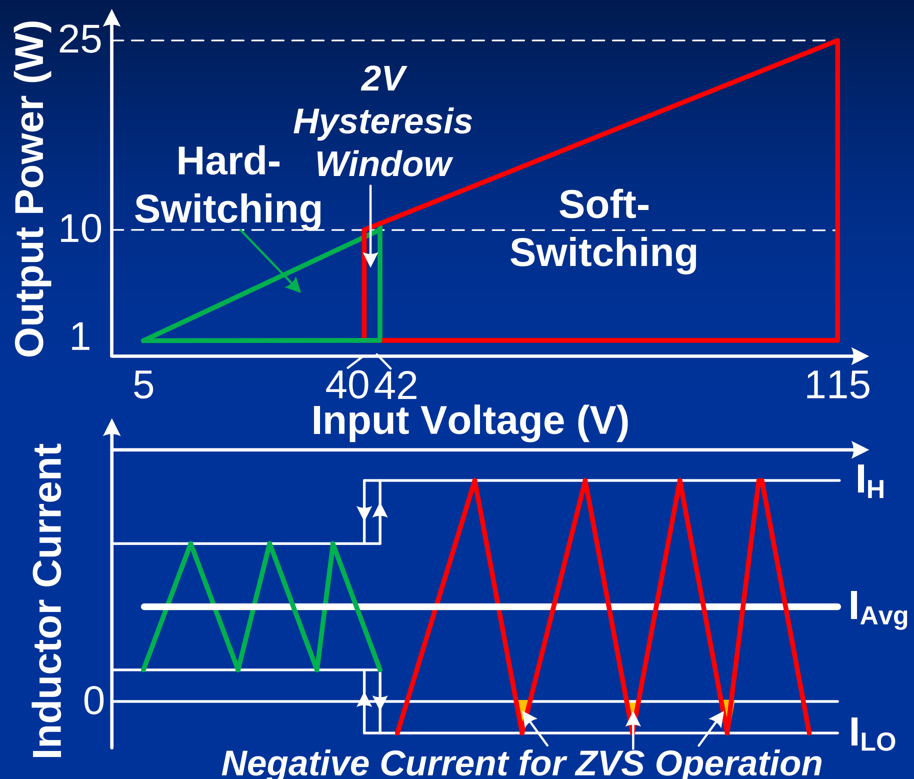
- In HV condition, the switching loss is significant due to hard-switching, seriously degrading the converter power efficiency.
- For C_X = 500pF, f_S = 1MHz, the switching loss is increased by 6.25 times when input increases from 40V to 100V.

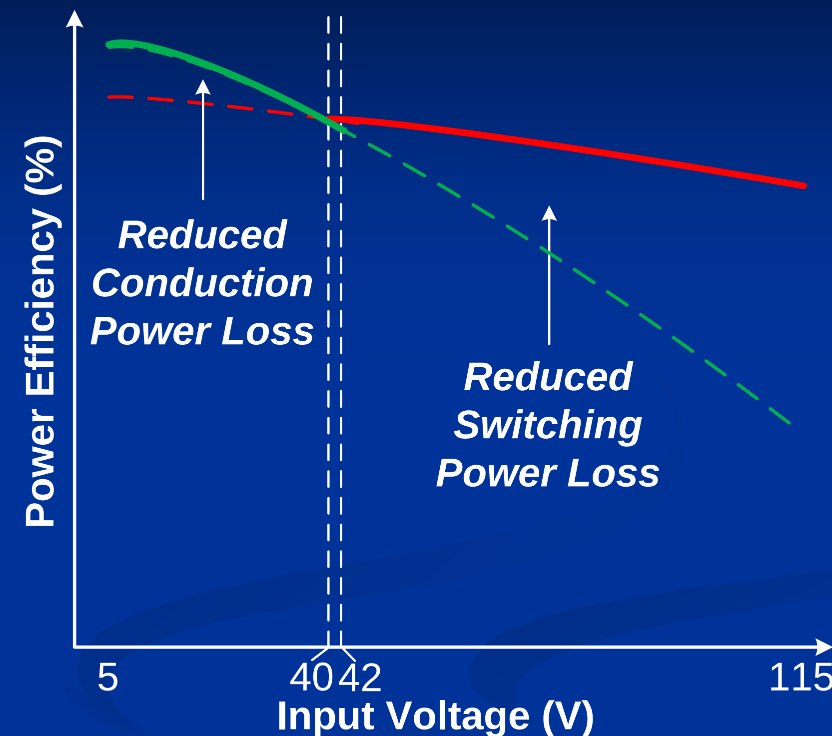
Proposed Wide-Input-Range LED Driver



- The proposed adaptive resonant timing control (ARTC) supports wide input range and improves the power efficiency.

Auto-Configurable Switching Scheme

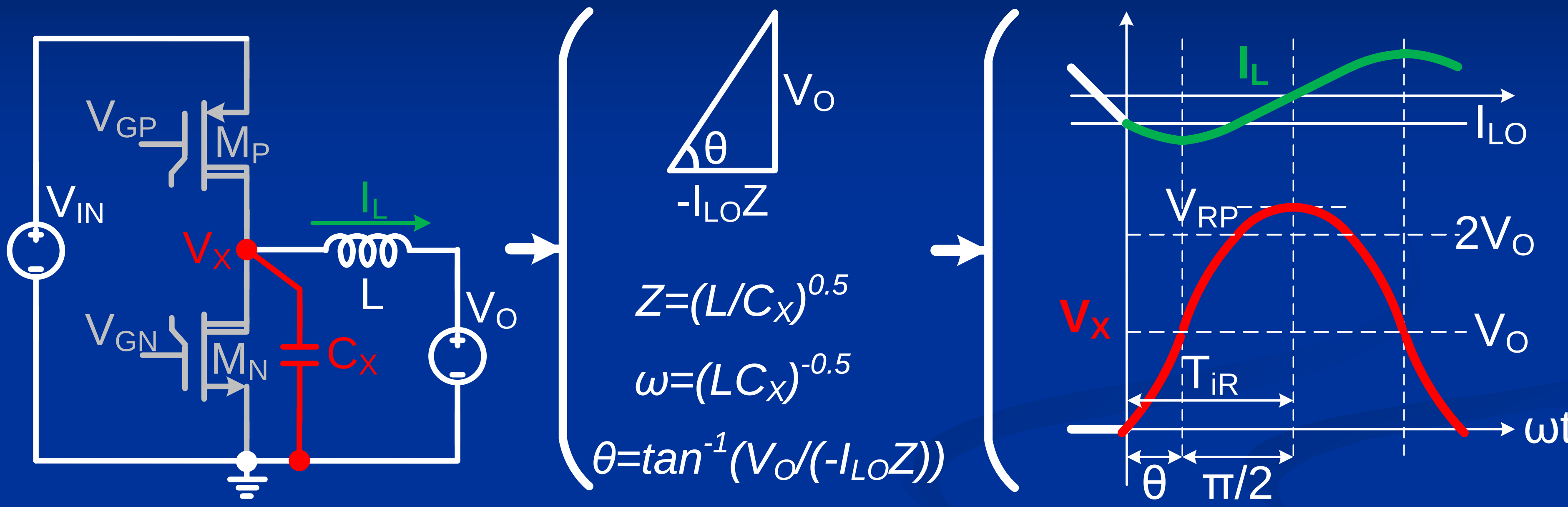




- **Auto configuration between hard-switching (HS) and soft-switching (SS) dependent on the input voltage**
- ✓ **Wide input range (5V to 115V) and output range (1 to 25 LEDs)**
- ✓ **The switching loss is minimized in the SS mode under high input voltages.**

Equivalent Circuit of LC Resonance

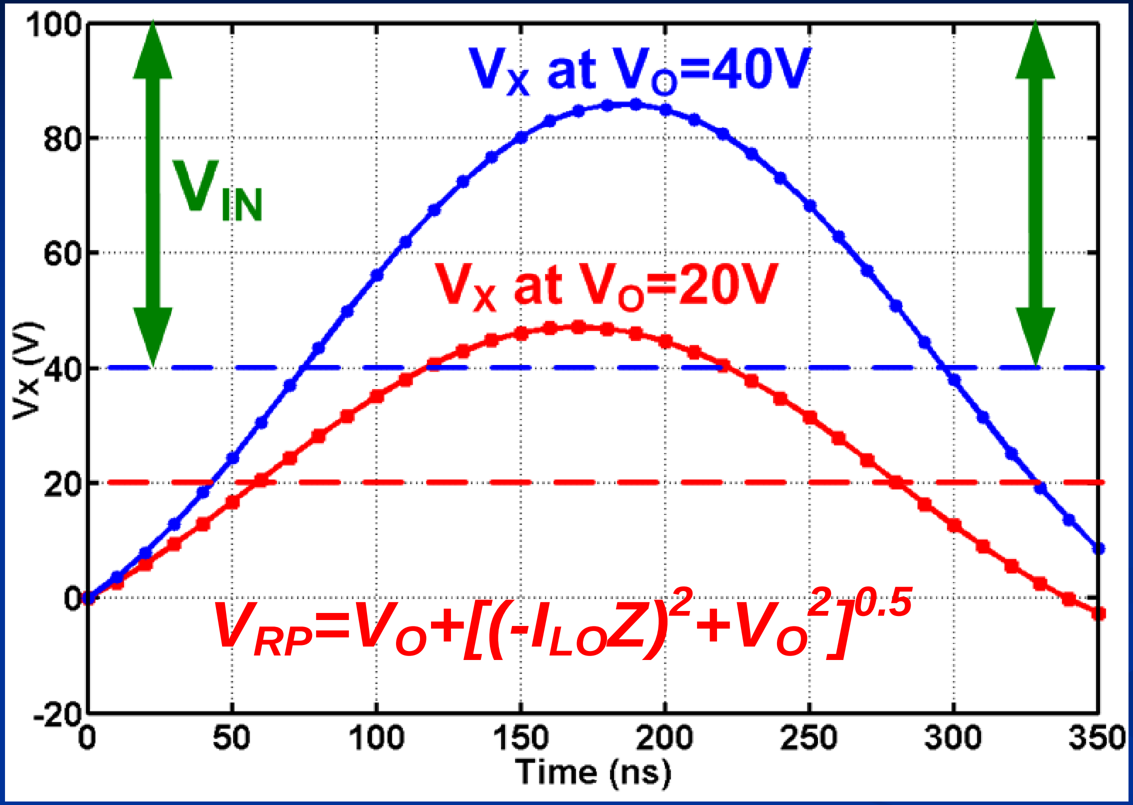
- LC resonance during the rising-edge transition of V_X



$$V_X = V_O + [(-I_{LO}Z)^2 + V_O^2]^{0.5} \sin(\omega t - \theta)$$

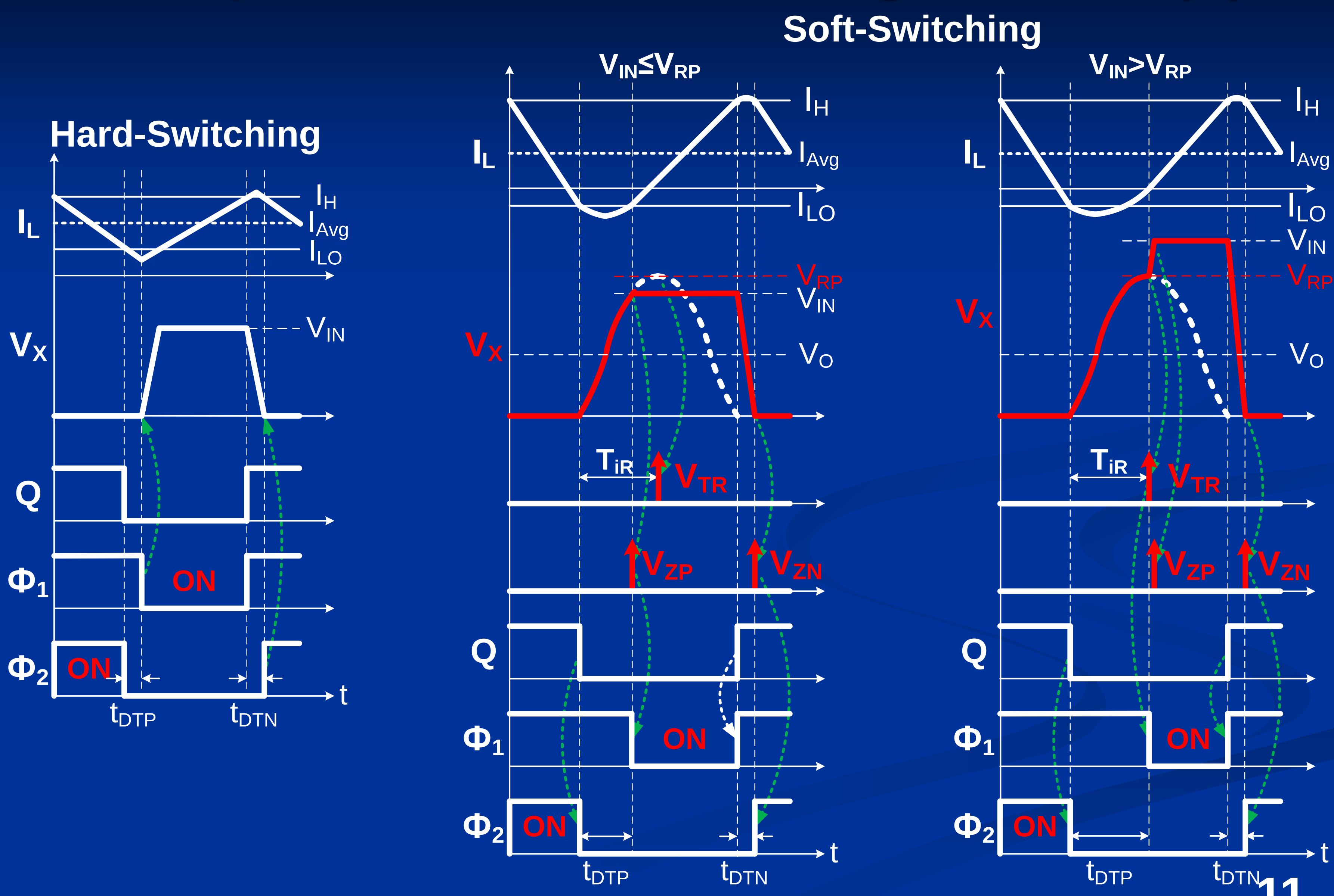
- Both power switches are off during the transition, V_X would be increased by the negative valley inductor current based on the second-order resonance of L and C_X.

Resonant Peak with Output Voltage



- V_{RP} is positively related to V_O and is at least 2 times larger than V_O.
- V_{RP} could be lower than V_{IN} when V_{IN} is large, leading to the quasi-ZVS by the LC resonance.

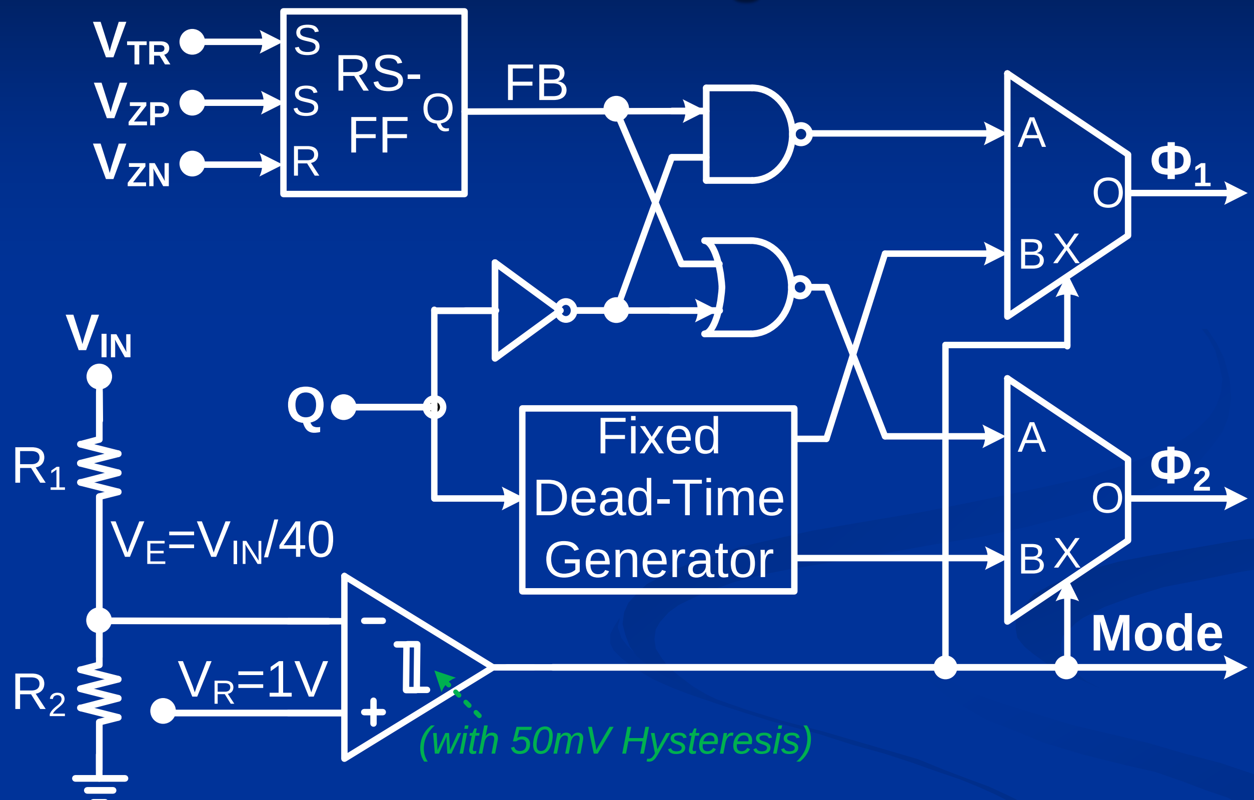
Adaptive Resonant Timing Control (1)



Adaptive Resonant Timing Control (2)

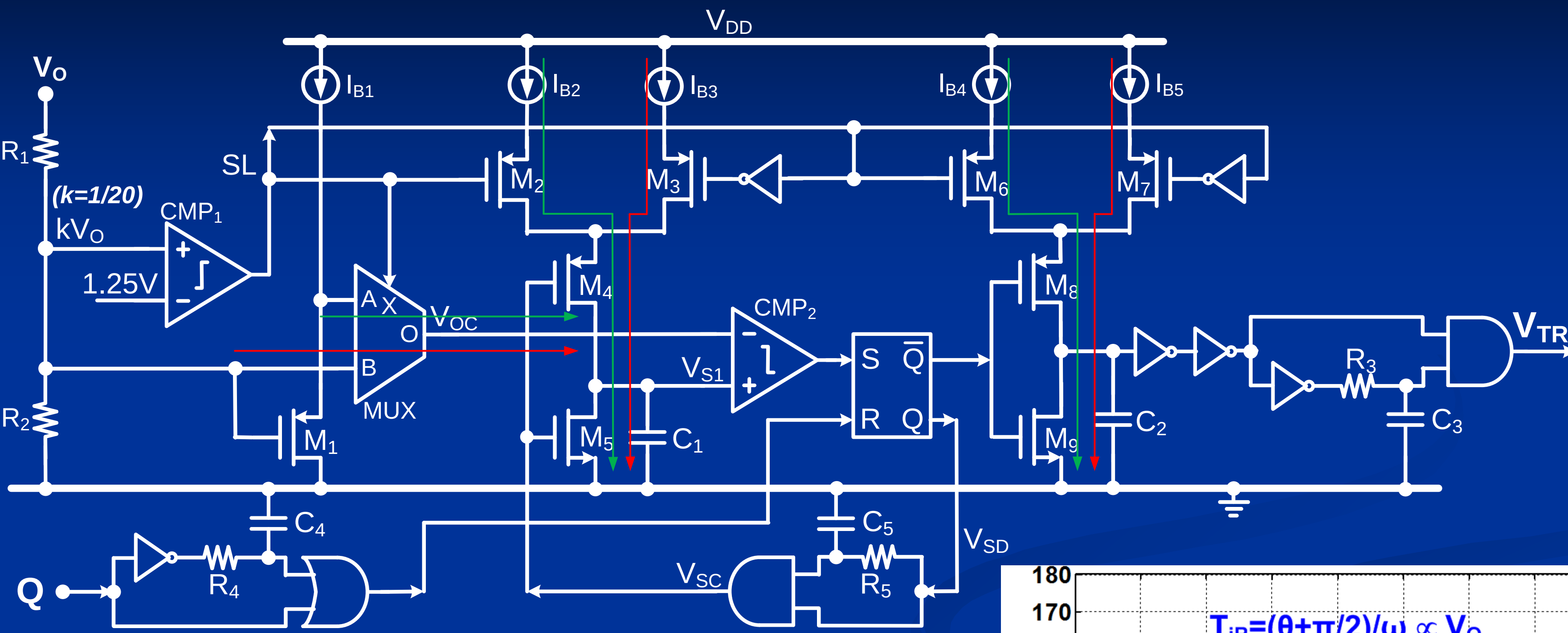
- **Auto-configurable hard/soft switching mode controller (ACHSSC)**

  - **Mode=1: Hard-Switching**
  - **Mode=0: Soft-Switching**

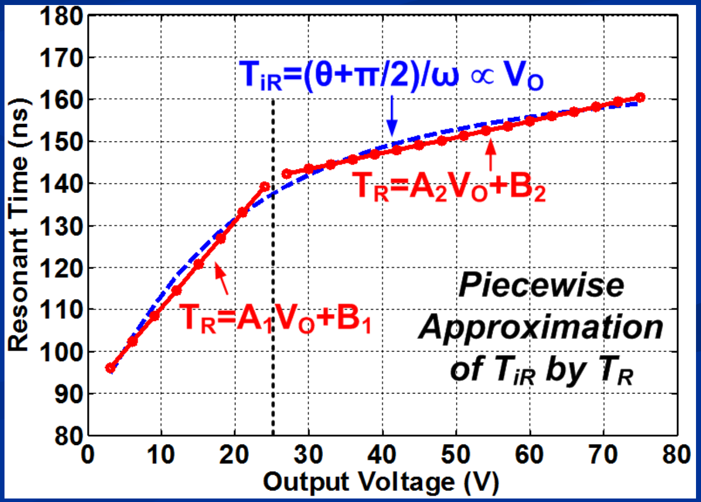


- **The ACHSSC takes outputs from zero-voltage detectors (V_{ZP}, V_{ZN}), the adaptive resonant timing emulator (V_{TR}), and the synchronous current controller (Q) to produce the optimal dead-time for controlling M_P and M_N.**

Proposed Adaptive Resonant Time Emulator

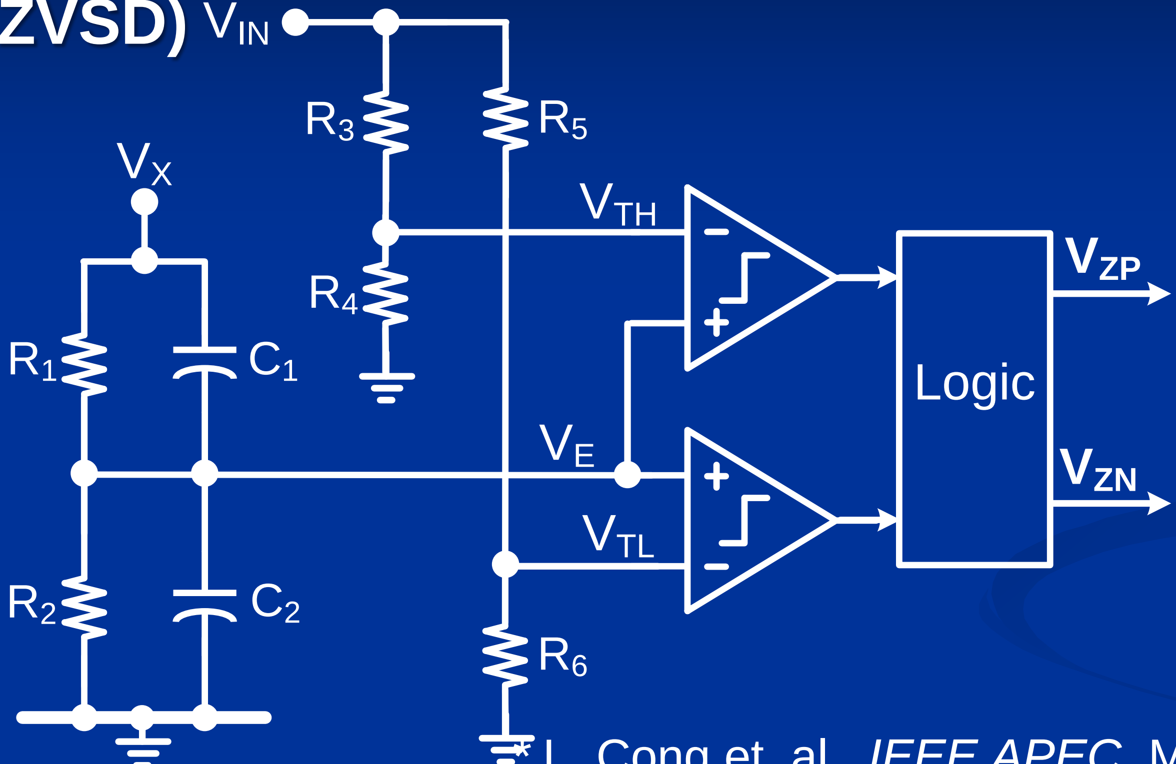


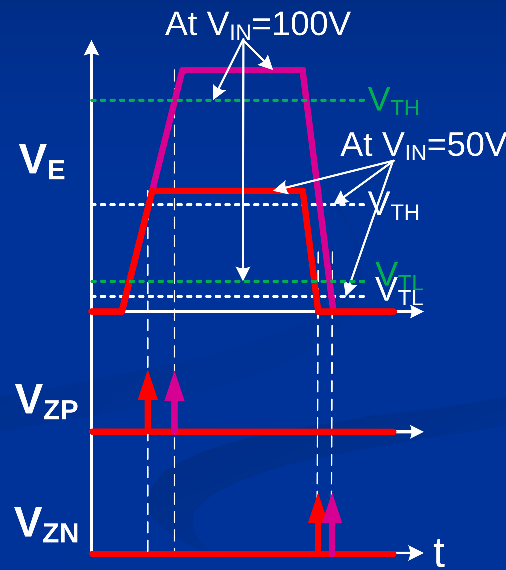
- When $V_{IN} > V_{RP}$, the proposed ARTE generates T_R under different output voltages for achieving quasi-ZVS operation of M_P.



State-of-the-Art HV ZVS Detector

- **Comparator-based HV zero-voltage-switching detector (ZVSD)**

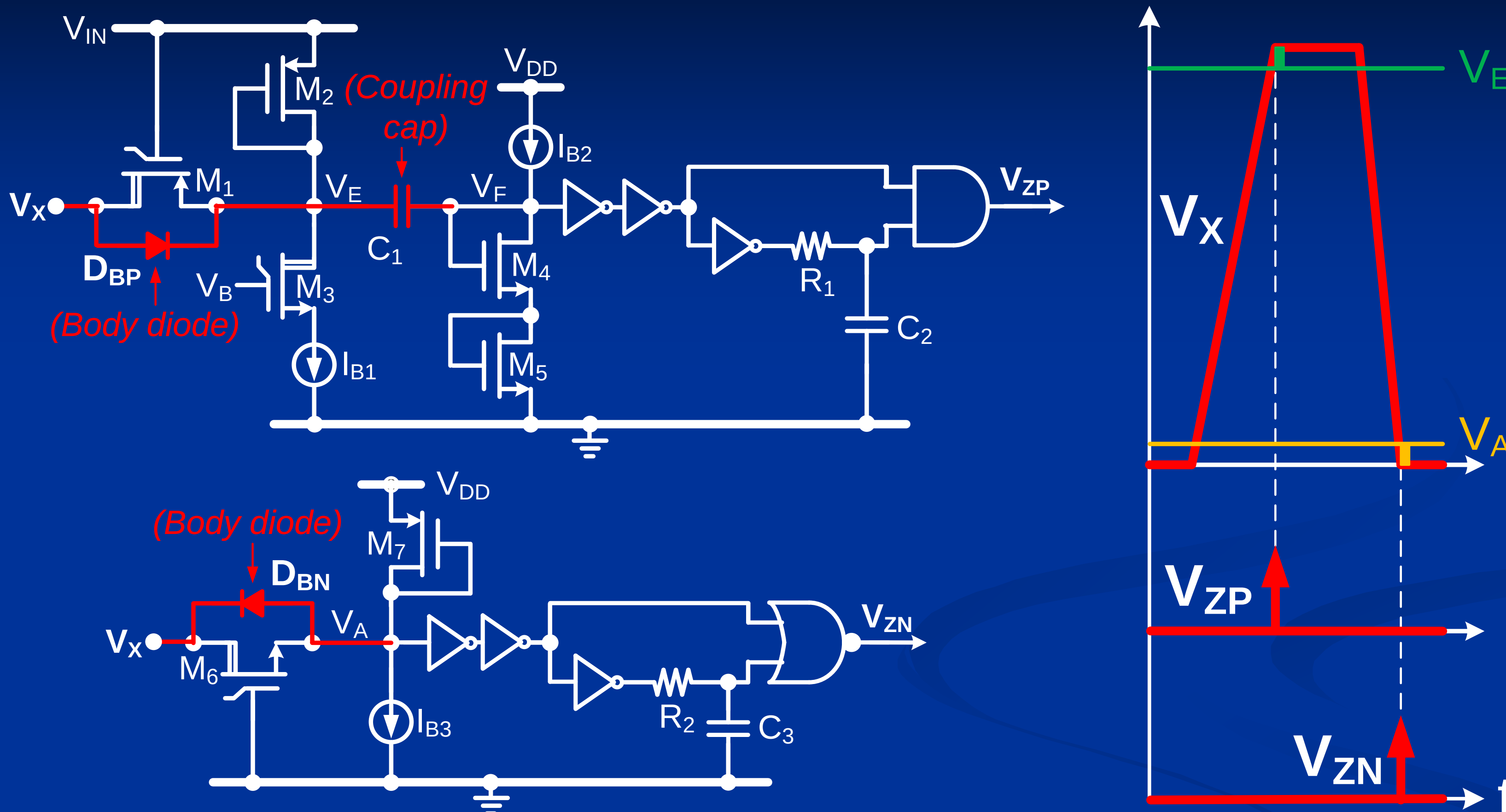




* L. Cong et. al., *IEEE APEC*, Mar. 2015, pp. 2007 – 2010.

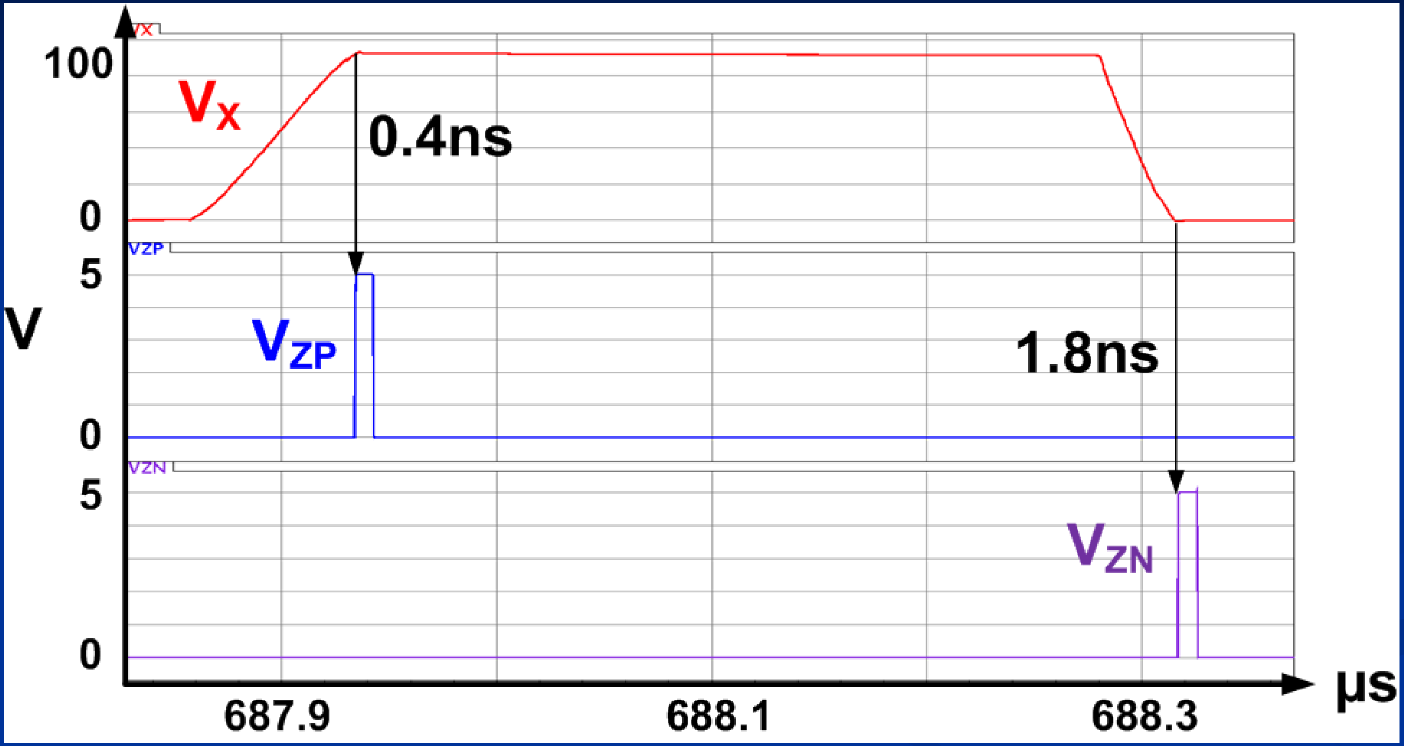
- **Enable adaptive ZVS detection under different input voltages.**
- **Propagation delays of comparators and voltage divider result in long ZVS detection delay in 10s of ns.**

Proposed Body-Diode Based HV ZVSDs (1)



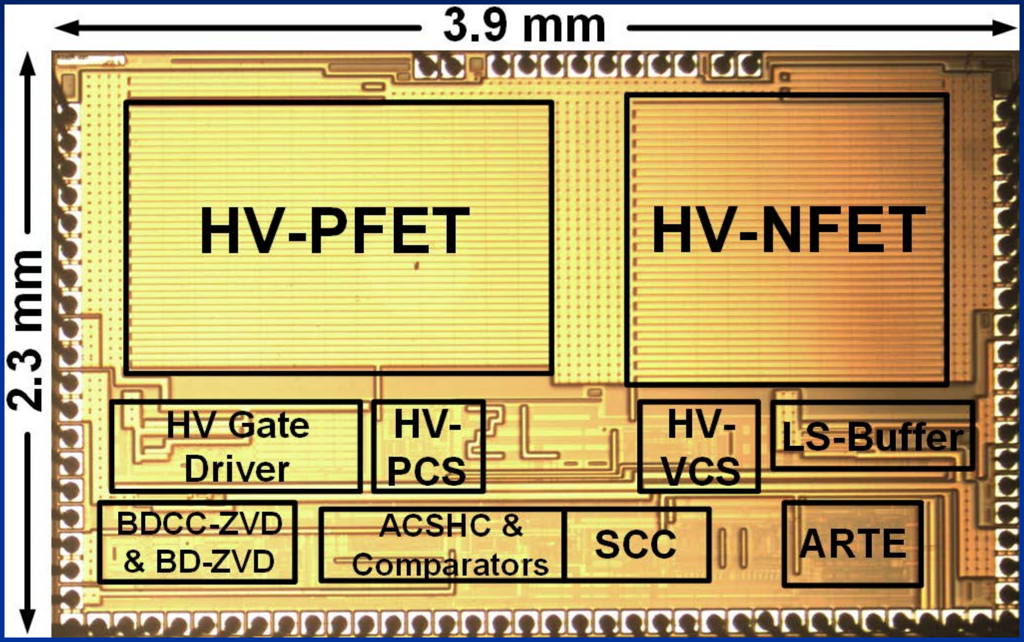
- When V_X is approaching V_{IN}, a short pulse is generated and then coupled to the LV domain as V_{ZP} when $V_X = V_A$.
- When V_X is approaching 0, a short pulse V_{ZN} is generated when $V_X = V_A$.

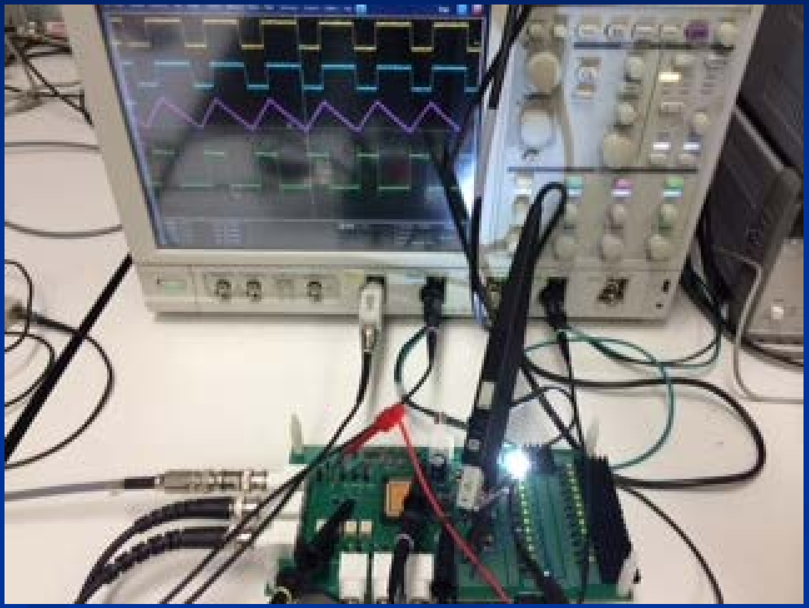
Proposed Body-Diode Based HV ZVSDs (2)



- The detection delays of the proposed ZVSDs in the LED driver are only 0.4ns and 1.8ns, respectively, at V_{IN} = 115V.
- The proposed HV ZVSDs enable high-speed and precise zero-voltage-switching detection of M_P and M_N.

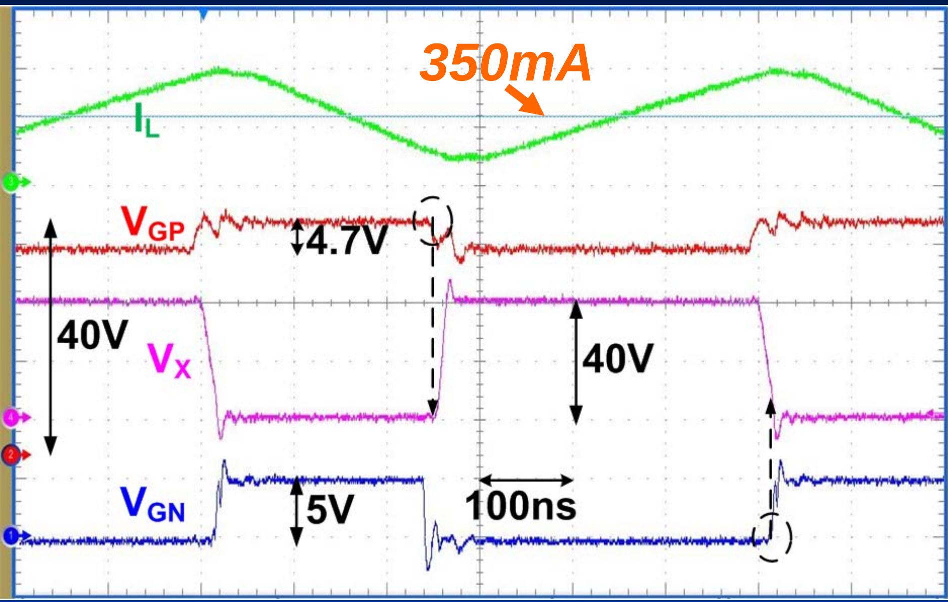
Chip Micrograph and Experimental Prototype



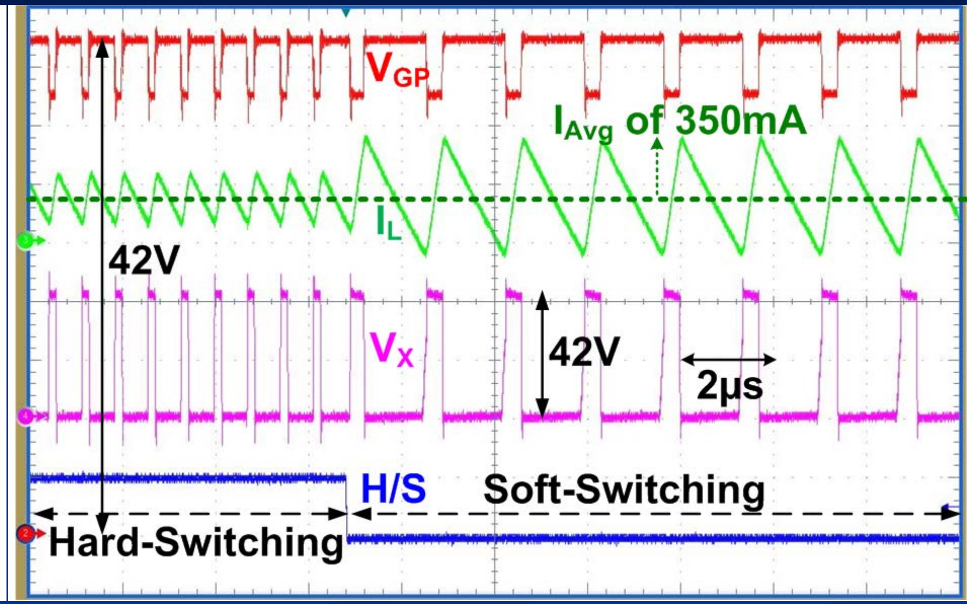


- The proposed on-chip LED driver is fabricated in a 0.5µm 120V CMOS process.
- Total chip area is 9.4mm^2 including bonding pads.
- Testing using Cree XB-D white LEDs

Measured HS Operation and Mode Change



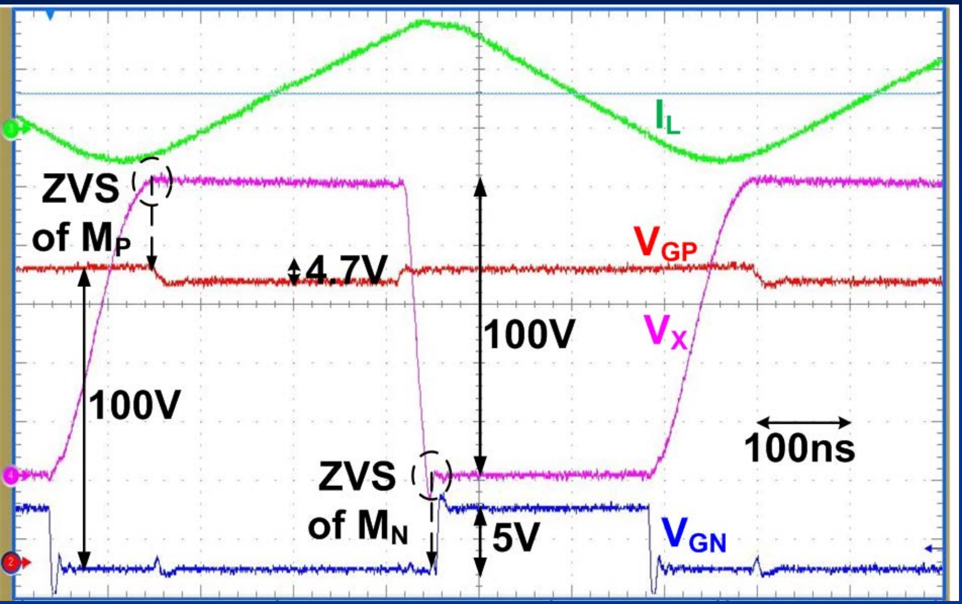
(HS under V_{IN}=40V, 8 LEDs)



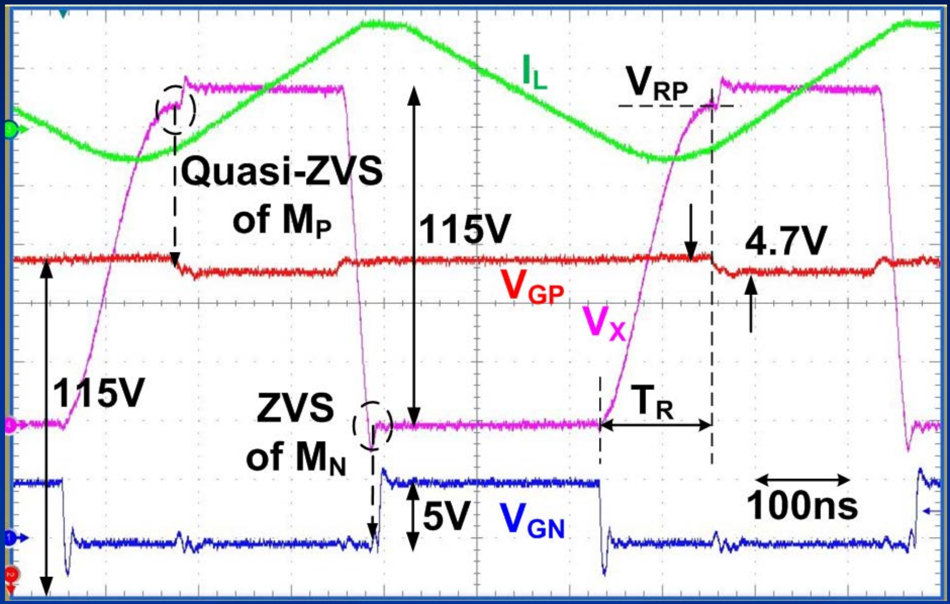
(Mode change from HS to SS)

- I_{Avg} is regulated at 350mA in the HS mode at V_{IN} = 40V.
- The LED driver automatically changes from the HS mode to the SS mode when $V_{IN} \geq$ 42V.
- I_{Avg} is the same in both modes to achieve good LED current accuracy.

Measured ZVS Operation in SS Mode



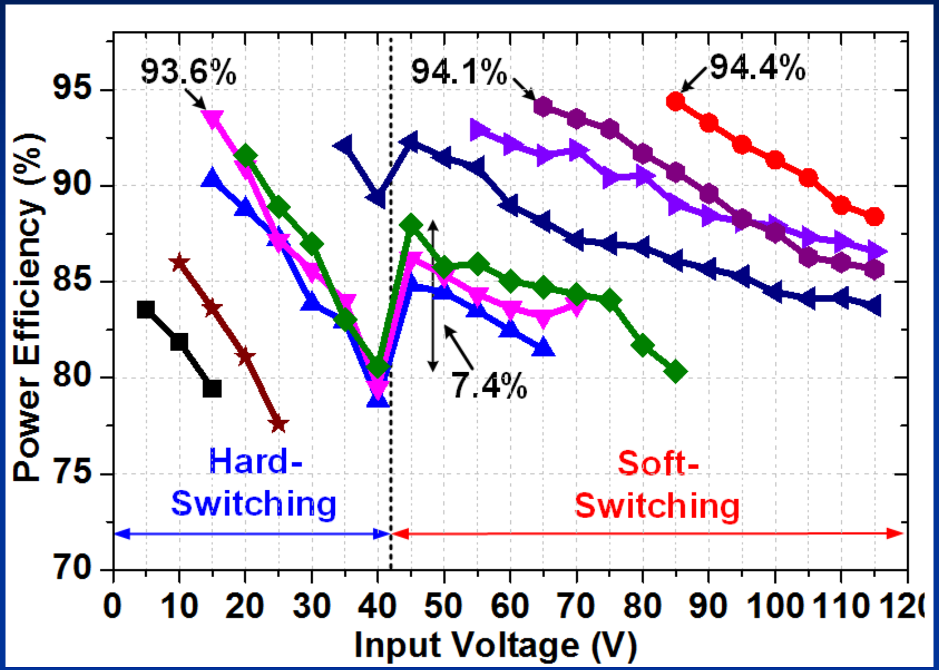
(V_{IN} = 100V, 18 LEDs, $V_{IN} < V_{RP}$)

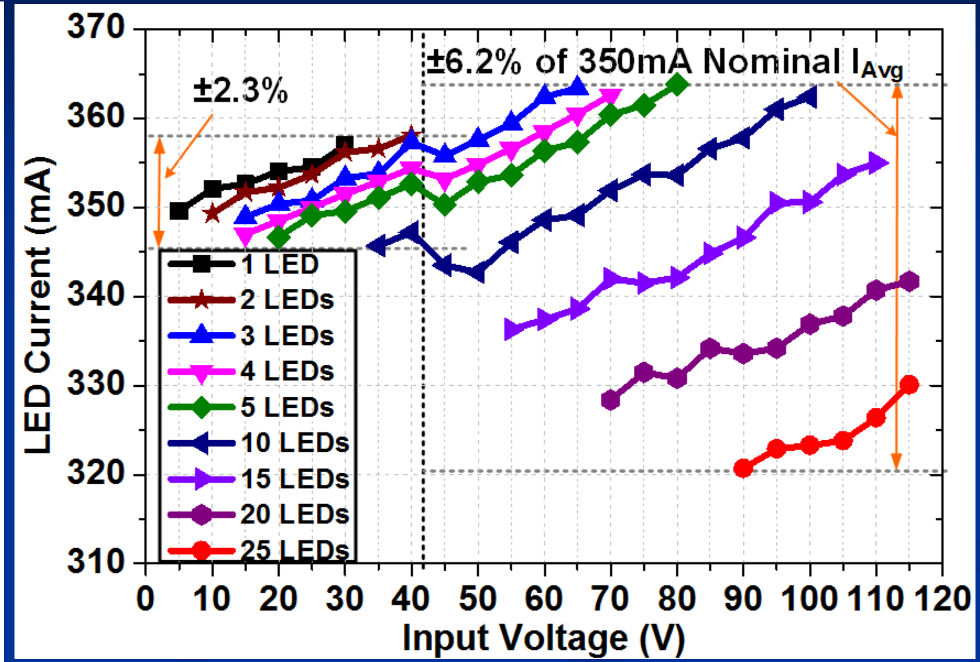


(V_{IN} = 115V, 18 LEDs, $V_{IN} > V_{RP}$)

- **Full ZVS of M_P**: V_{GP} goes "low" after V_X settles to V_{IN}; **Full ZVS of M_N**: V_{GN} goes "high" after V_X decreases to 0.
- **Quasi-ZVS of M_P**: V_{GP} goes "low" when $V_X = V_{RP}$; while M_N still achieves full ZVS.

Measured Efficiency and Current Accuracy





- **Peak power efficiencies** are **93.6% (HS)** and **94.4% (SS)** with a **7.4% efficiency improvement by using SS mode** at V_{IN} = 45V.
- The variations of I_{Avg} are within ±2.3% (HS, 1 – 10 LEDs) and ±6.2% (SS, 3 – 25 LEDs).

Comparison of Different HV LED Drivers

	LM3404HV	JSSC 2014	JSSC 2014	This Work
Process	N. A.	0.5µm 5V CMOS	0.35µm 50V CMOS	**0.5µm 120V CMOS**
Input Voltage (V)	6 – 75	11 – 20	10 – 40	**5 – 115**
Switching Mode	Hard-Switching	Hard-Switching	Hard-Switching	**Auto-Configurable Hard / Soft-Switching**
Average LED Current (mA)	1000	50 / 100	350	**350**
No. of Drivable LEDs	N. A.	3 – 4	1 – 10	**1 – 25**
Max. Output Power (W)	N. A.	N. A.	10	**25**
Switching Frequency	~200 kHz	≤200 kHz	≤1 MHz	**≤2.2 MHz in HS ≤1.6 MHz in SS**
Inductor (µH)	68 / 330	100 – 1000	22 / 39*	**10 – 39**
Settling Time (µs)	N. A.	165*	8.5	**2.5**
Dimming Frequency (Duty Cycle)	<1 kHz (N. A.)	N. A.	10 kHz (0.2 – 1)	**20 kHz (0.1 – 1)**
LED Current Accuracy (LEDs No.)	±10% (N. A.)	10% (3 – 4)	±2.8% (2 – 10)	**±2.3% (1 – 10 in HS) ±6.2% (3 – 25 in SS)**
Max. Power Efficiency	88%*	91%	92.5%	**93.6% in HS 94.4% in SS**

Conclusions

- A wide-input-range (5V to 115V) auto-configurable hard/soft switching LED driver is introduced and verified.
- An adaptive resonant timing control (ARTC) establishes optimal ZVS of power FETs to minimize the converter switching loss in different input/output conditions.
- The proposed body-diode based zero-voltage-switching detectors (ZVSDs) significantly reduce the ZVS detection delay.
- The proposed LED driver supports the widest ranges of input voltages and output LED numbers, provides the highest power efficiency and achieves the best current accuracy compared to the prior art.

Acknowledgement

The authors would like to thank the financial support from US National Science Foundation (ECCS-1056013).

Q & A

Thank you!