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V^1 Control for fast transient response in Power Converters on Chip

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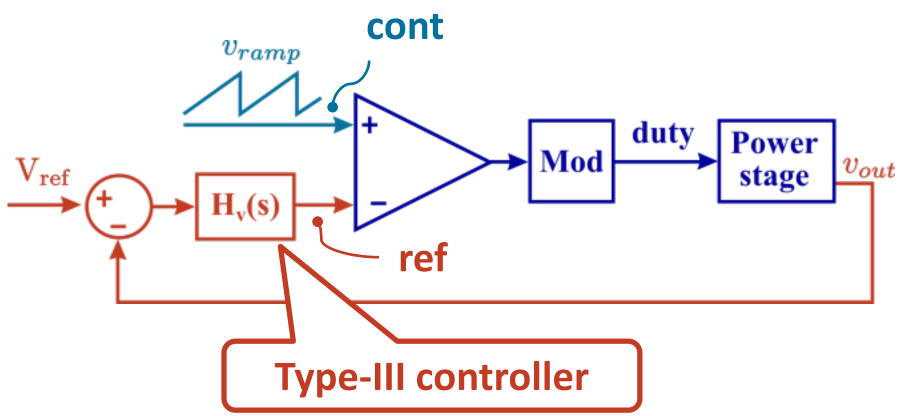
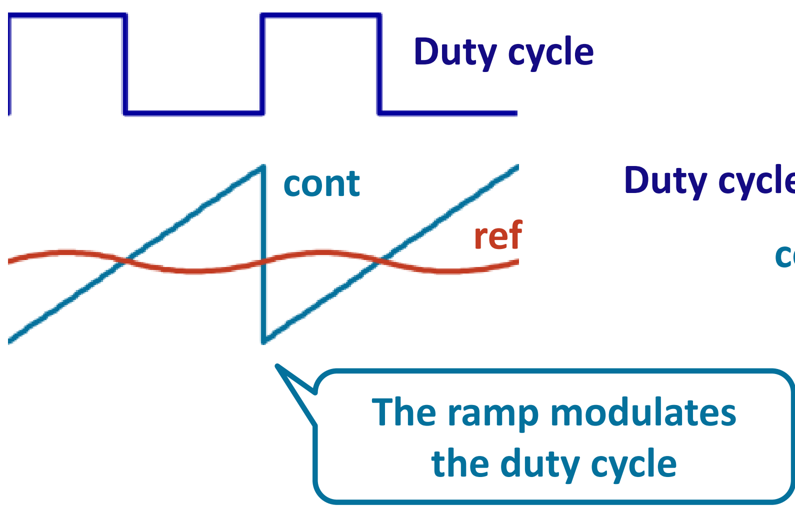
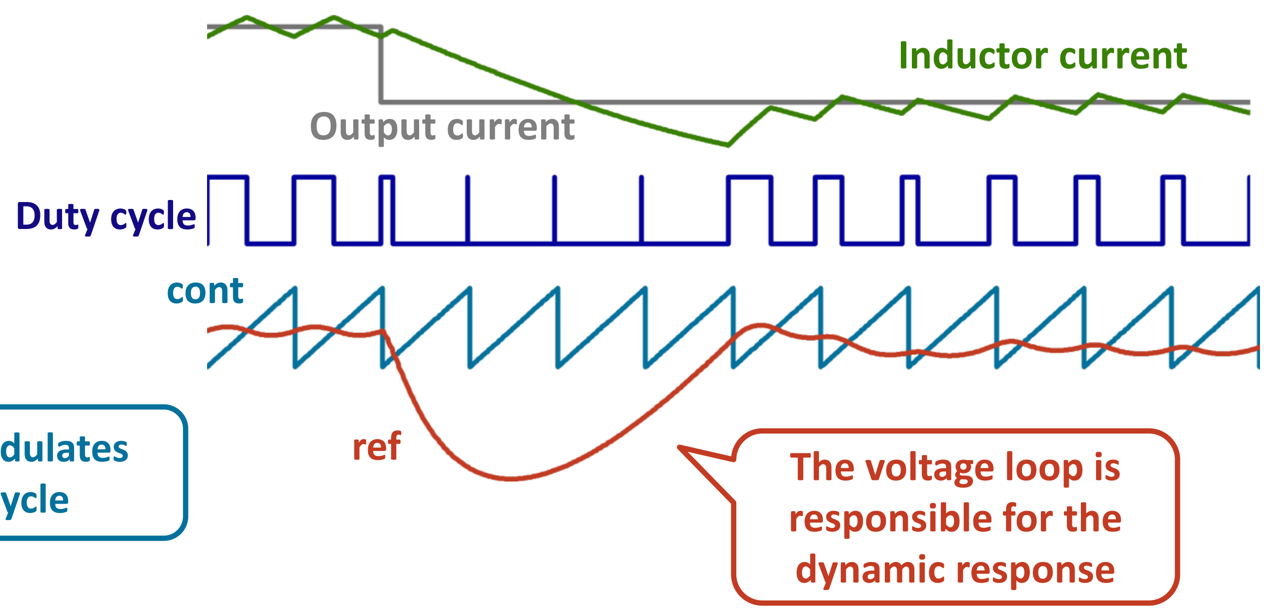
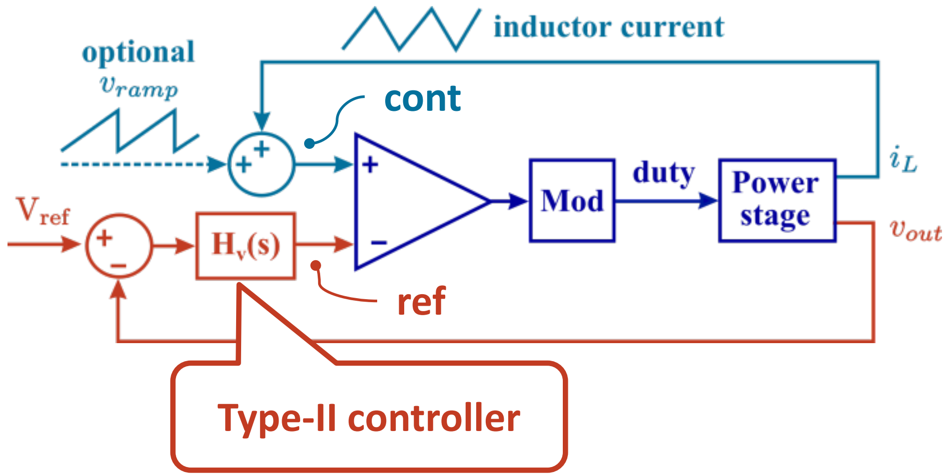
Introduction: Voltage mode control

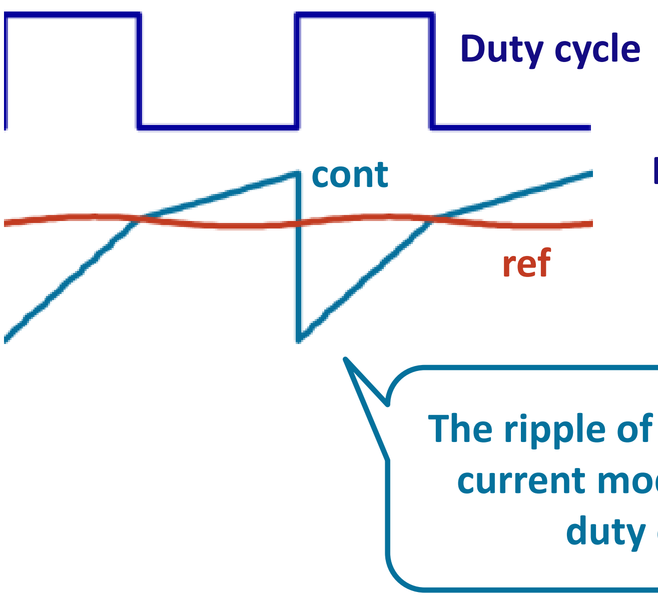


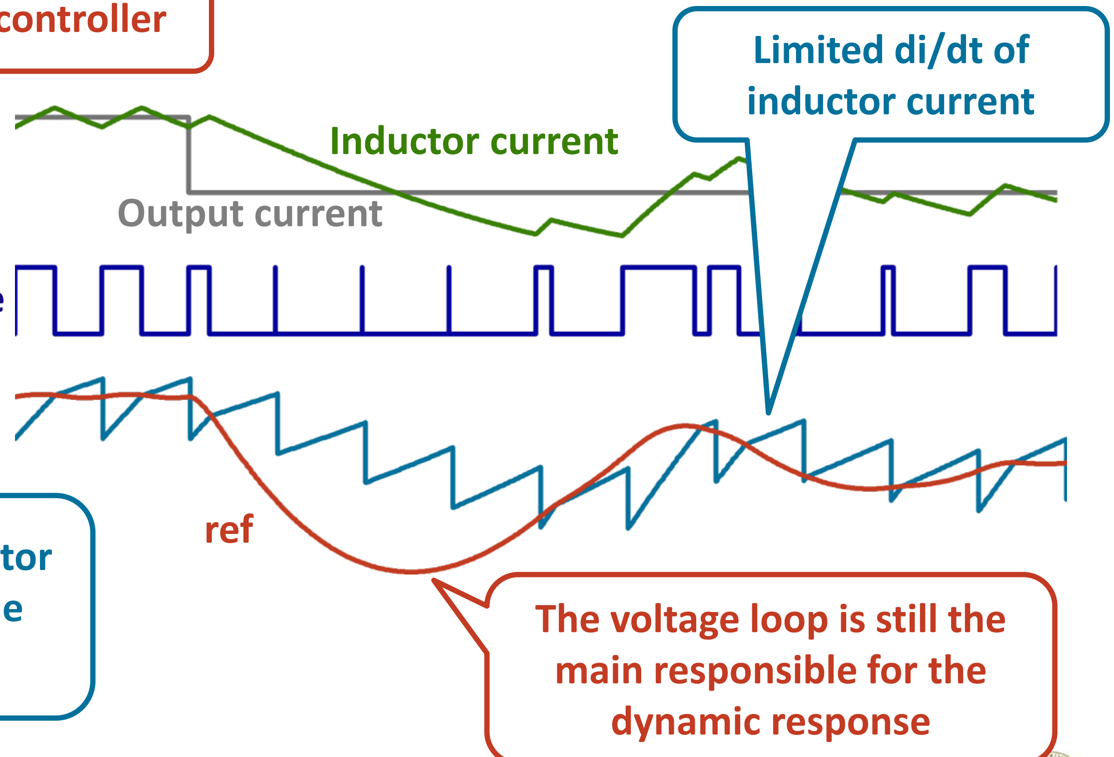




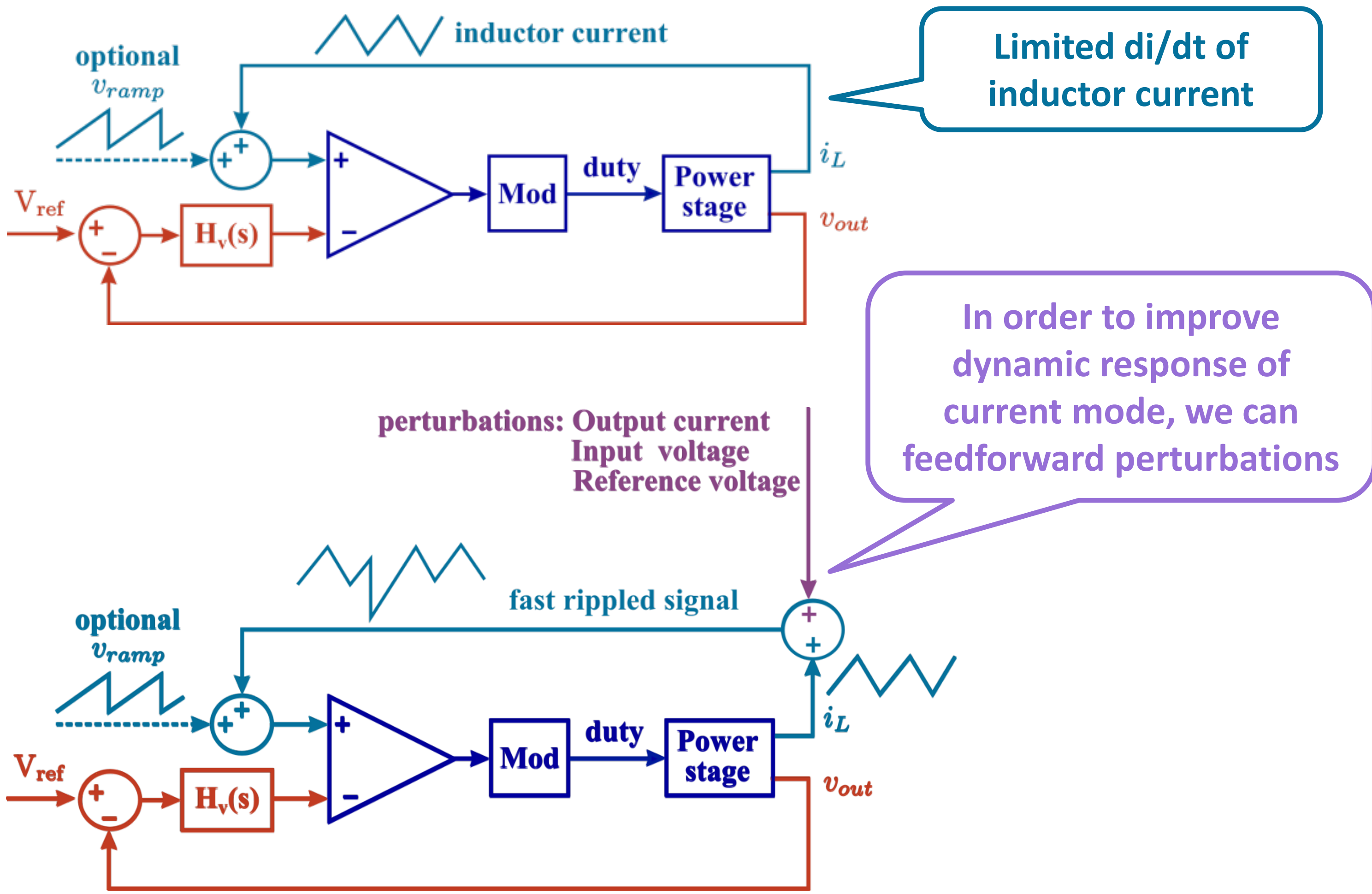
Introduction: Current mode control



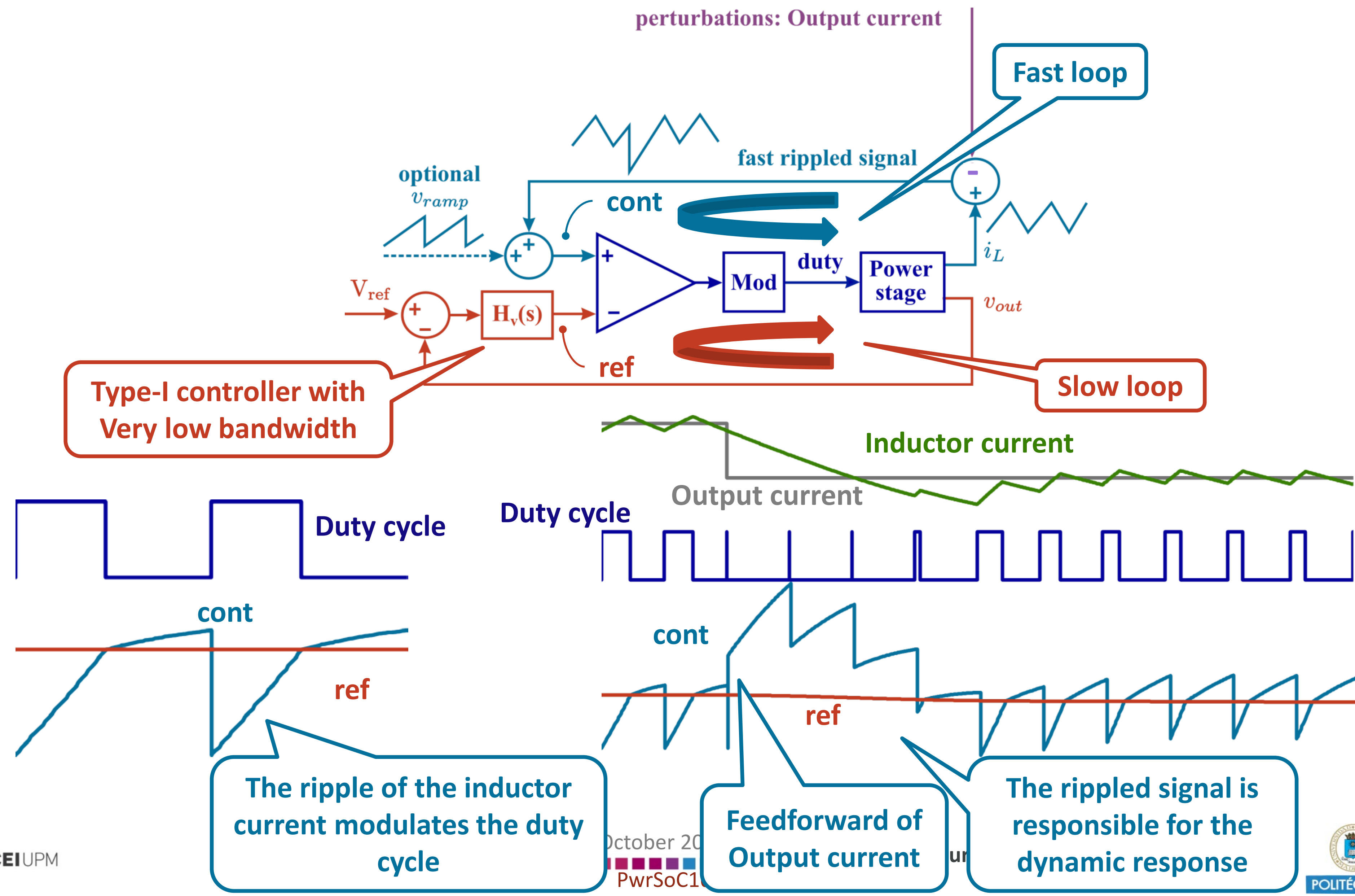




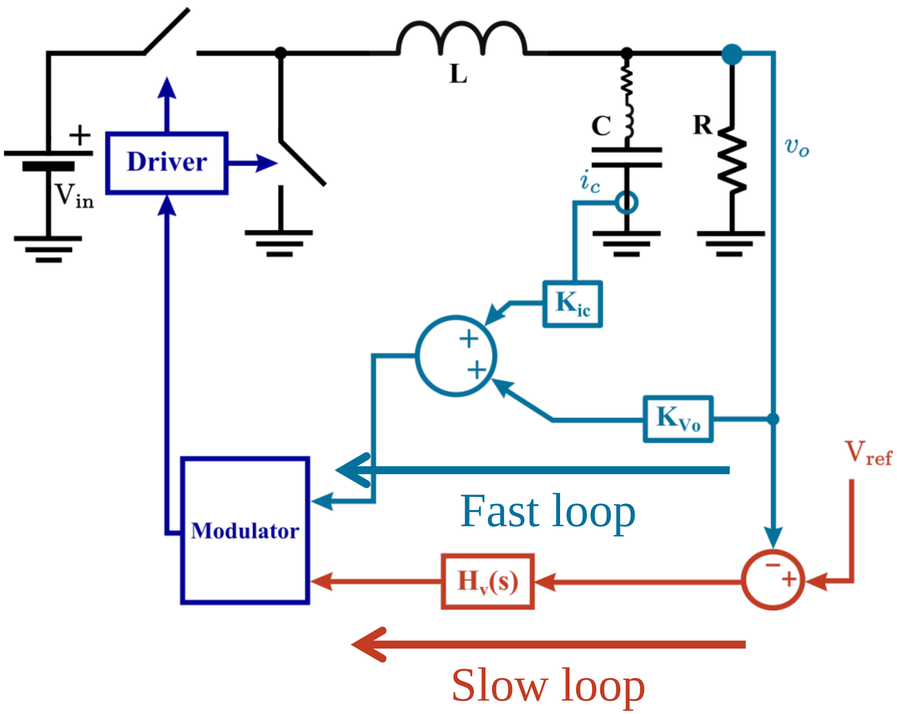
Introduction: Ripple-based control

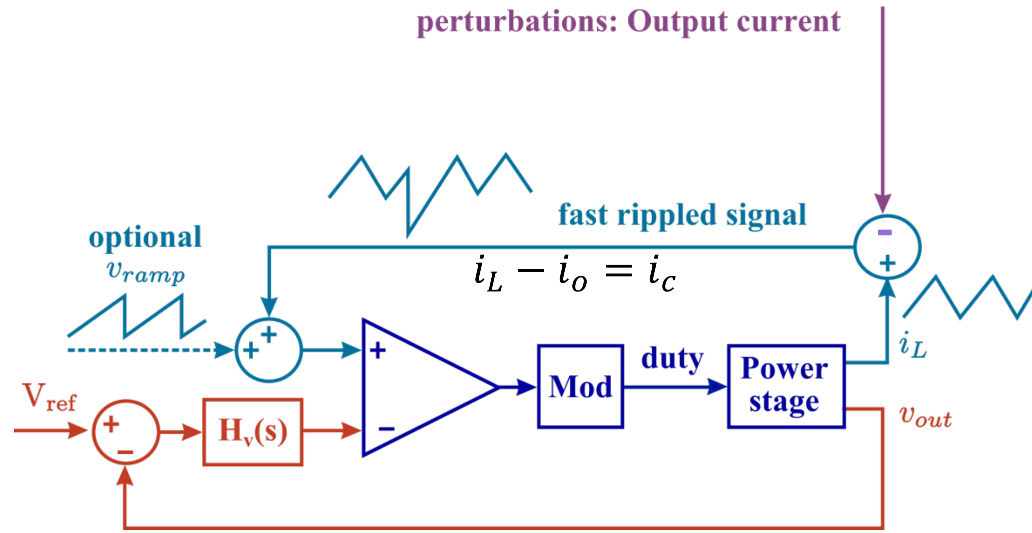


Introduction: Ripple-based control

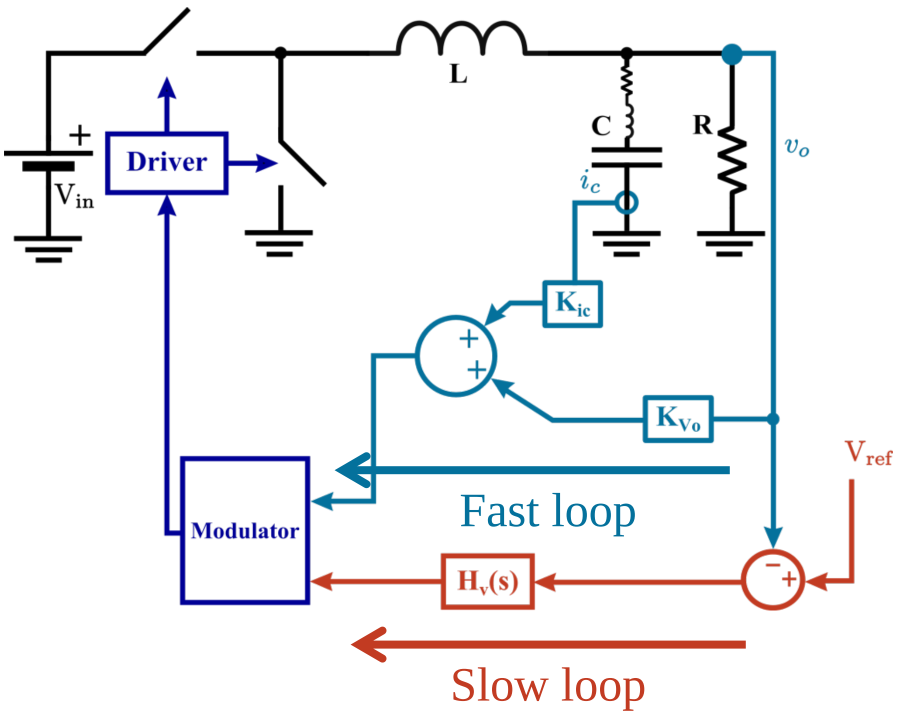


Introduction: $v^2 i_c$





Introduction: $v^2 i_c$



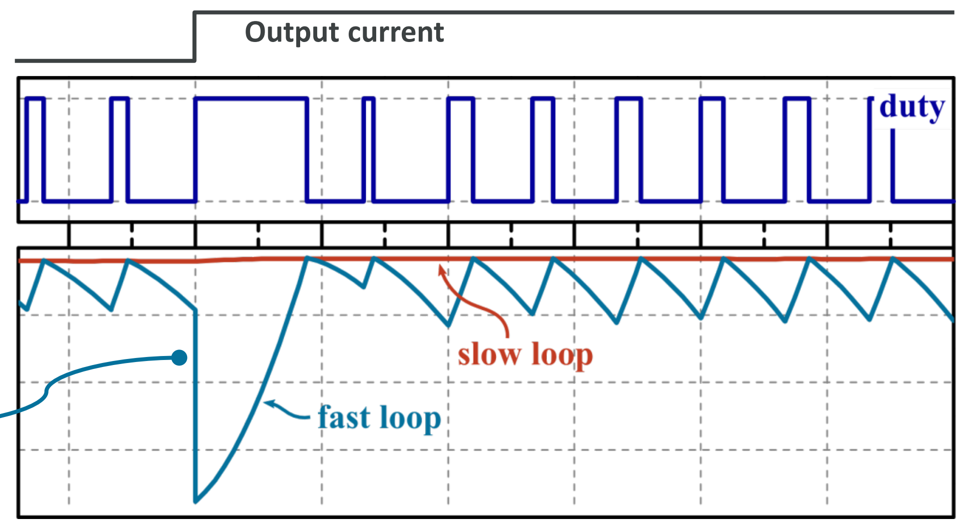
Fast loop:

- Responsible for fast dynamic response

Slow loop:

- Responsible to regulate tightly the output voltage.
- Very low bandwidth

Due to feedforward of output current



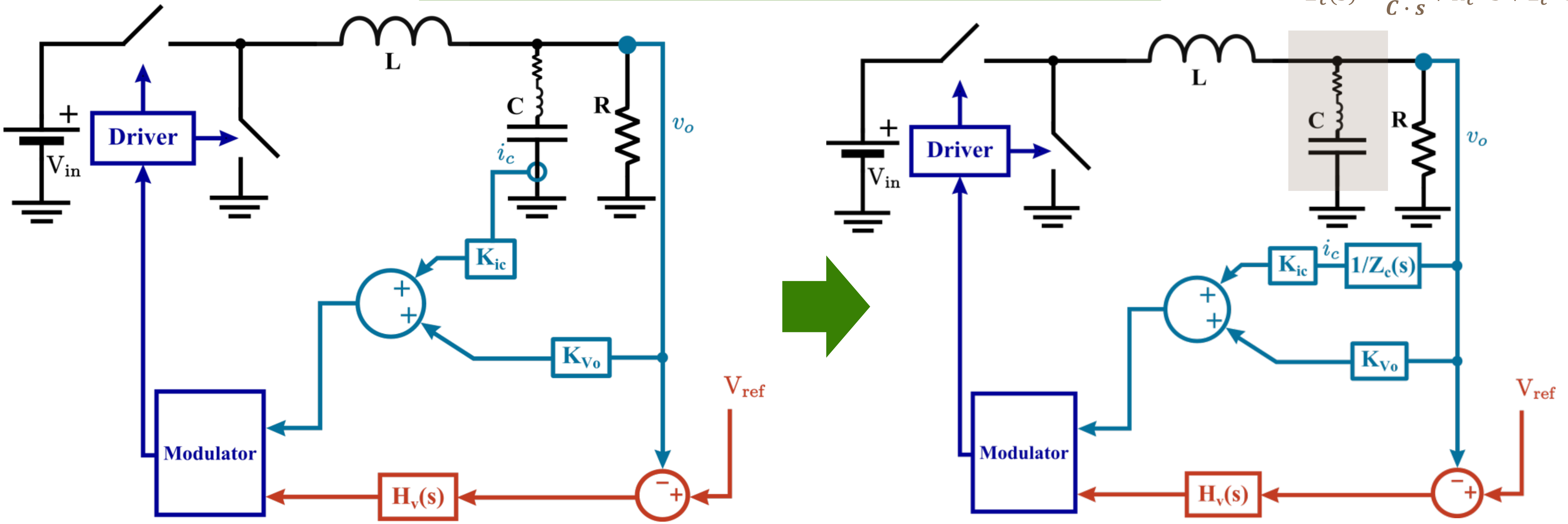
In load perturbances, the feedforward of the output current allows for a fast dynamic response

Introduction: v^2i_c

How can we measure the capacitor current?

We can estimate it by measuring only the output voltage and designing a transfer function 1/Zc(s)

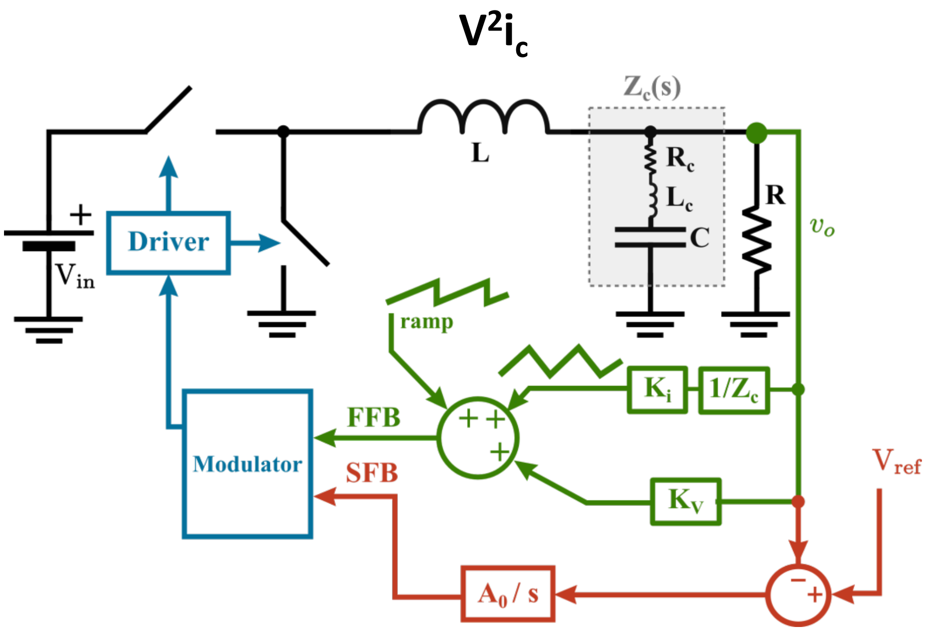
$$Z_c(s) = \frac{1}{C \cdot s} + R_c \cdot s + L_c \cdot s$$

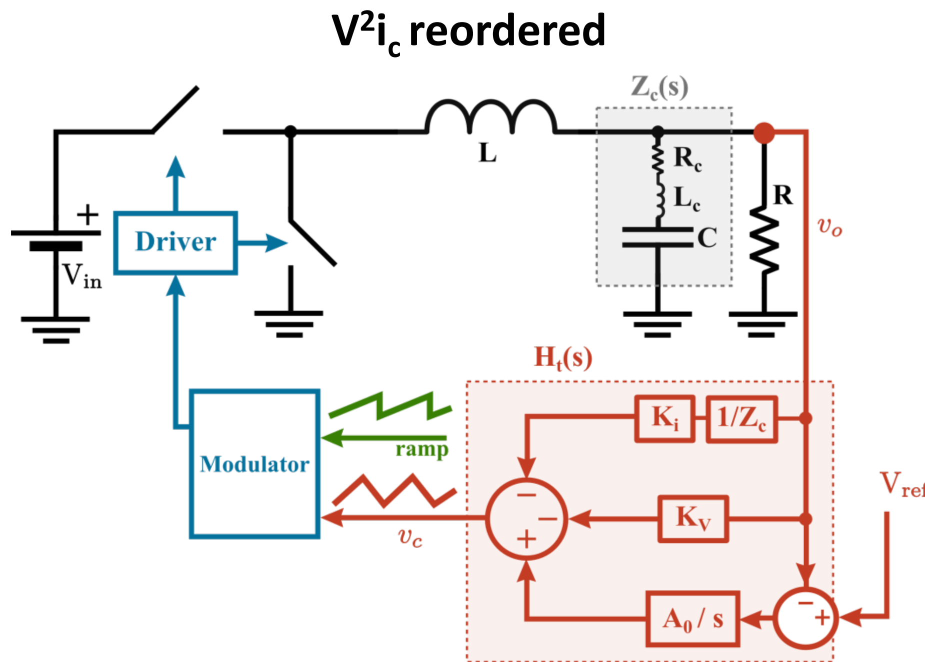


[ ] M. Del Viejo, P. Alou, J. A. Oliver, O. Garcia, and J. A. Cobos, “V2IC control: A novel control technique with very fast response under load and voltage steps,” in *2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2011, pp. 231–237.

[ ] Y. Yan, P.-H. Liu, F. Lee, Q. Li, and S. Tian, “V2 control with capacitor current ramp compensation using lossless capacitor current sensing,” in *2013 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2013, pp. 117–124.

v^1 concept

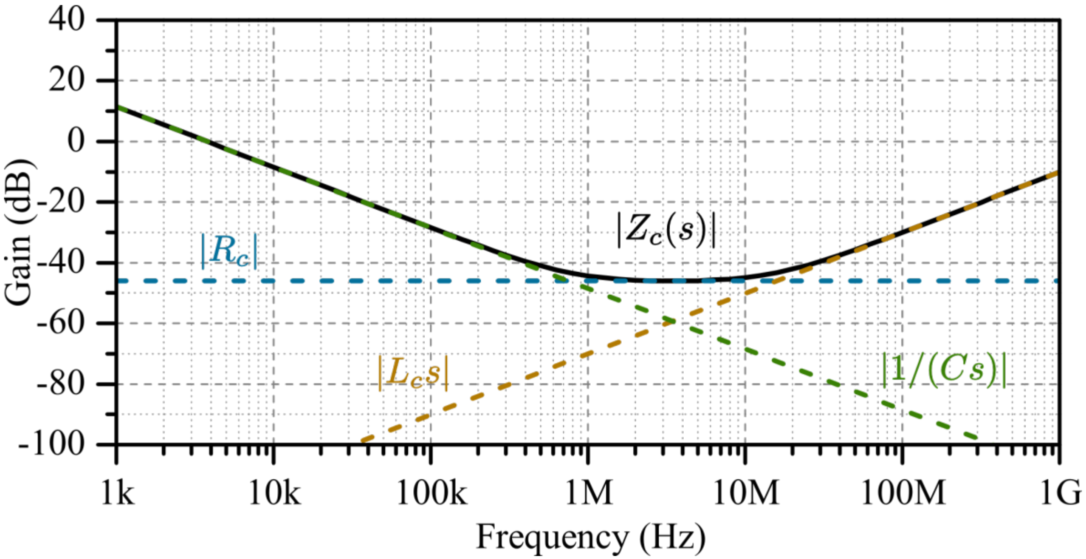


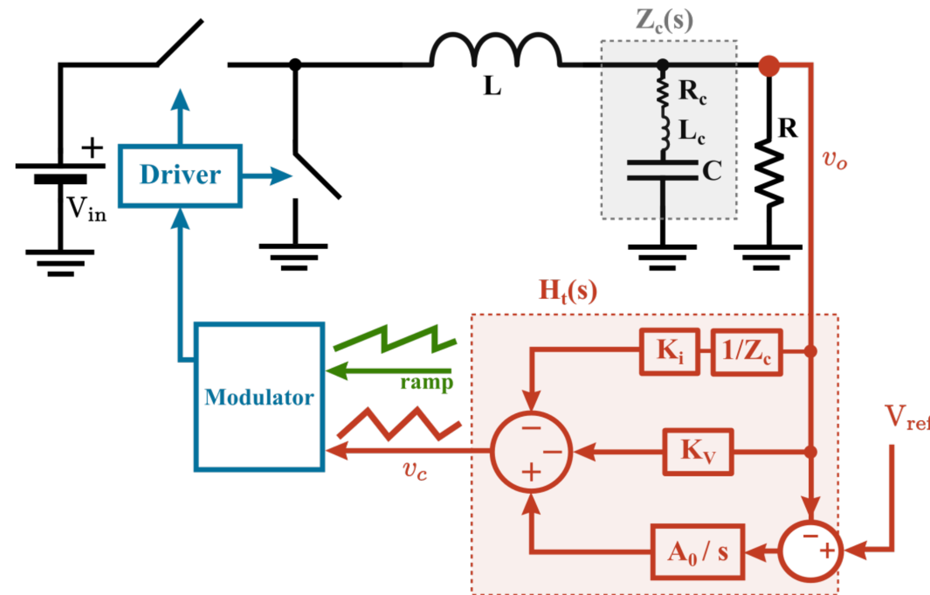


Is it possible to replicate V^2I_C in voltage mode?

v^1 concept

Low-Q output capacitor

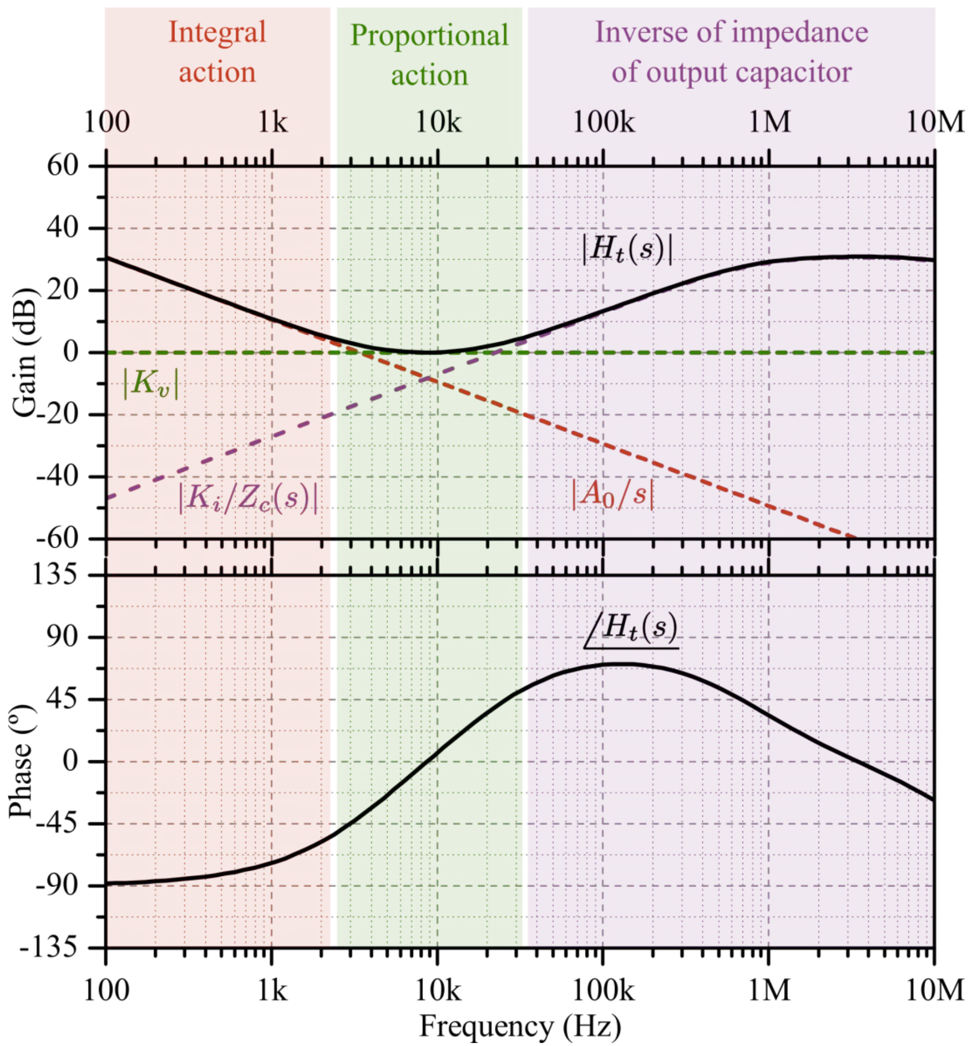


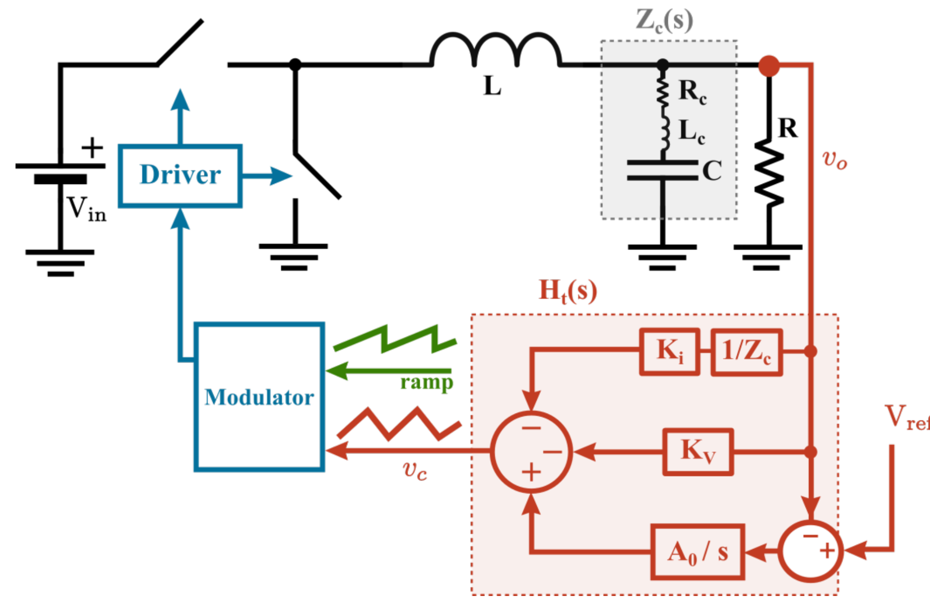


$$Z_c(s) = \frac{(1 + sCR_c)\left(1 + s\,{}^{L_c}/_{R_c}\right)}{Cs}$$

$$H_t(s) = \frac{A_o}{s} + K_v + K_i \frac{1}{Z_c(s)}$$

v[1] concept

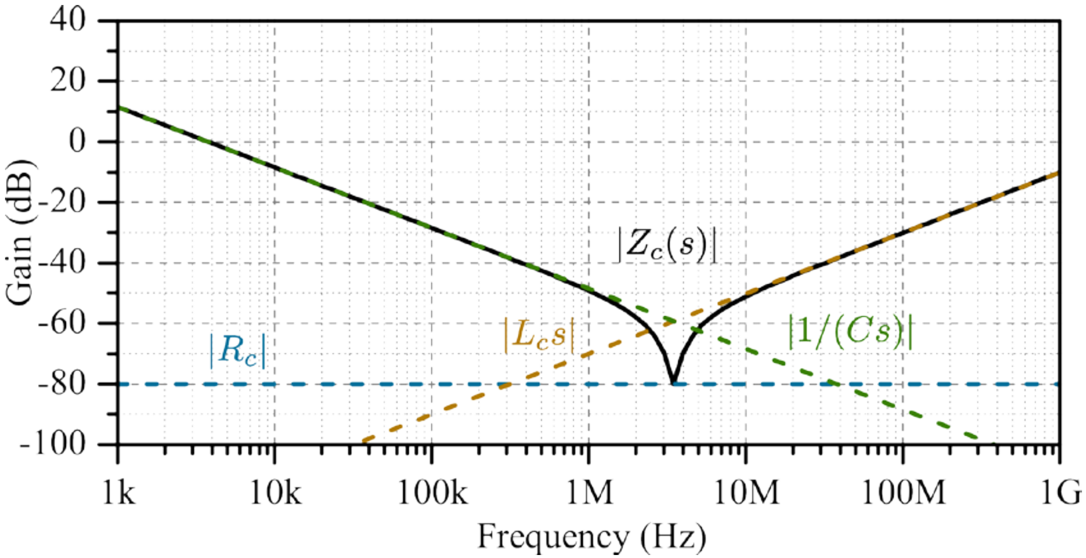


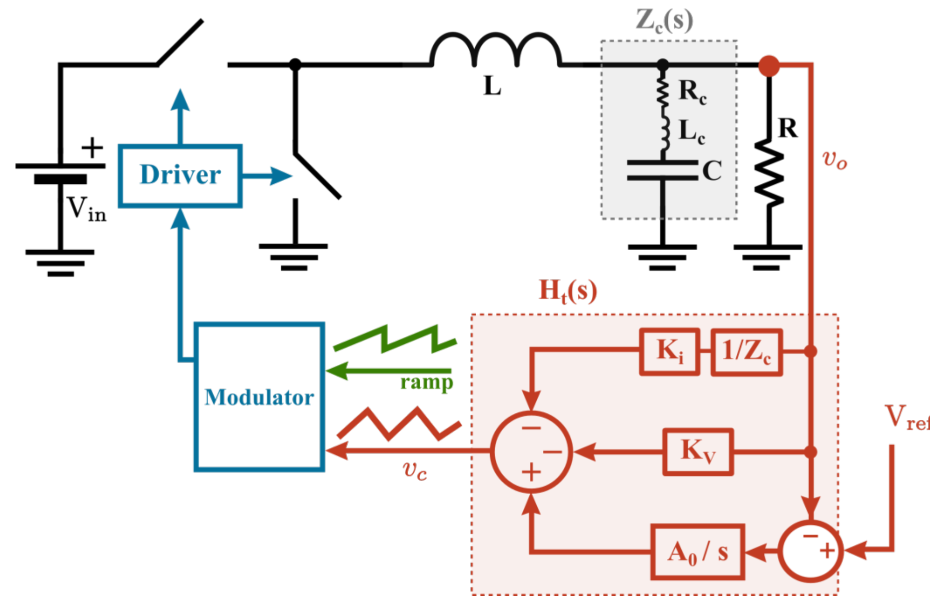


$$H_t(s) = \frac{A_o}{s} + K_v + K_i \frac{1}{Z_c(s)}$$

v^1 concept

High-Q output capacitor





$$Z_c(s) = \frac{s\left(1 + \frac{1}{Qw_c}s + \frac{1}{w_c^2}s^2\right)}{Cs}$$

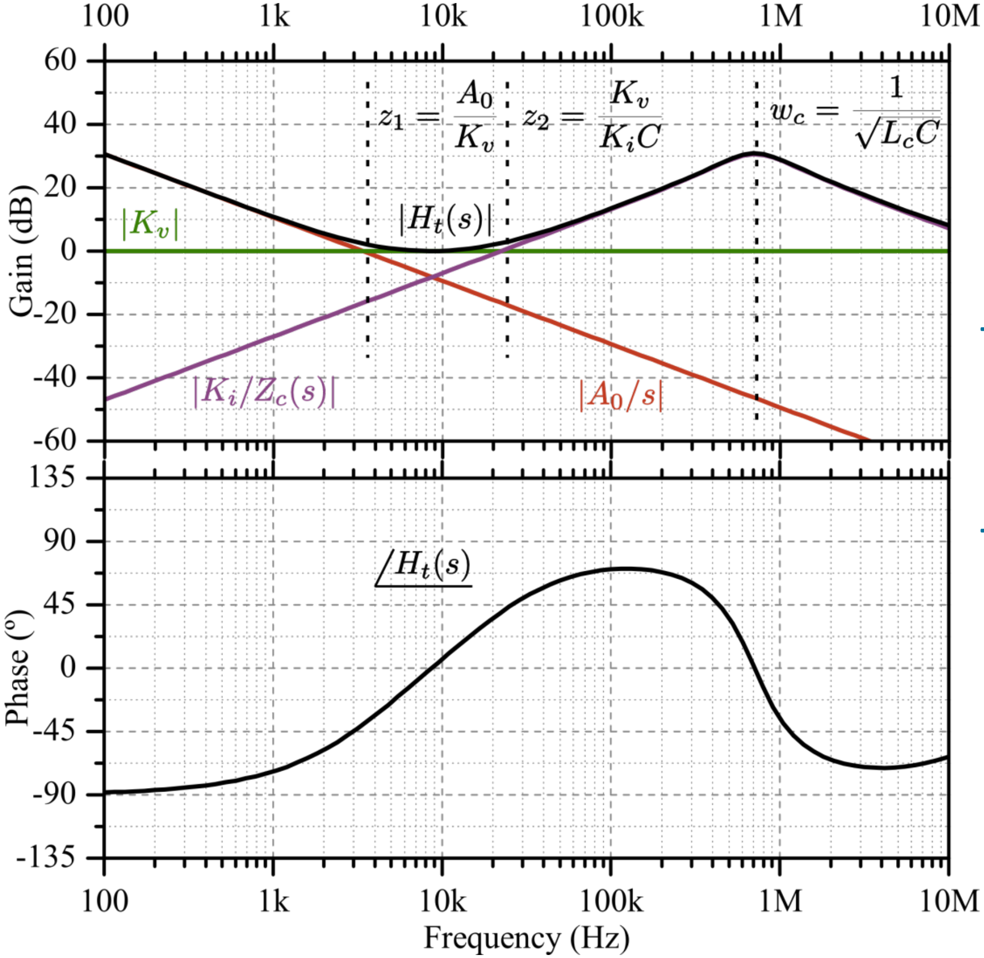
$$H_t(s) = \frac{A_o}{s} + K_v + K_i\frac{1}{Z_c(s)}$$

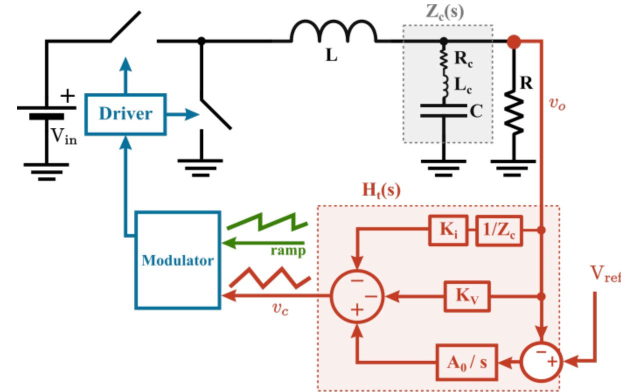
$$Q = \frac{\sqrt{L_c/C}}{R_c} \qquad w_c = \frac{1}{\sqrt{L_c C}}$$

v^1 concept

High-Q output capacitor

$$H_t(s) = A_o \frac{\left(1 + {}^{s}/_{z_1}\right)\left(1 + {}^{s}/_{z_2}\right)}{s\left(1 + \frac{1}{Qw_c}s + \frac{1}{w_c^2}s^2\right)}$$





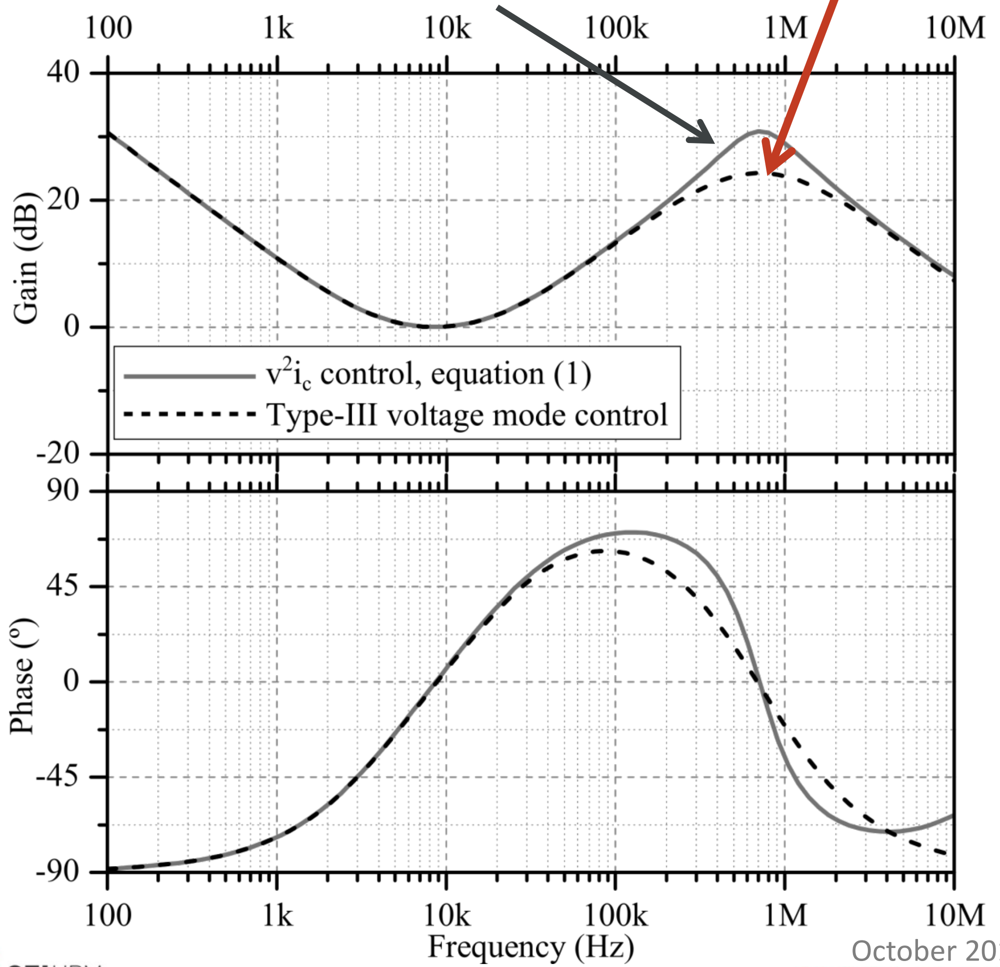
- $H_t(s)$ has complex poles. It cannot be implemented as a type-III controller!
- But it can be approximated if ΔB < $w_c/10$

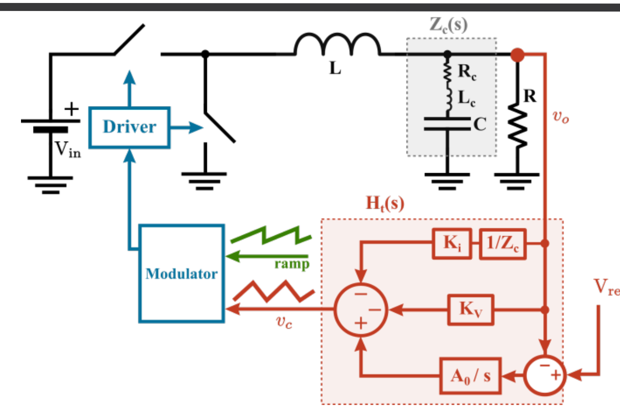
v^1 concept

High-Q output capacitor

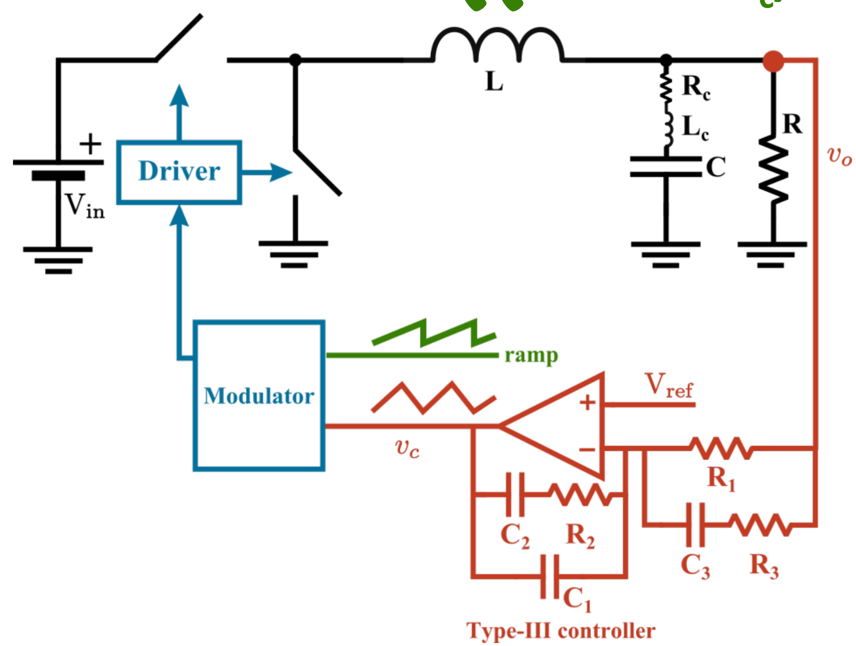
$$H_t(s) = A_o \frac{(1+{}^{s}/_{z_1})(1+{}^{s}/_{z_2})}{s\left(1+\frac{1}{Qw_c}s+\frac{1}{w_c^2}s^2\right)}$$

$$H_{type-III}(s) = A_o \frac{(1+{}^{s}/_{z_1})(1+{}^{s}/_{z_2})}{s\left(1+\frac{1}{w_c}s\right)^2}$$





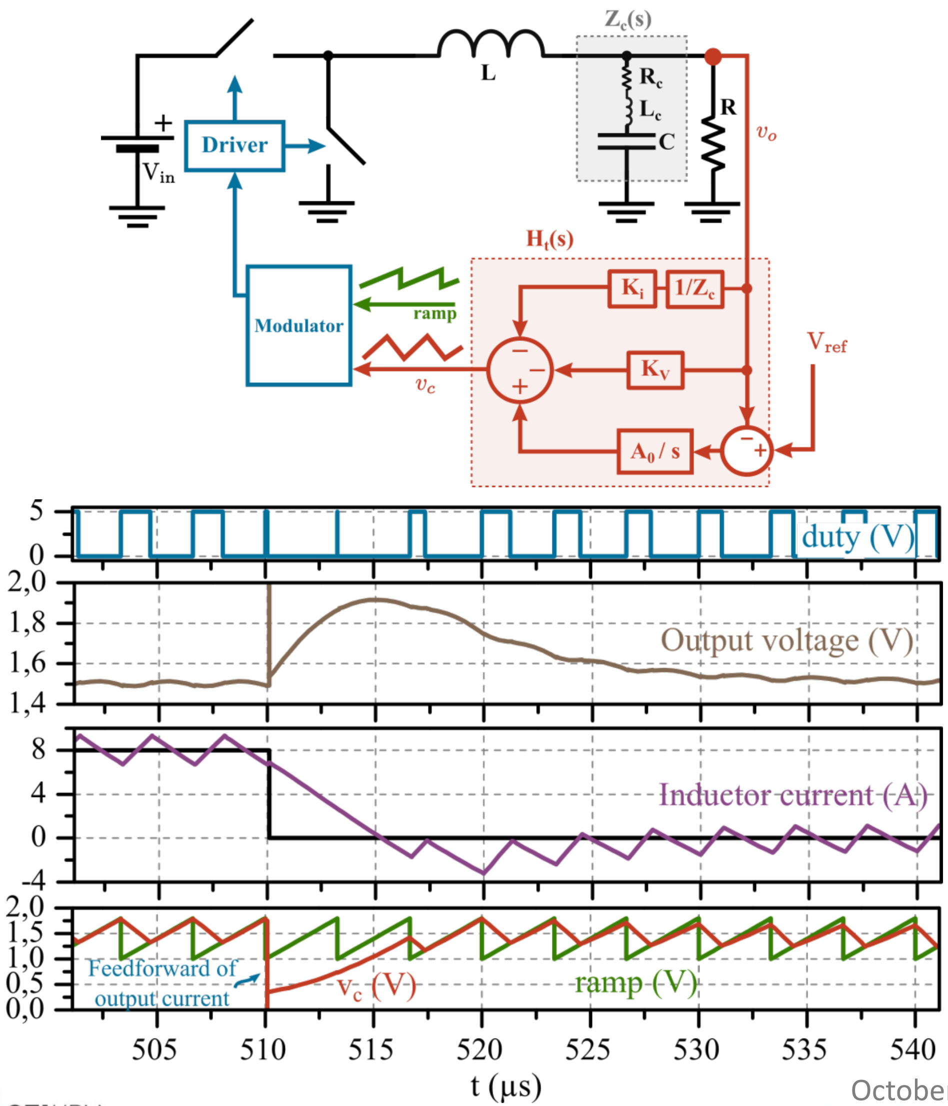
≈ If ΔB < $w_c/10$



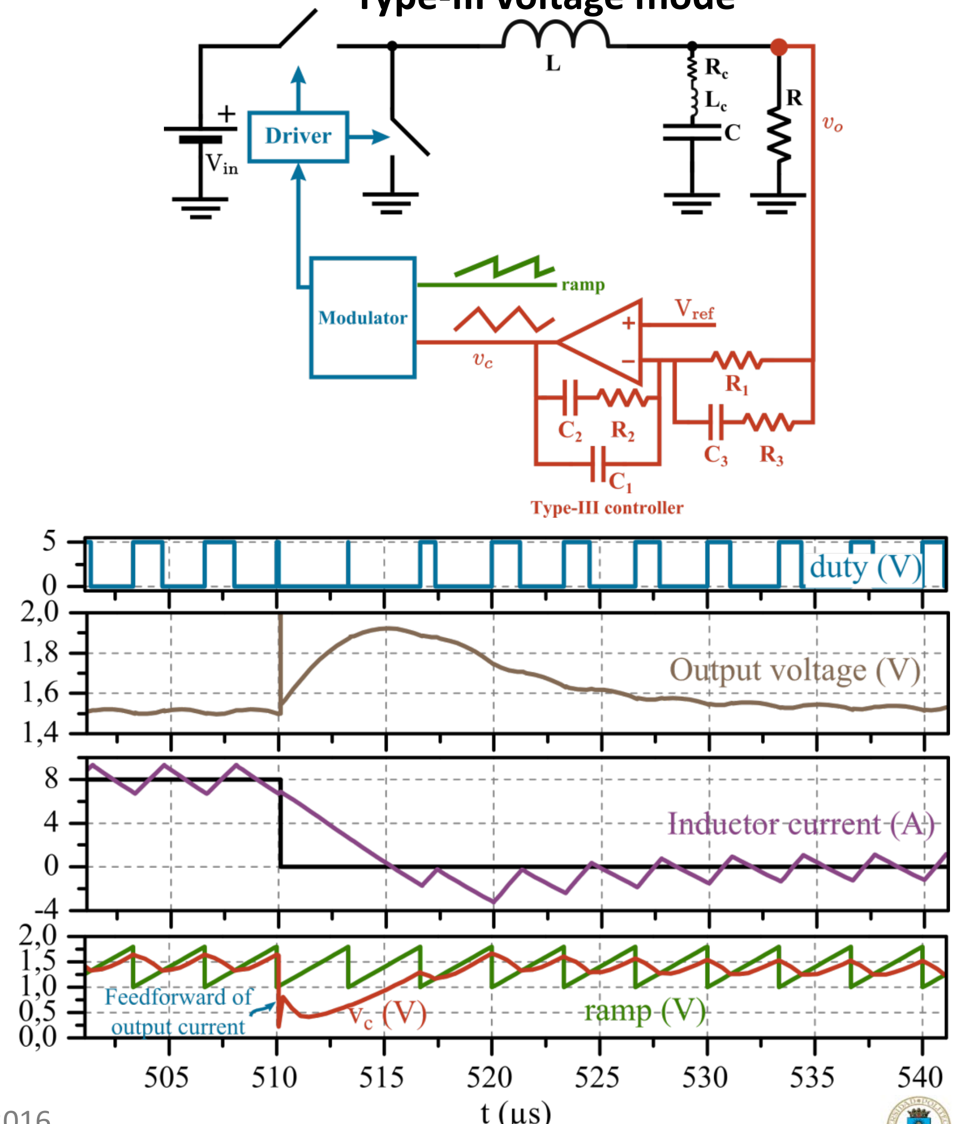
v^1 concept

High-Q output capacitor

V^2i_c reordered



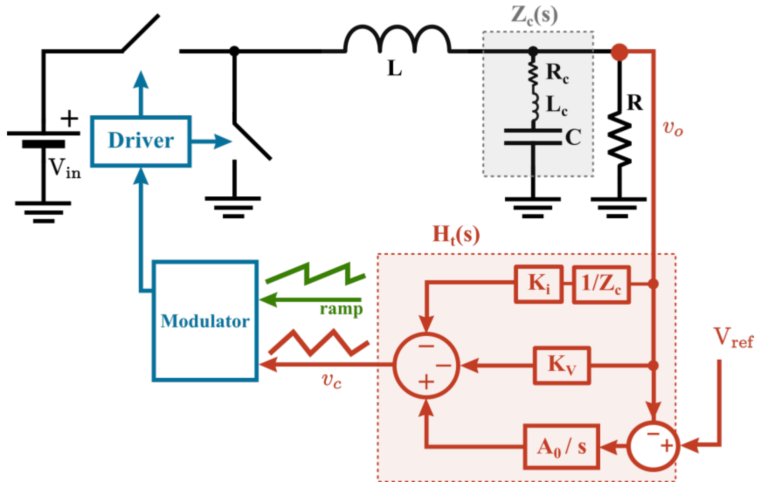
Type-III voltage mode



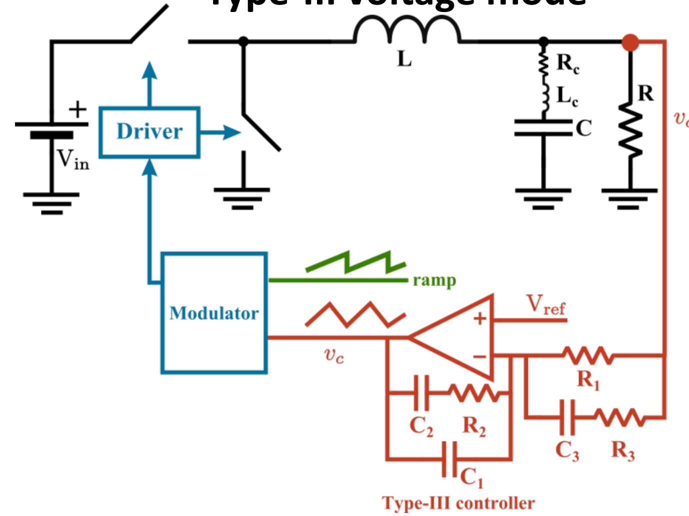
v^1 concept

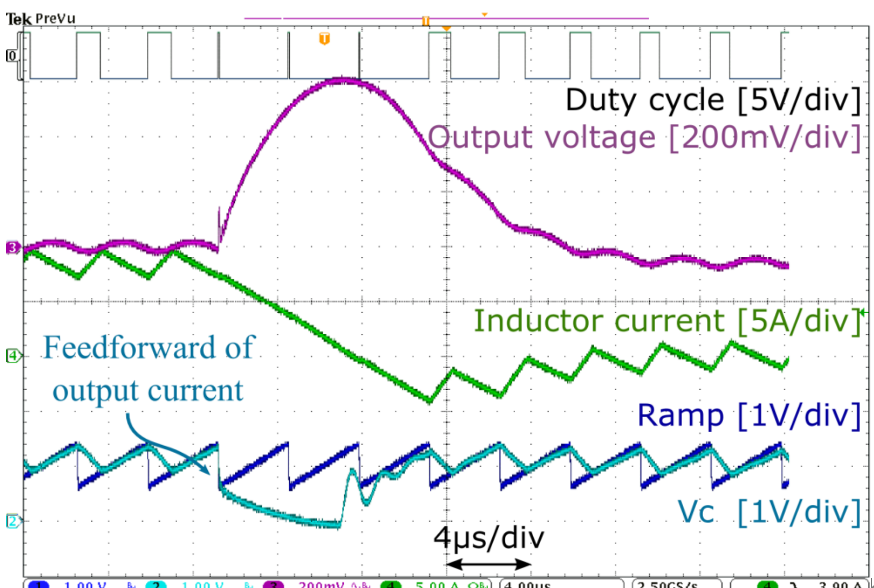
High-Q output capacitor

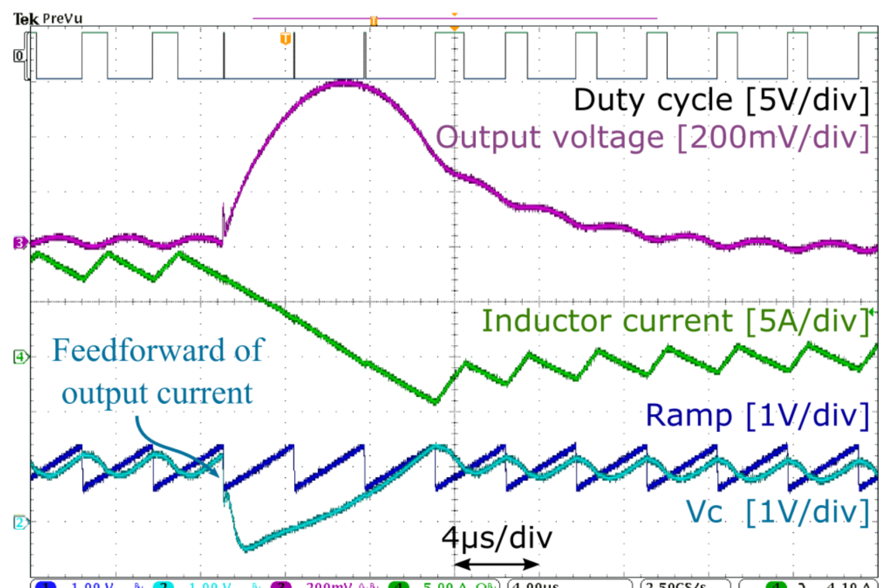
V^2i_c reordered



Type-III voltage mode

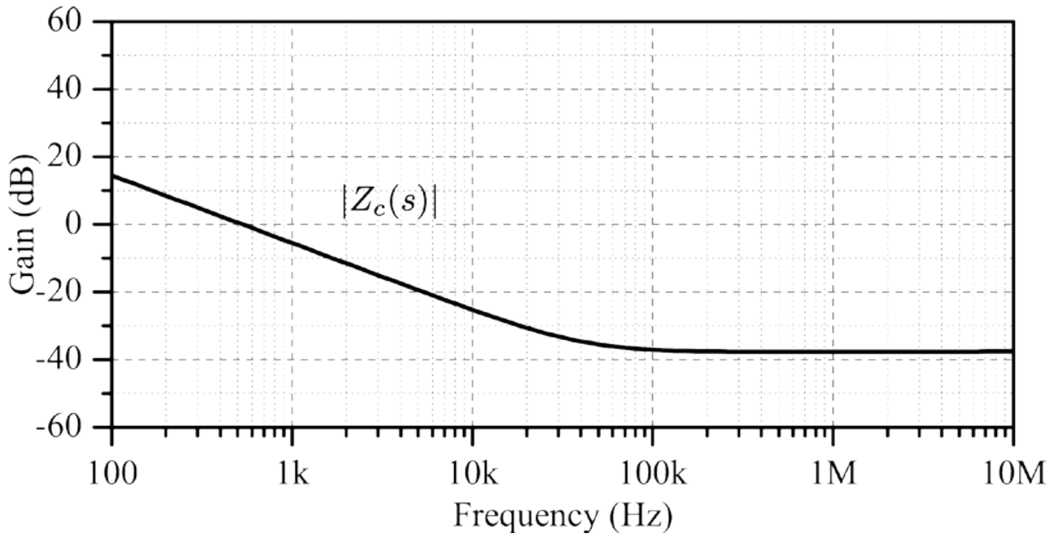


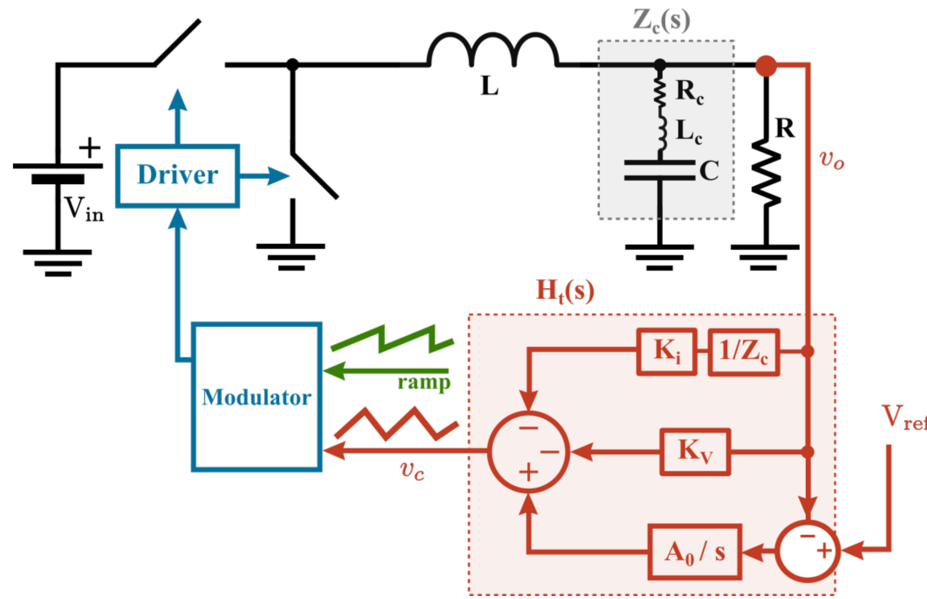




v^1 concept

Low-ESR zero output capacitor



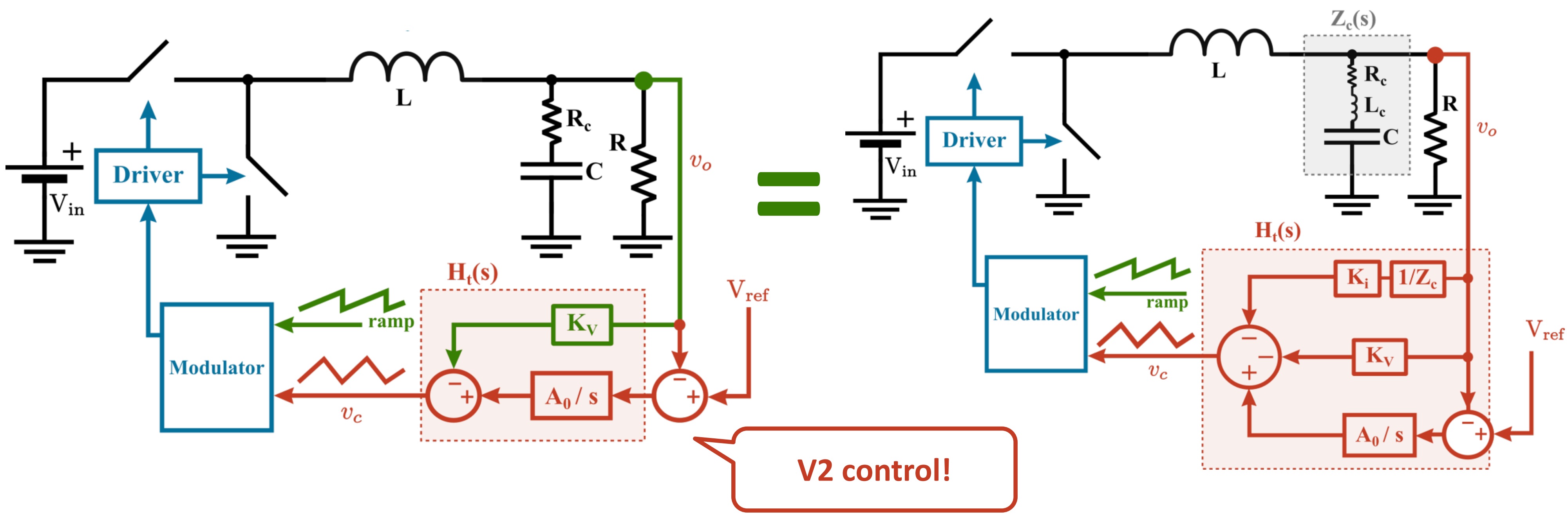


$Z_c(s) = R_c$ (For the frequencies of interest!)

$$H_t(s) = \frac{A_o}{s} + K_v + K_i \frac{1}{Z_c(s)}$$

v^1 concept

Low-ESR zero output capacitor



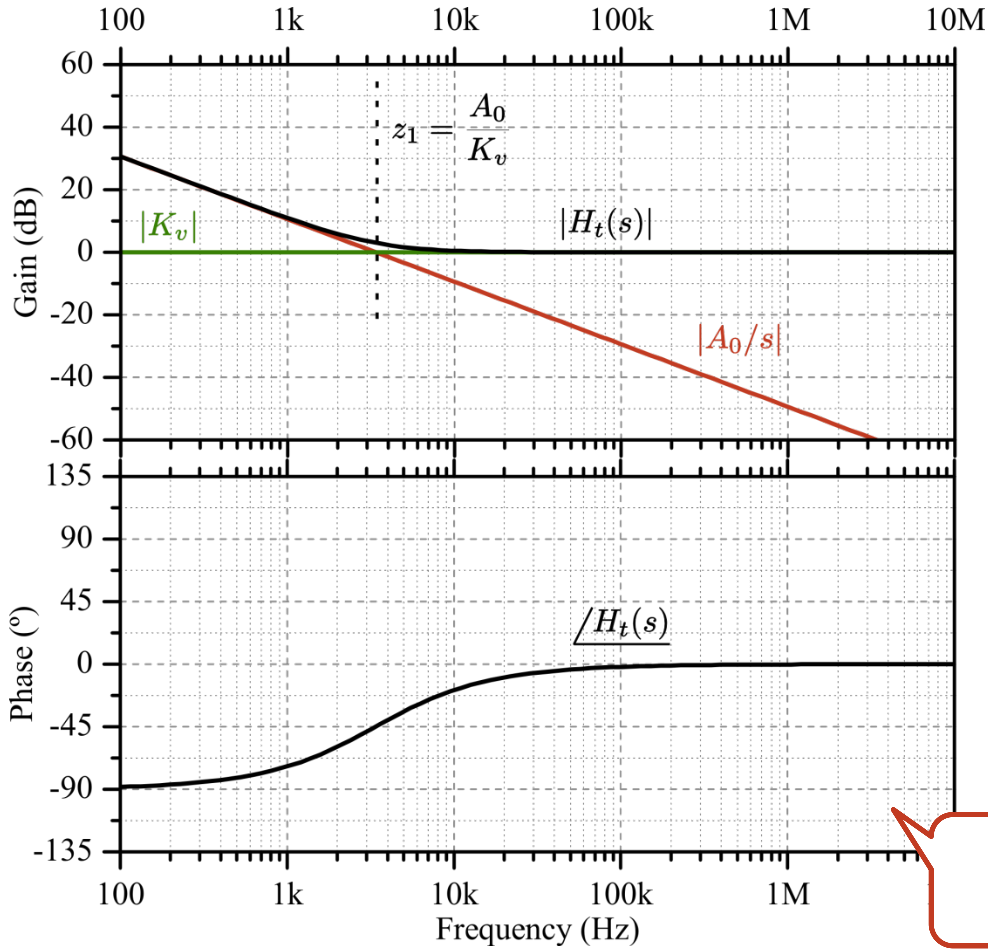
$Z_c(s) = R_c$ (For the frequencies of interest!)

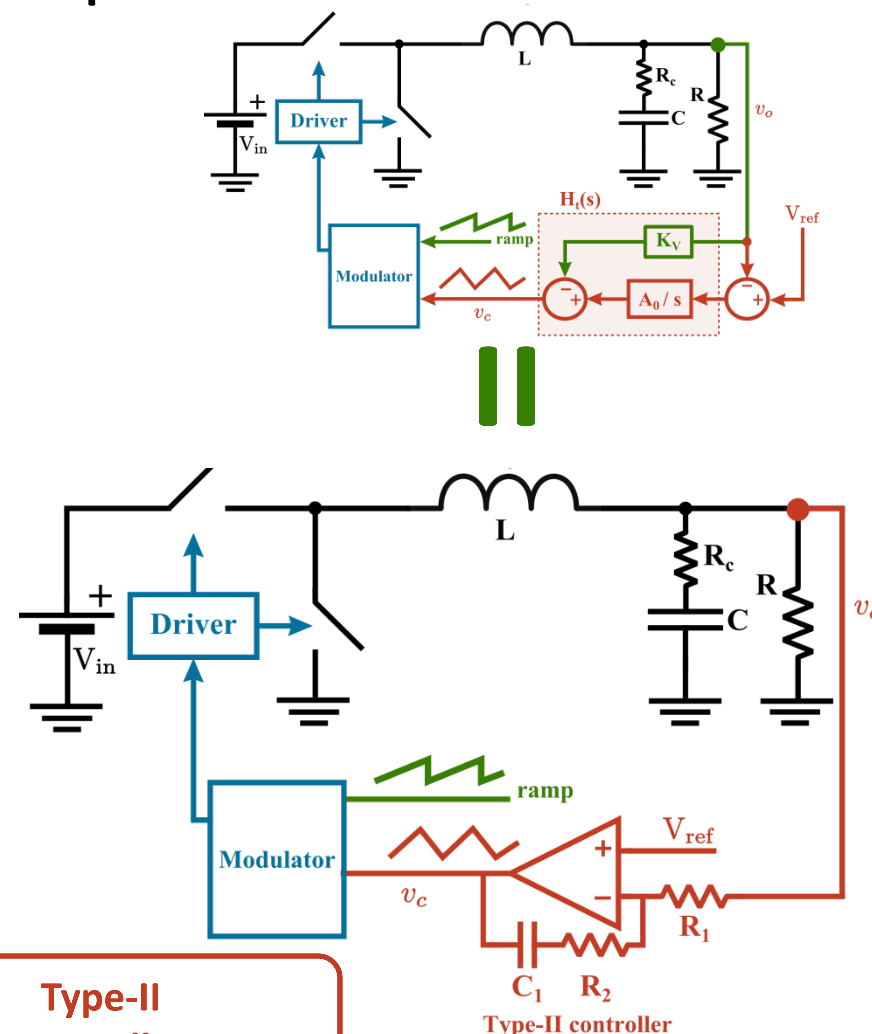
$$H_t(s) = \frac{A_o}{s} + K_v + K_i \frac{1}{Z_c(s)}$$

v^1 concept

Low-ESR zero output capacitor

$$H_t(s) = A_o \frac{\left(1 + {}^{s}/_{z_1}\right)}{s}$$



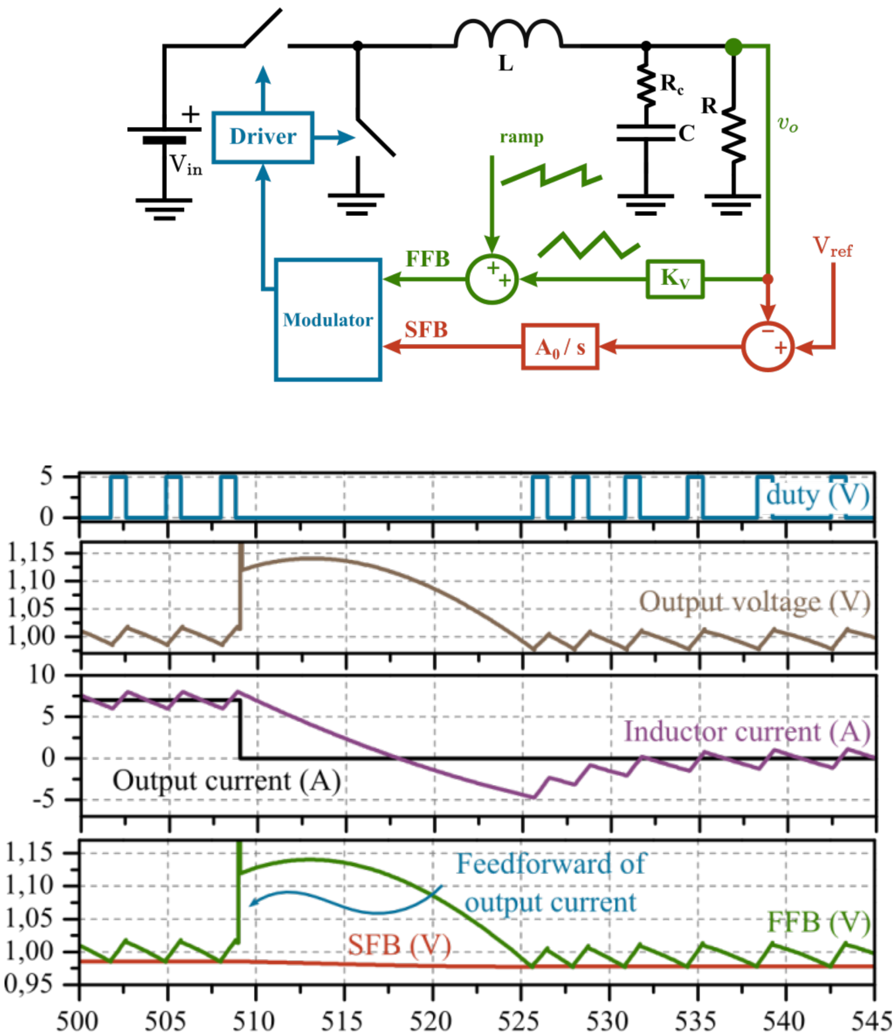


Type-II controller

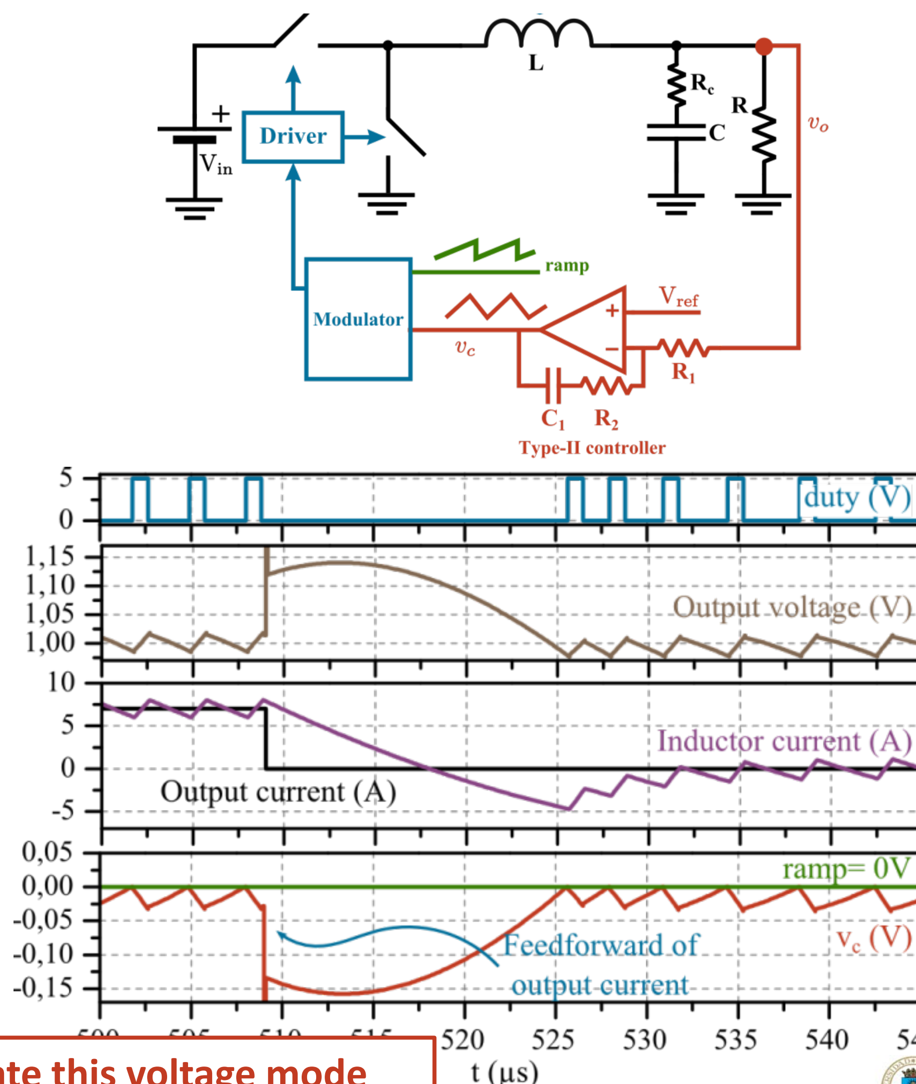
v¹ concept

Low-ESR zero output capacitor

V²



Type-II voltage mode

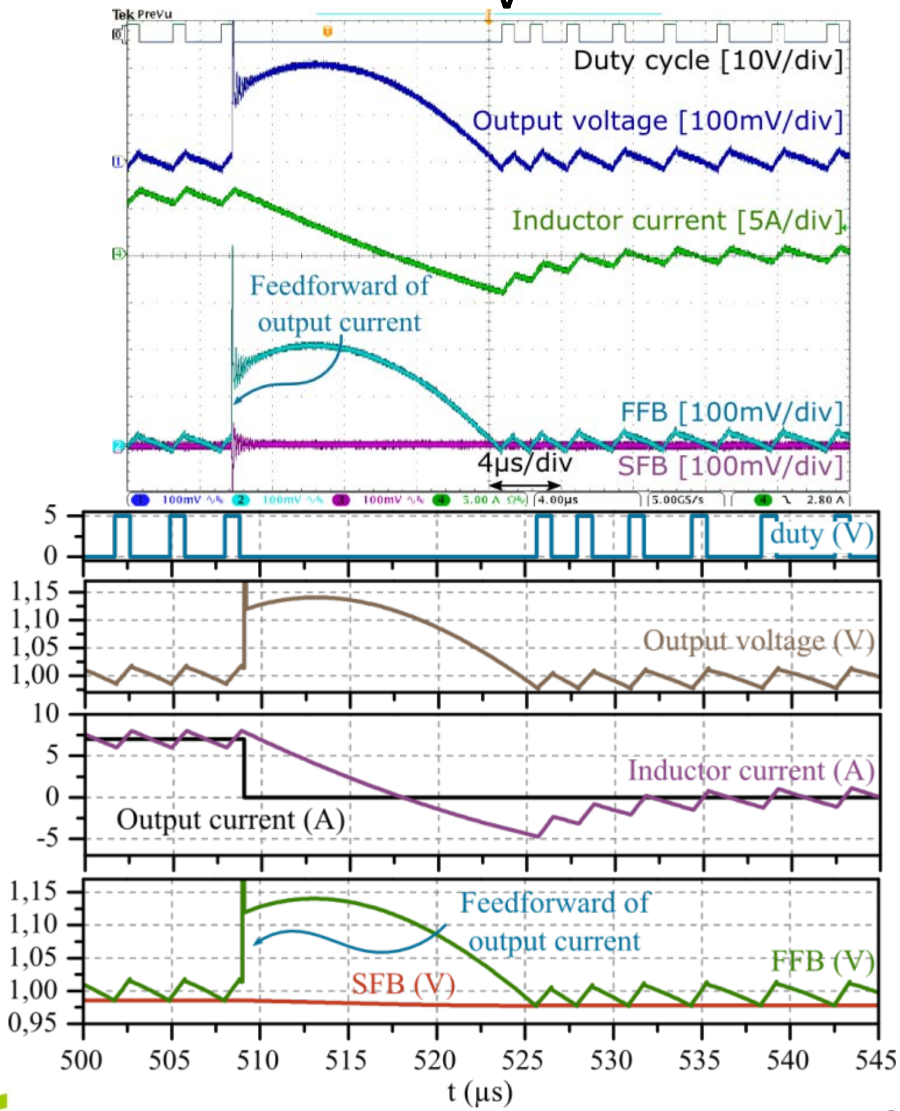


Again, it is possible to modulate this voltage mode control with constant on-time and no ramp!

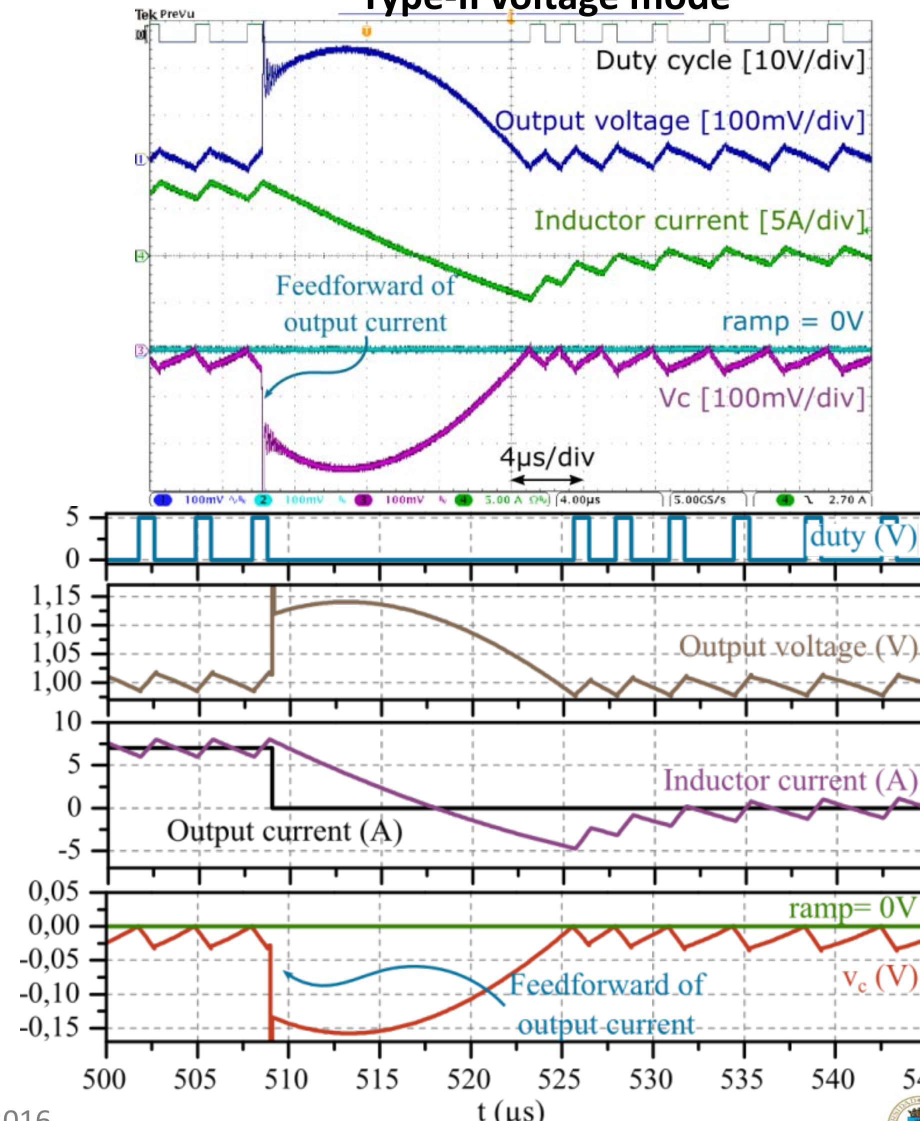
v^1 concept

Low-ESR zero output capacitor

V^2

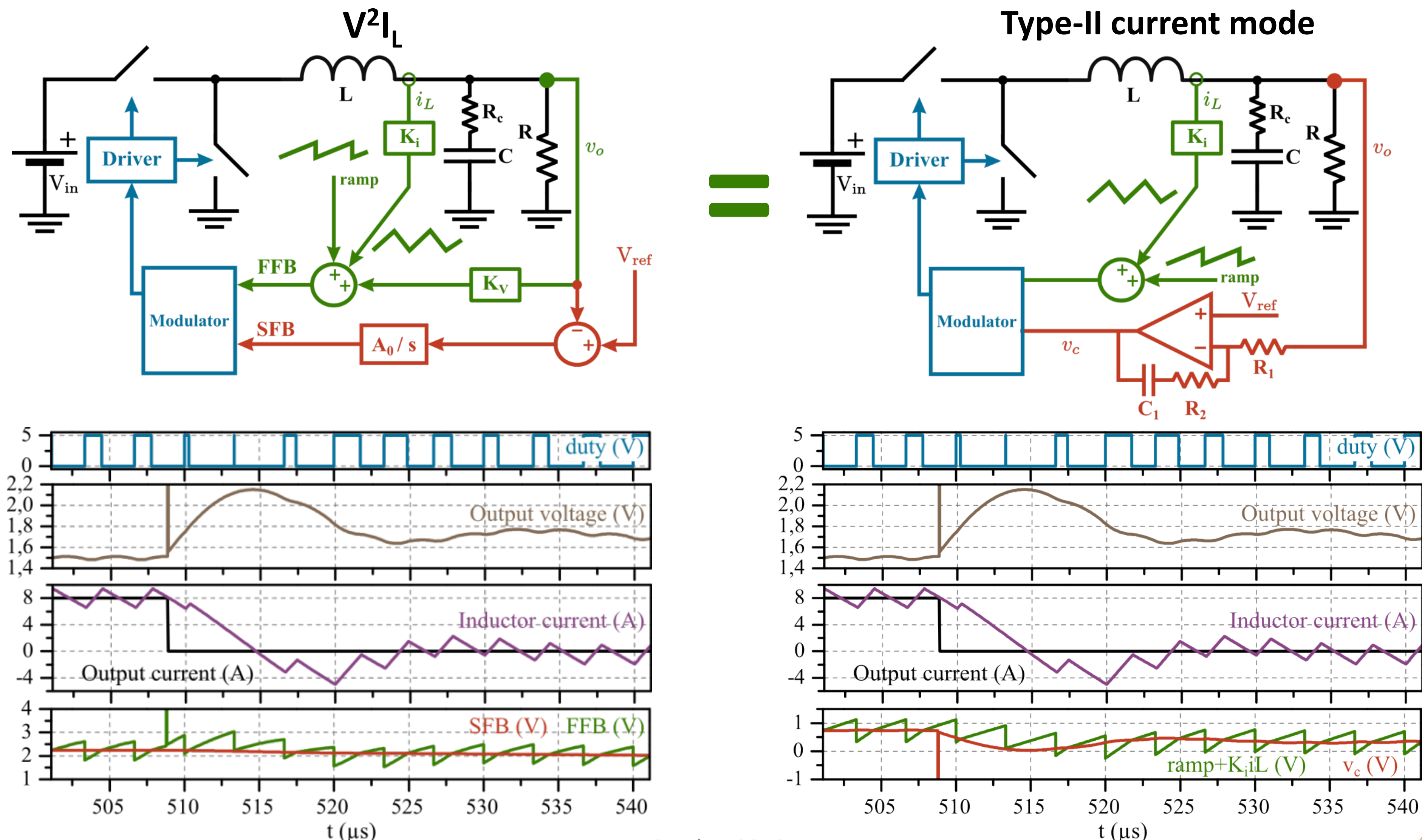


Type-II voltage mode



v^1 concept

V^2 control compensated with the inductor current



v^1 concept

$$H_t(s) = \frac{A_o}{s} + K_v + K_i \frac{1}{Z_c(s)}$$

POSSIBLE IMPLEMENTATIONS OF H_t ACCORDING TO OUTPUT CAP

Low-Q cap (Q<0.5)

v^2i_c

type-III voltage mode

High-Q cap (Q>0.5)

If $\Delta B < w_c/10$

v^2i_c

type-III voltage mode (approx)

If $\Delta B > w_c/10$

v^2i_c

Low-ESR zero cap

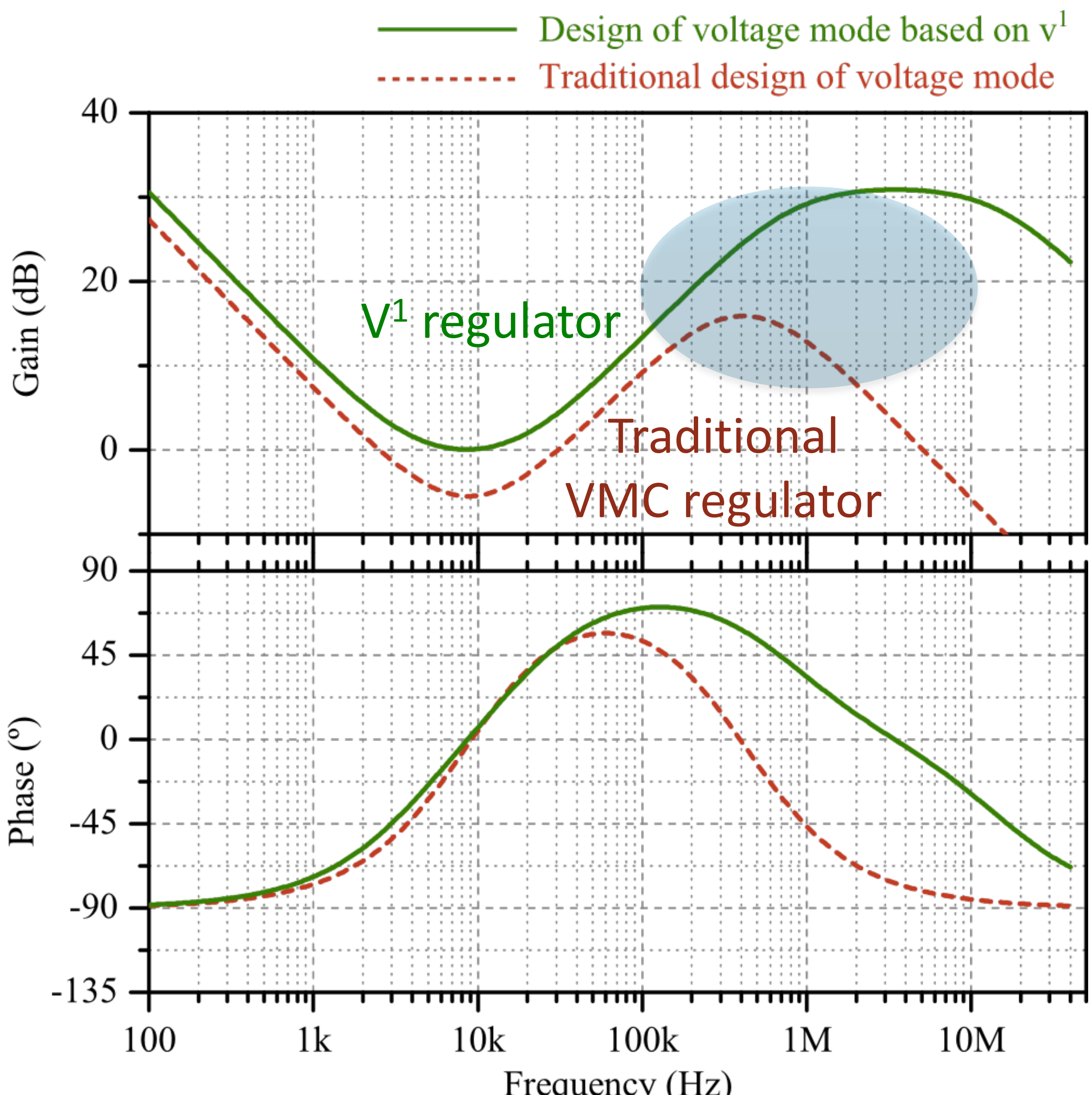
v^2i_c

v^2

type-II voltage mode

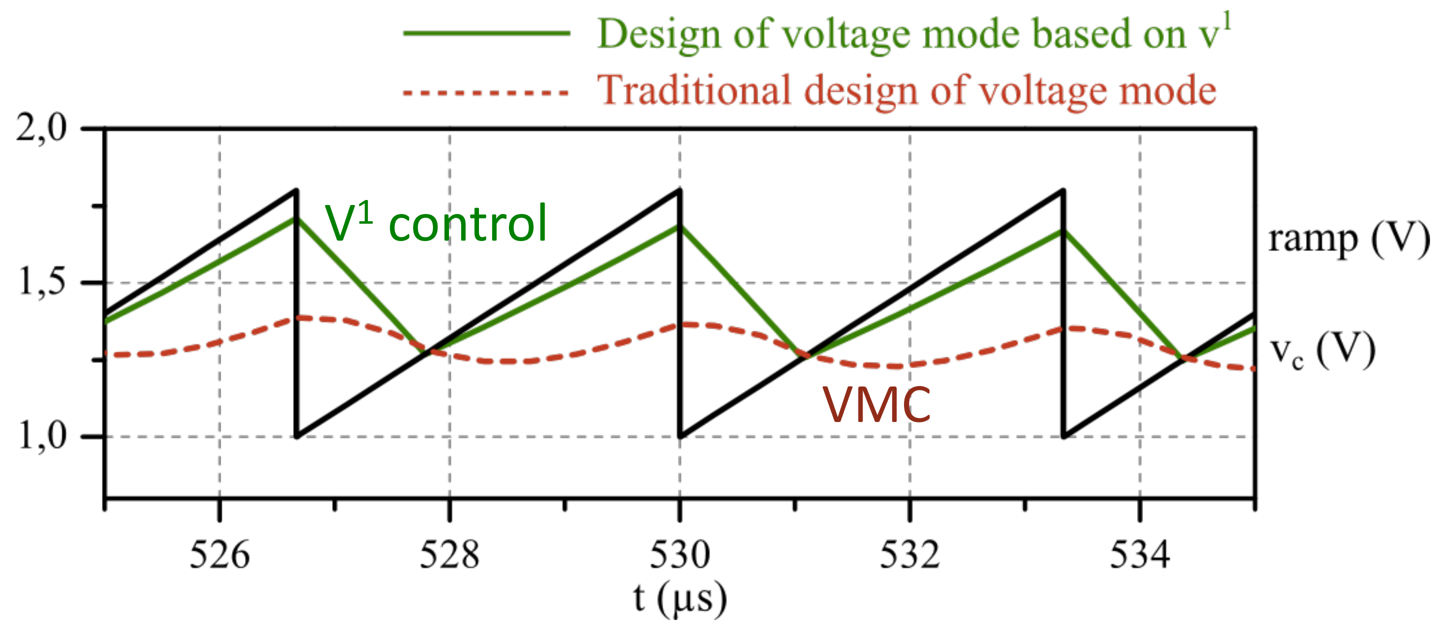
- V^2, V^2i_c , V^2i_L and V^1 are just different implementations of $H_t(s)$.
- By using only the output voltage, it is possible to emulate a current mode control with feedforward of output current → V^1 concept
- Keep the ripple information in the loop!!!

Comparison of traditional VMC design and V1 concept



Keep the ripple information in the loop!!!

V1 concept is a ripple based control: subharmonic oscillations!!



… BUT accurate models are needed to design with robustness….

Discrete modelling and Floquet theory

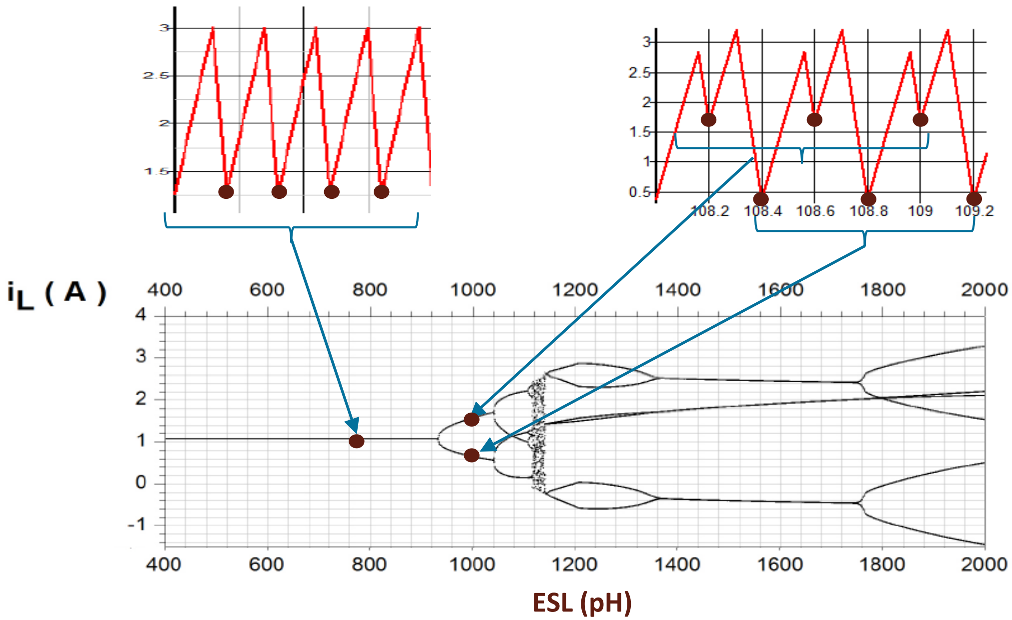
- Robustness analysis and optimization
- High accuracy

Cortes, J.; Svikovic, V.; Alou, P.; Oliver, J.; Cobos, J.; Wisniewski, R., "Accurate analysis of sub-harmonic oscillations of V2 and V2Ic controls applied to Buck converter," Power Electronics, IEEE Transactions on , early access

Floquet theory

Bifurcation phenomena

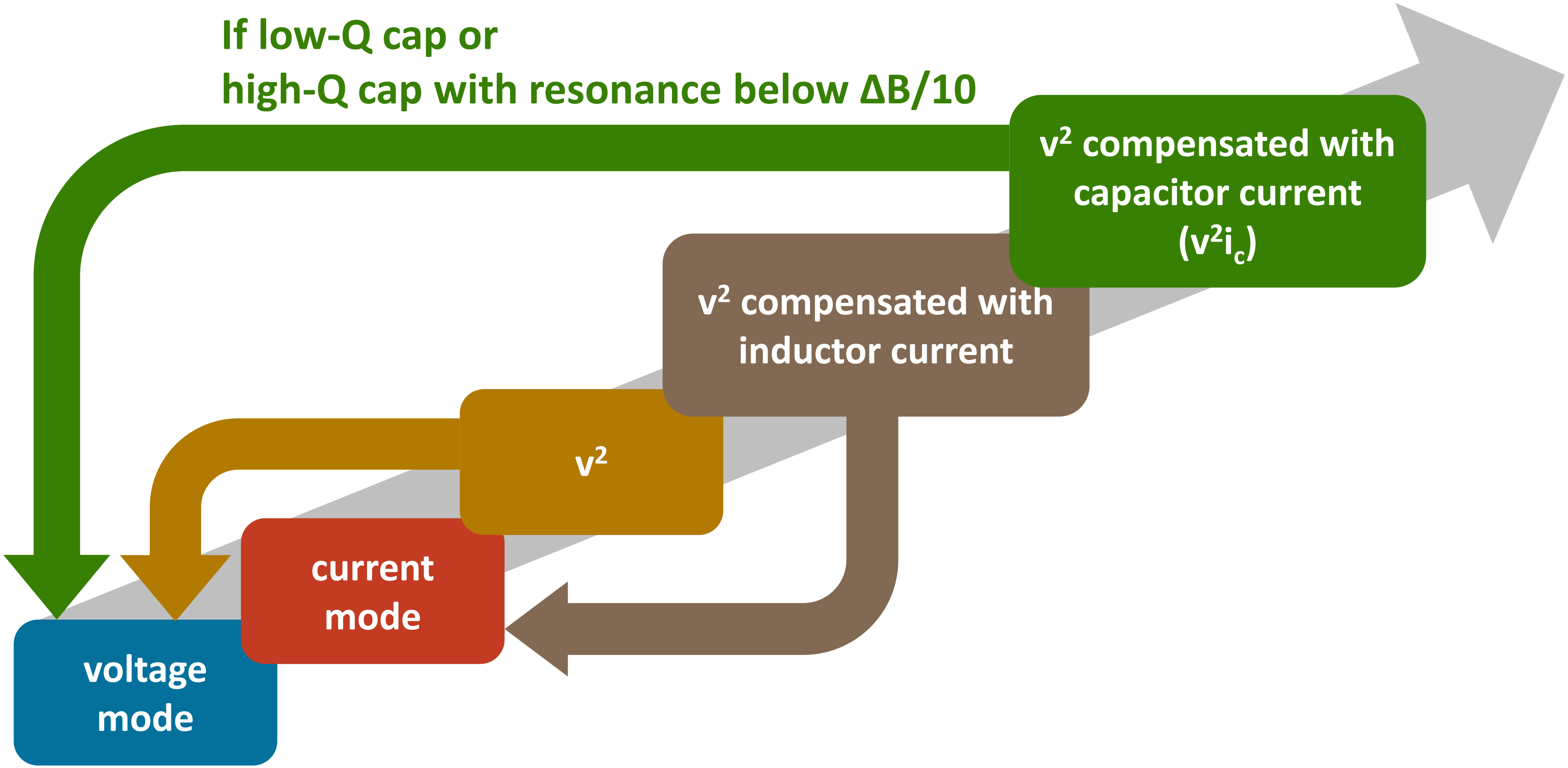
- Sub-harmonic oscillations can be seen as a bifurcation where the system is unable to maintain a T-periodic solution



Bifurcation diagram

v^1 concept

Equivalences between controls



Floquet theory

Bifurcation phenomena

- Sub-harmonic oscillations can be seen as a bifurcation where the system is unable to maintain a T-periodic solution

Stability is analyzed by Floquet theory.

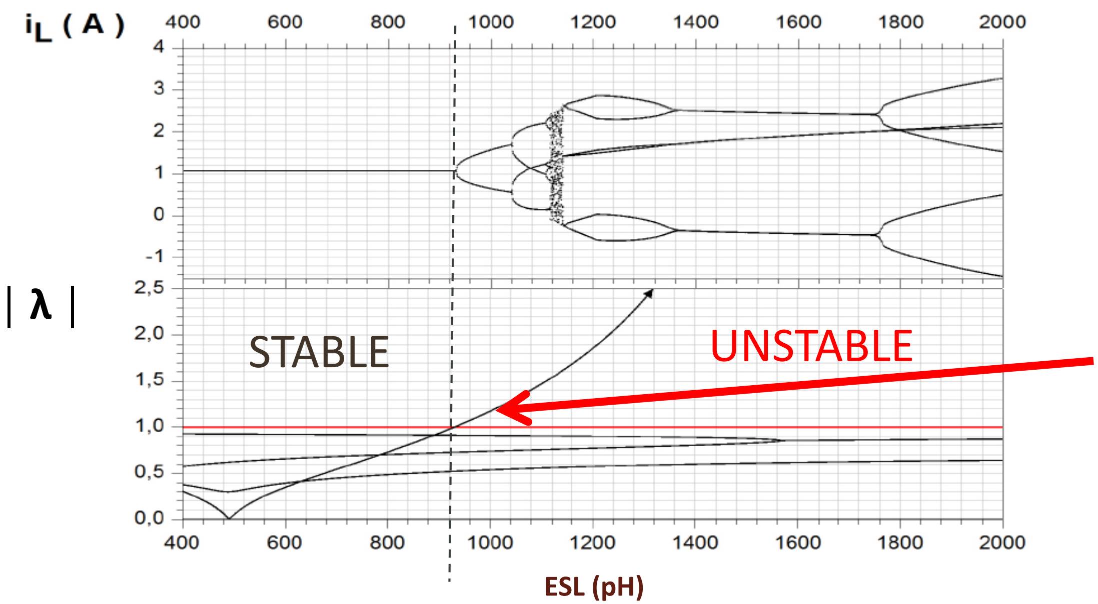
- If a perturbation grows over a period → unstable

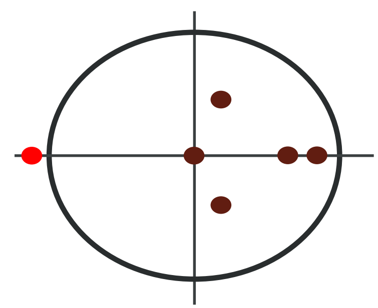
$$\Delta x_{k+1} = \Phi_{cycle} \cdot \Delta x_k$$

λ = eigenvalues of Φ_{cycle}

$|\lambda| < 1$, stable

$|\lambda| > 1$, sub-harmonic oscillation

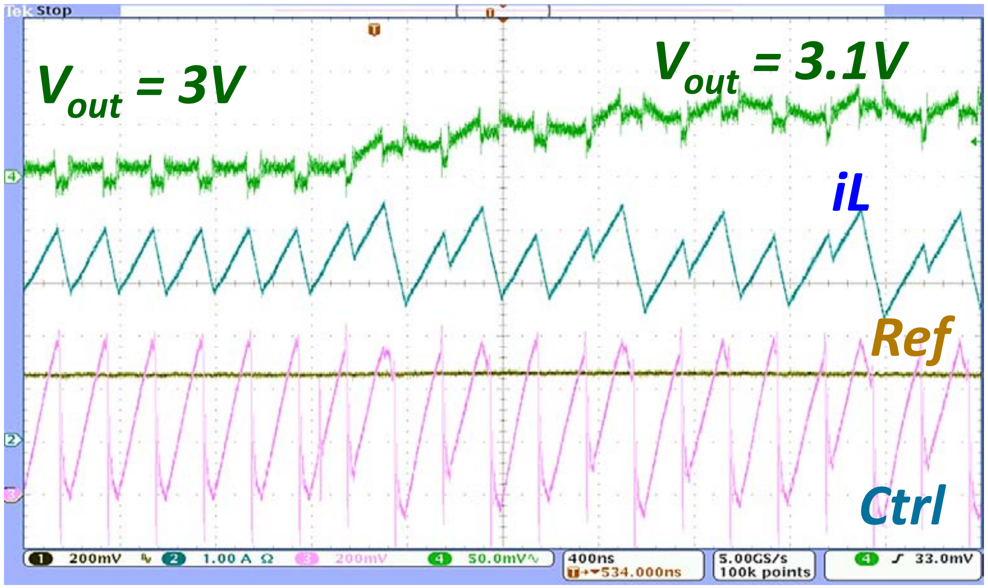




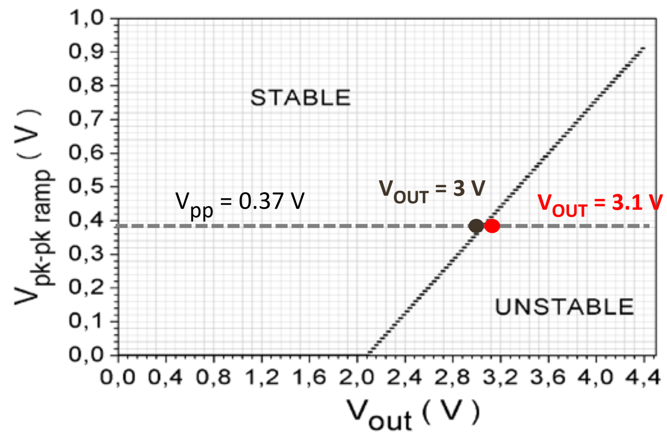
Floquet multipliers

Floquet Theory: robust design regarding all the tolerances

V^2I_C



Experimental sub-harmonic oscillation on V2Ic control



Predicted stability behavior

The Floquet theory predicts accurately the oscillation!

$V_{out} = 3V \rightarrow \lambda = -0.966$

$V_{out} = 3.1V \rightarrow \lambda = -1.06$

Out of unit circle!

v^1 concept

$$H_t(s) = \frac{A_o}{s} + K_v + K_i \frac{1}{Z_c(s)}$$

POSSIBLE IMPLEMENTATIONS OF H_t ACCORDING TO OUTPUT CAP

Low-Q cap (Q<0.5)

v^2i_c
type-III voltage mode

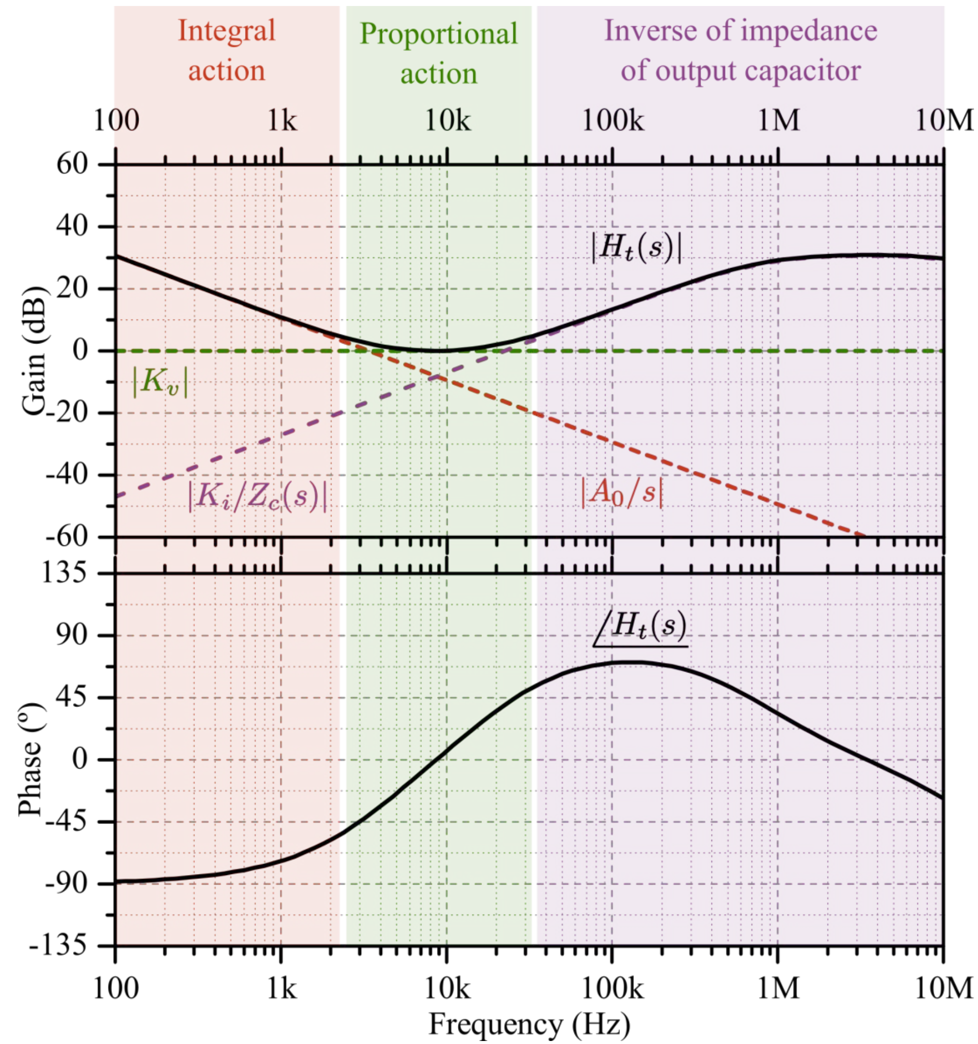
High-Q cap (Q>0.5)

<u>If $\Delta B < w_c/10$</u>
v^2i_c
type-III voltage mode (approx)

<u>If $\Delta B > w_c/10$</u>
v^2i_c

Low-ESR zero cap

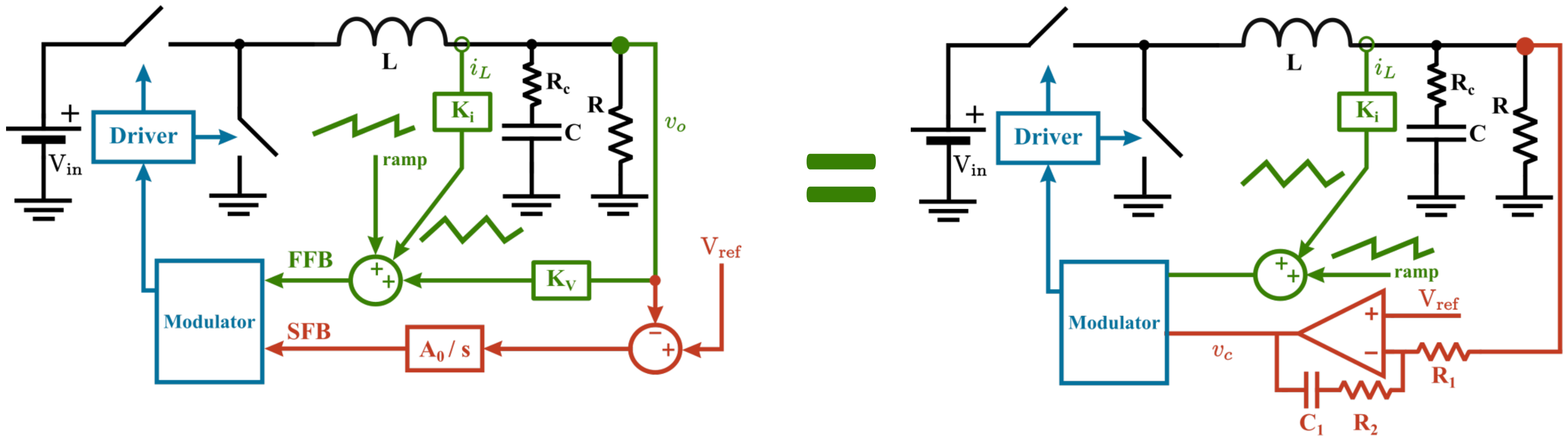
v^2i_c
v^2
type-II voltage mode



v^1 concept

And what happens to the v^2 control compensated with the inductor current?

V^2 compensated with the inductor current | **Type-II current mode**



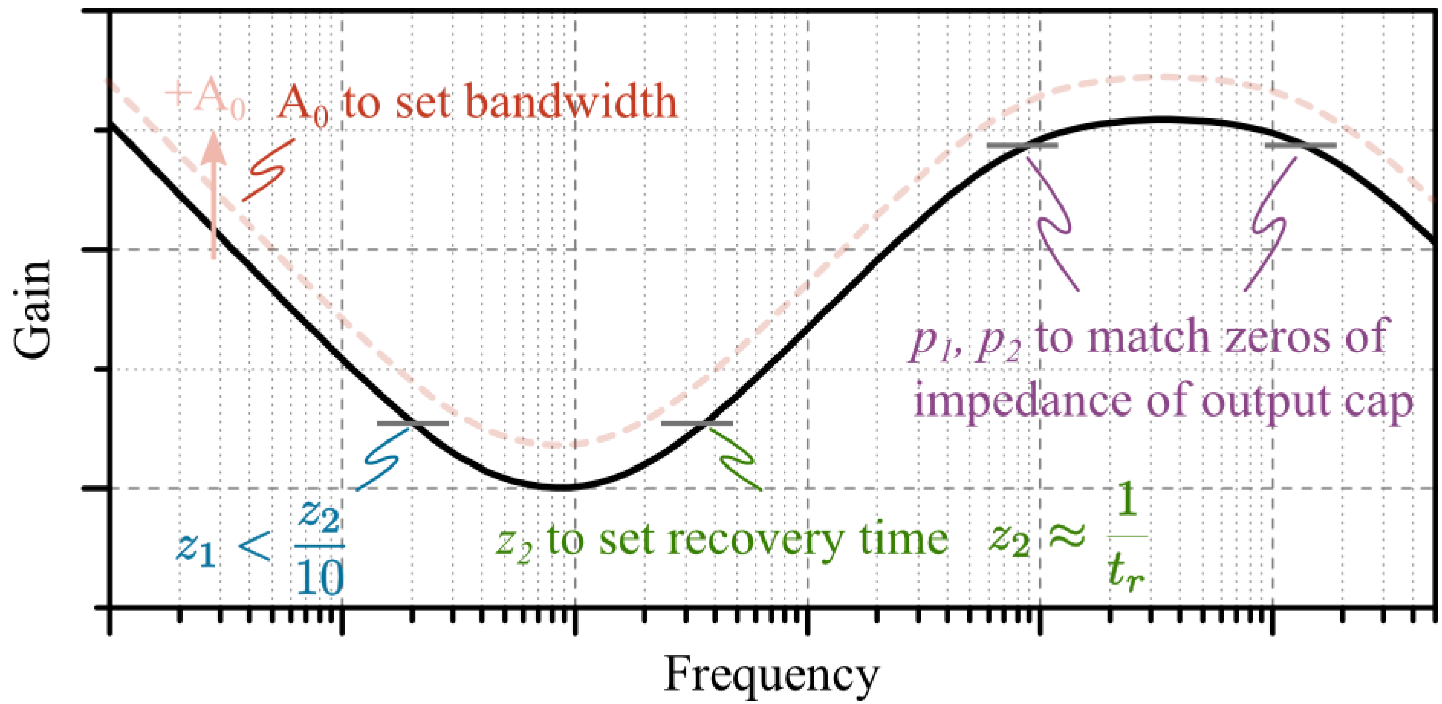
- As seen, the v^2 control is equivalent to a type-II control. In a Buck converter, the control relies on the ESR of the output capacitor to boost the phase of the loop gain.

- If the ESR is not dominant in the output voltage ripple, the phase margin is poor because the type-II controller cannot add any phase and the response is oscillatory or unstable.

- The v^2 control is commonly compensated with the inductor current for improved response for non-dominant ESR capacitors. What we are essentially doing is turning the v^2 control into a conventional current mode control that can now be regulated with a type-II controller.

v^1 concept: design guidelines

Proposed design of a type-III voltage mode control based on the v^1 concept



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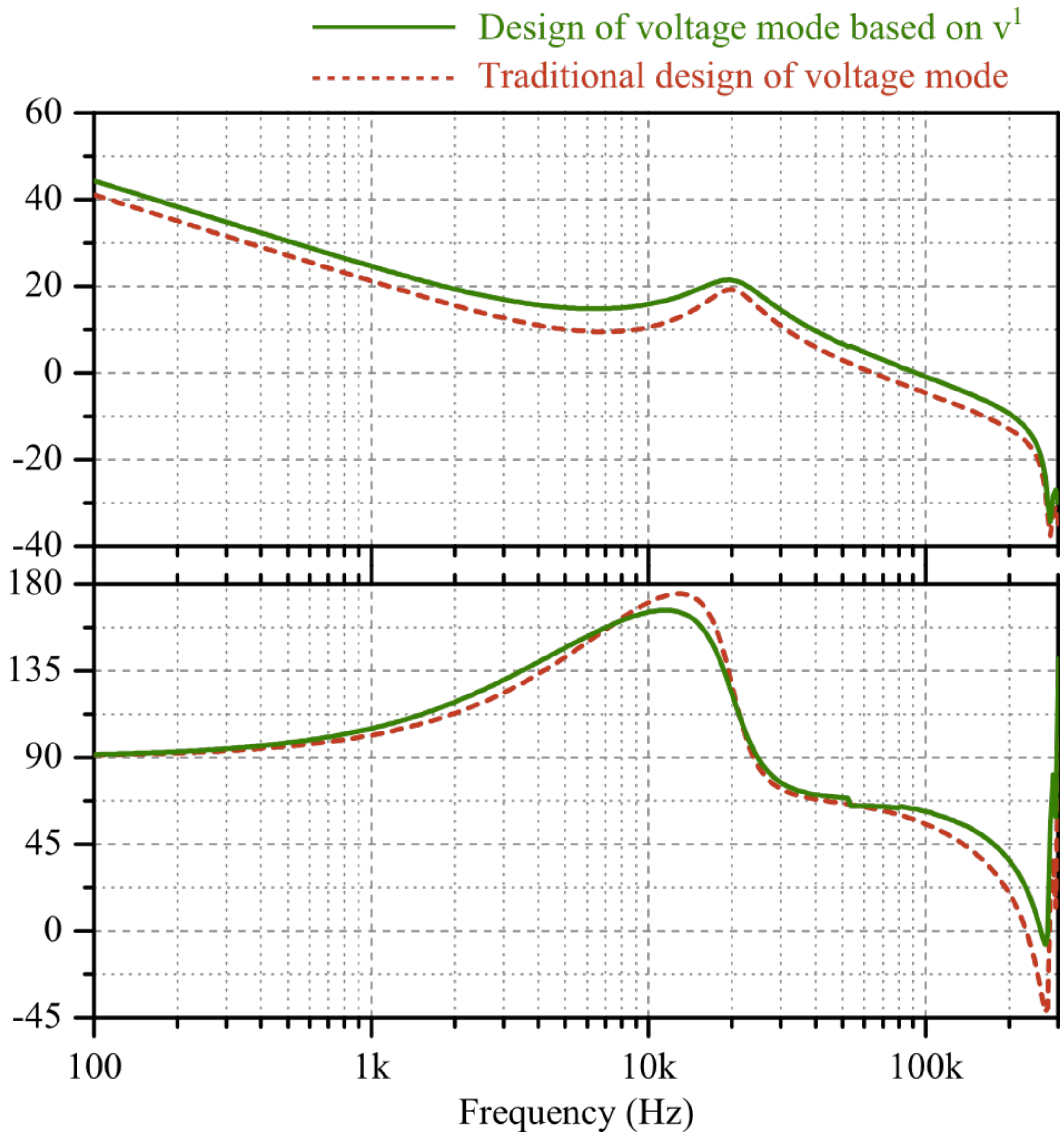
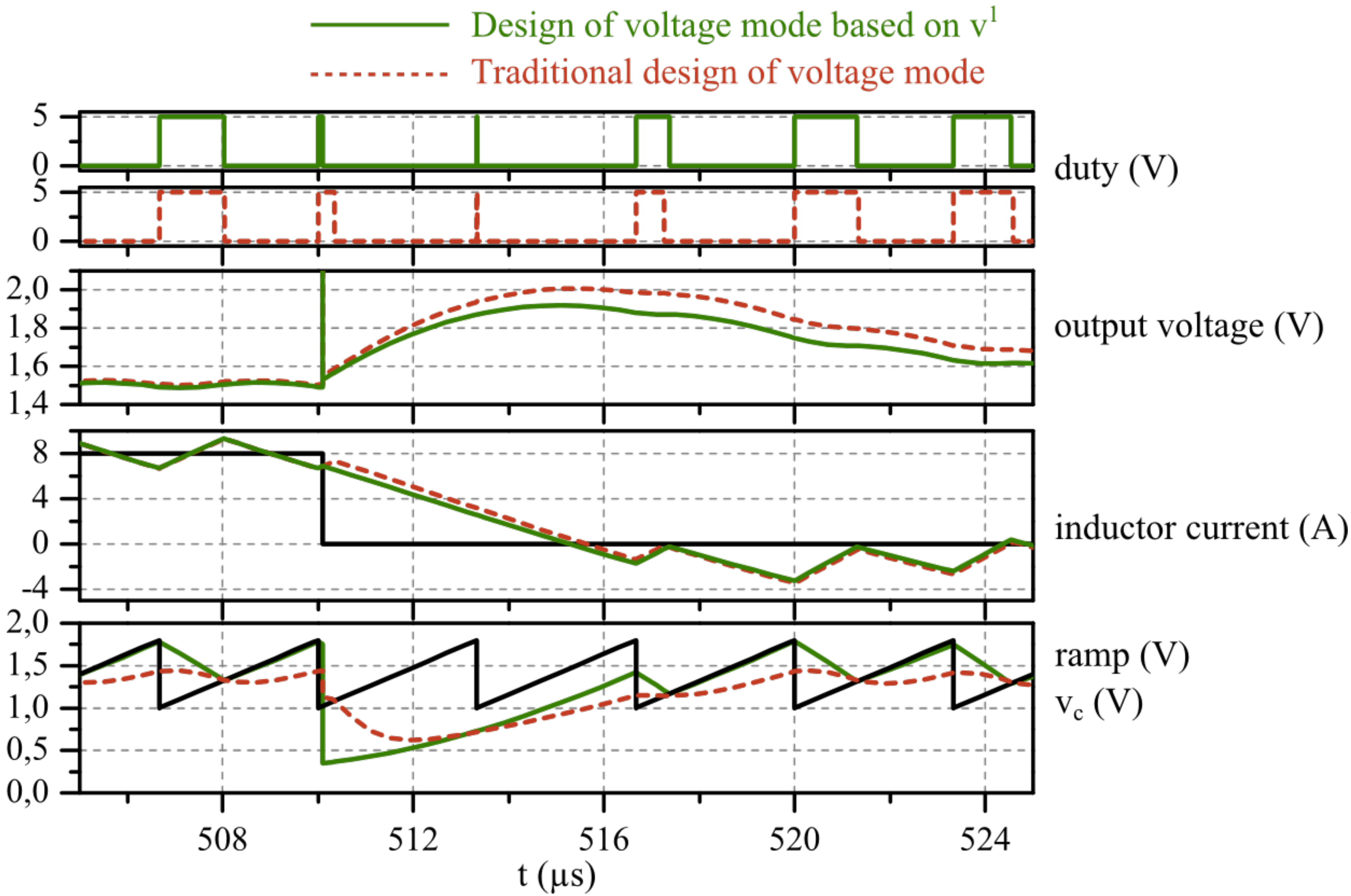
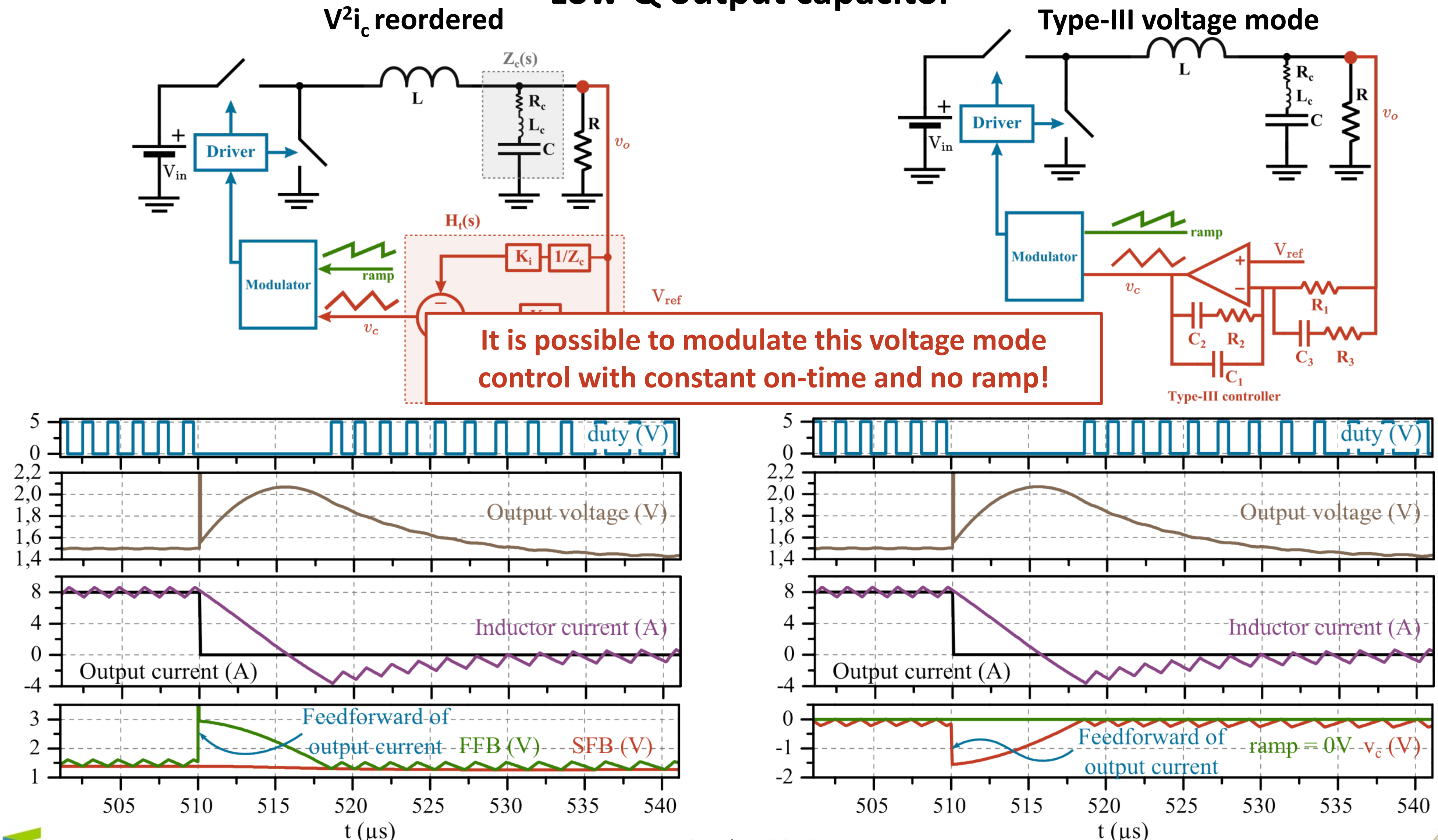


Comparison of traditional VMC design and V1 concept



v^1 concept

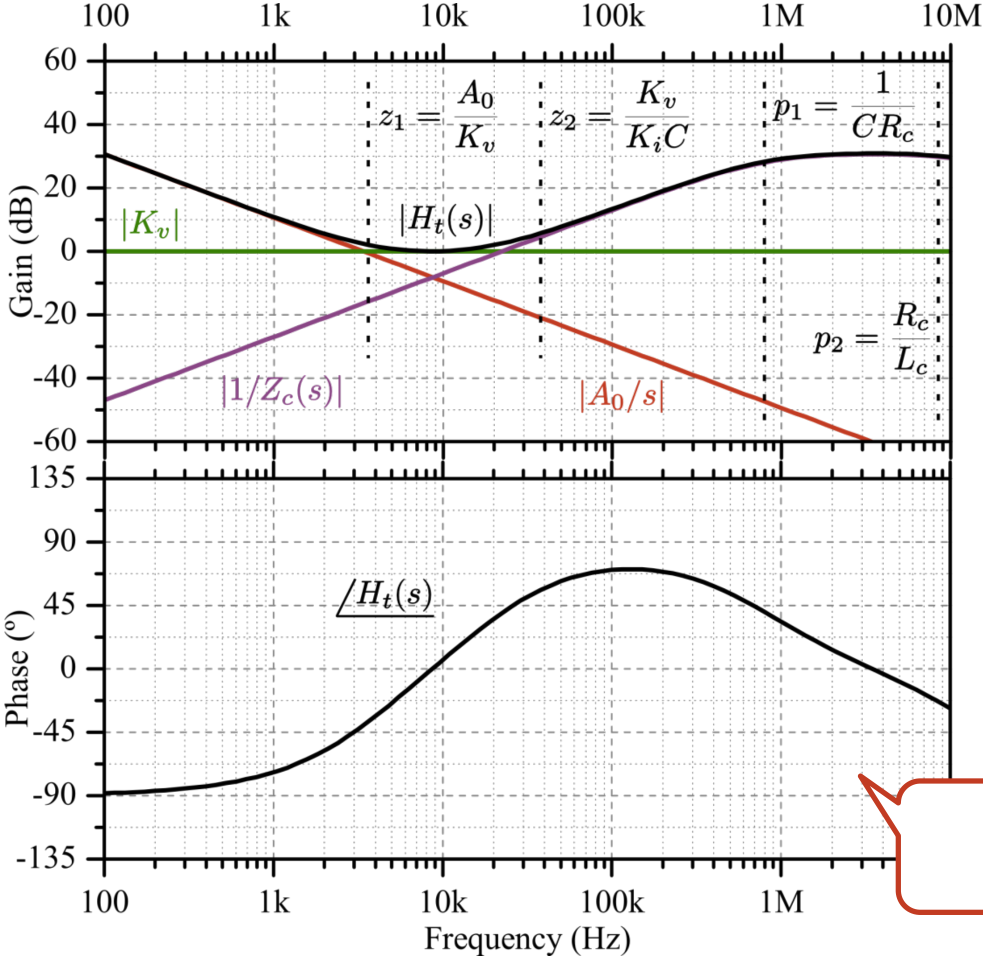
Low-Q output capacitor

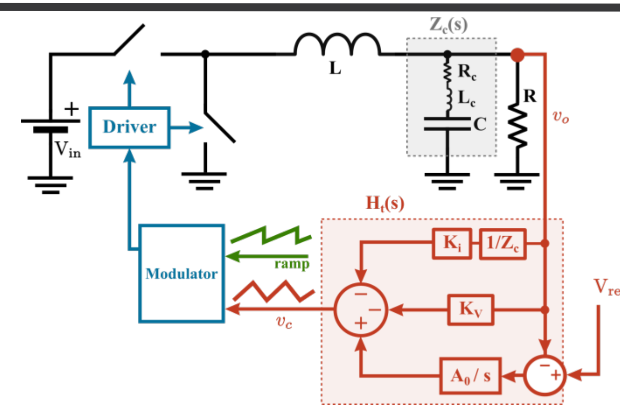


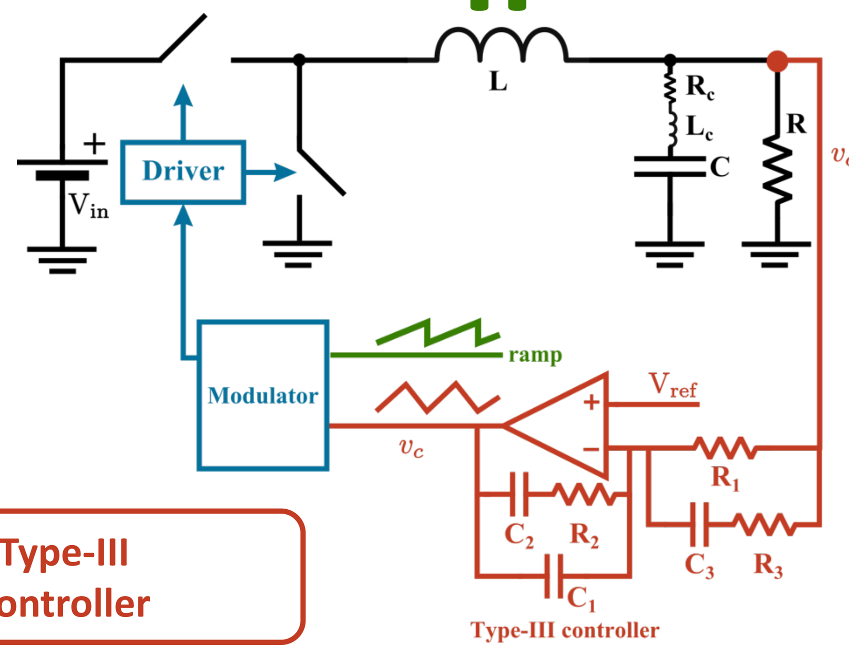
v[1] concept

Low-Q output capacitor

$$H_t(s) = A_o \frac{(1 + s/z_1)(1 + s/z_2)}{s(1 + s/p_1)(1 + s/p_2)}$$





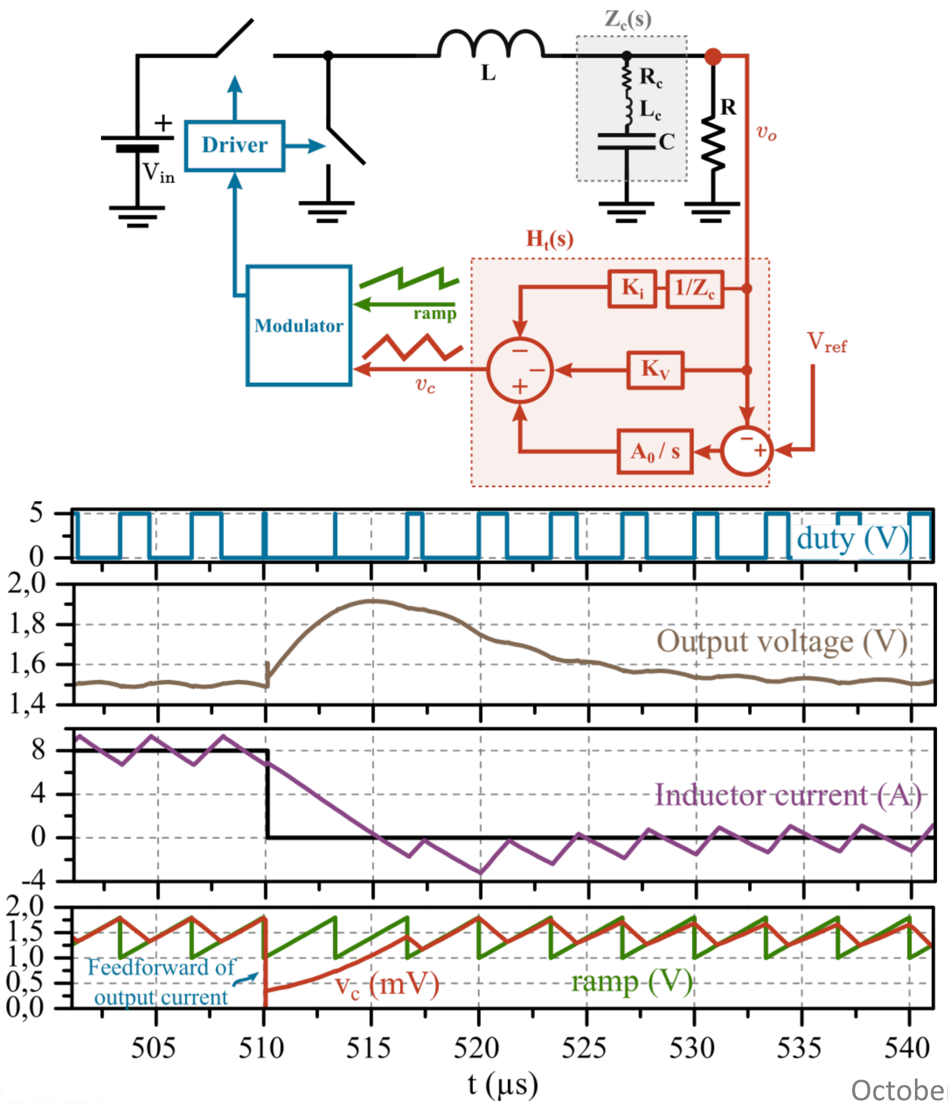


Type-III controller

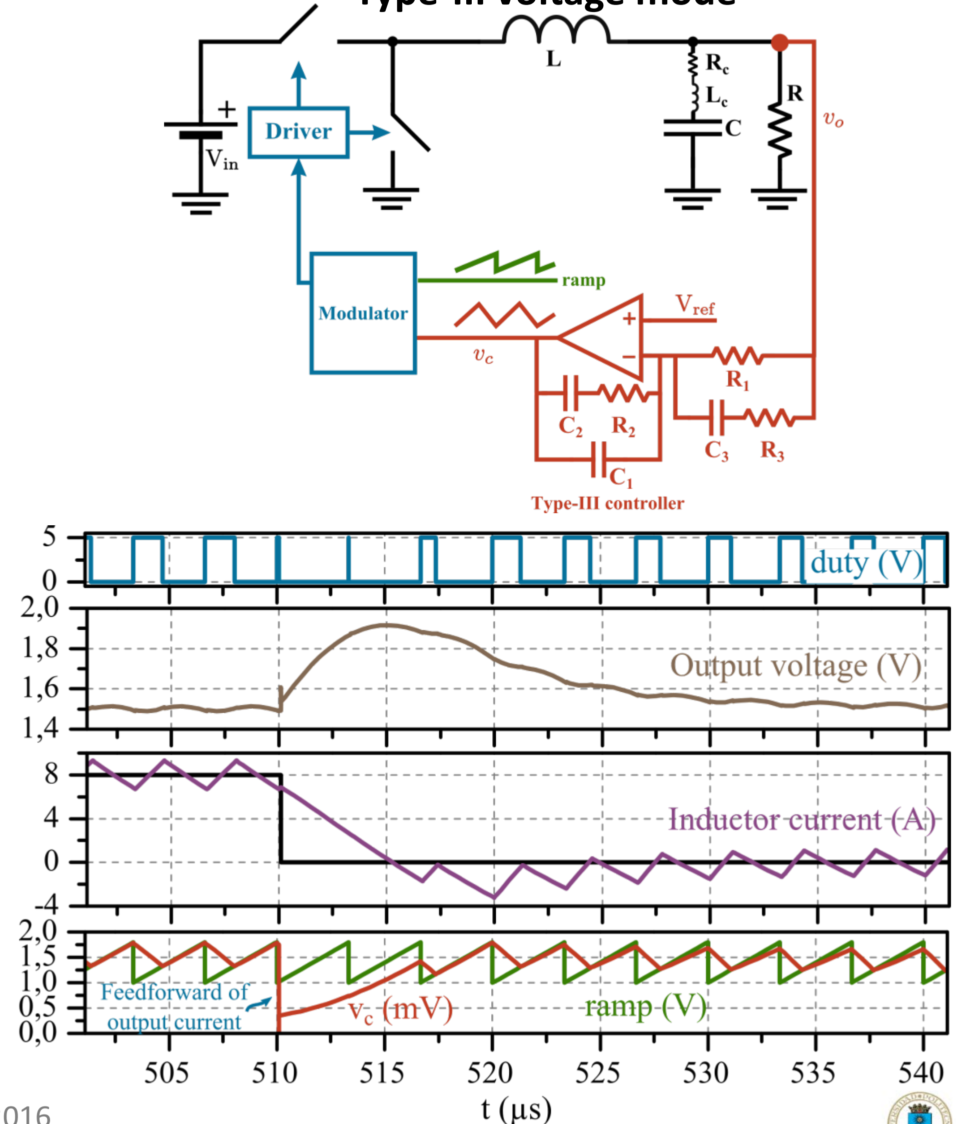
v^1 concept

Low-Q output capacitor

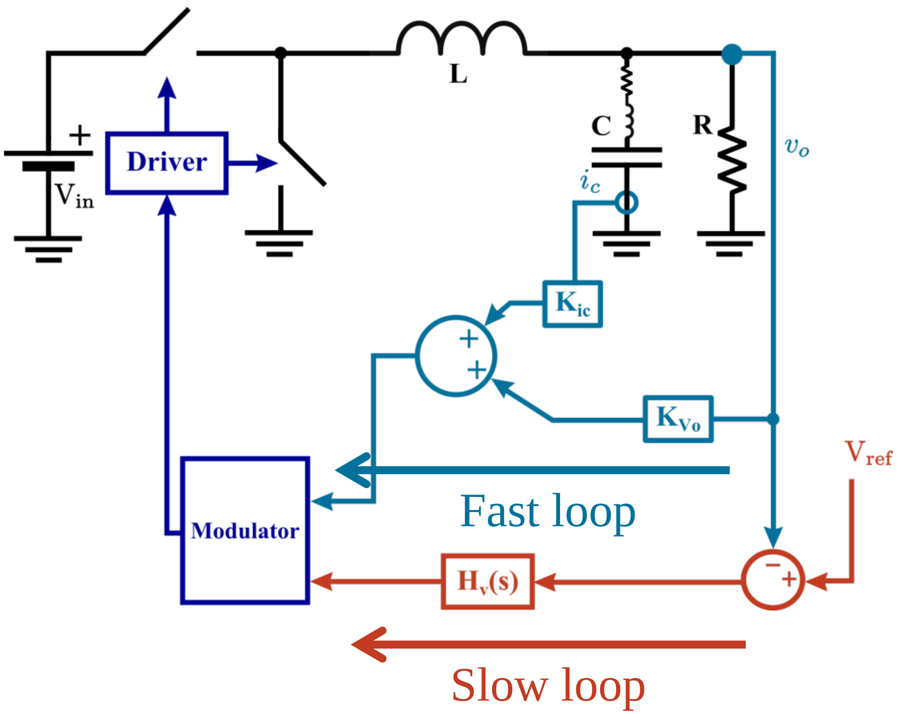
$V^2 i_c$ reordered



Type-III voltage mode



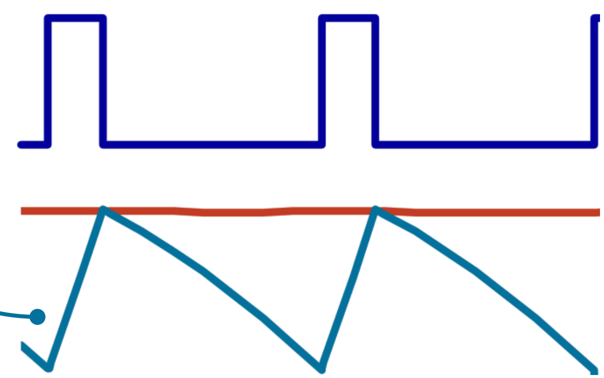
Introduction: $v^2 i_c$



Fast loop:
- Responsible for fast dynamic response

Slow loop:
- Responsible to regulate tightly the output voltage.
- Very low bandwidth

$$K_{ic} i_c + K_{vo} v_o$$



In steady-state, it behaves like a current mode control