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## Hybrid Control of Resonant Converters

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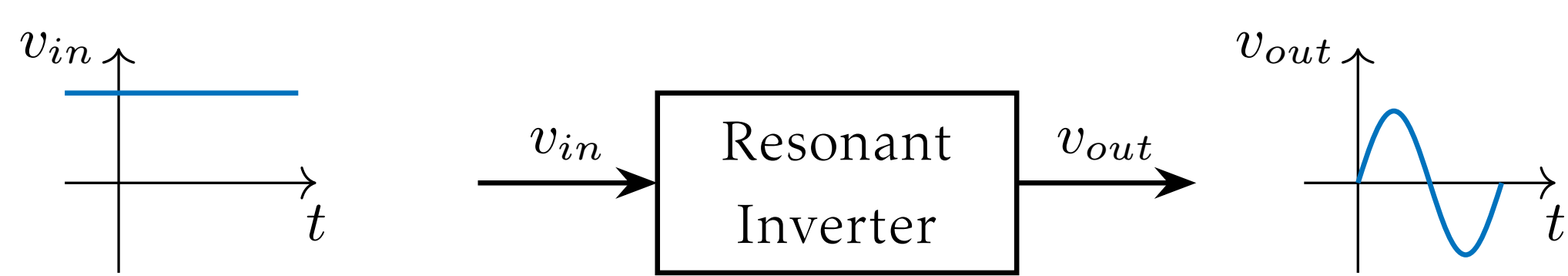
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## Motivation

Control of power resonant converters is a field where *Hybrid Dynamical Systems* theory can be naturally applied due to the dual nature of the systems: the continuous one related to the dynamics of the passive components, and the discrete one related to the switches. In this work we develop a control strategy that ensures a self-oscillating behavior in which the frequency and the amplitude of the signals in the resonant tank can be modulated.

## Resonant Converters

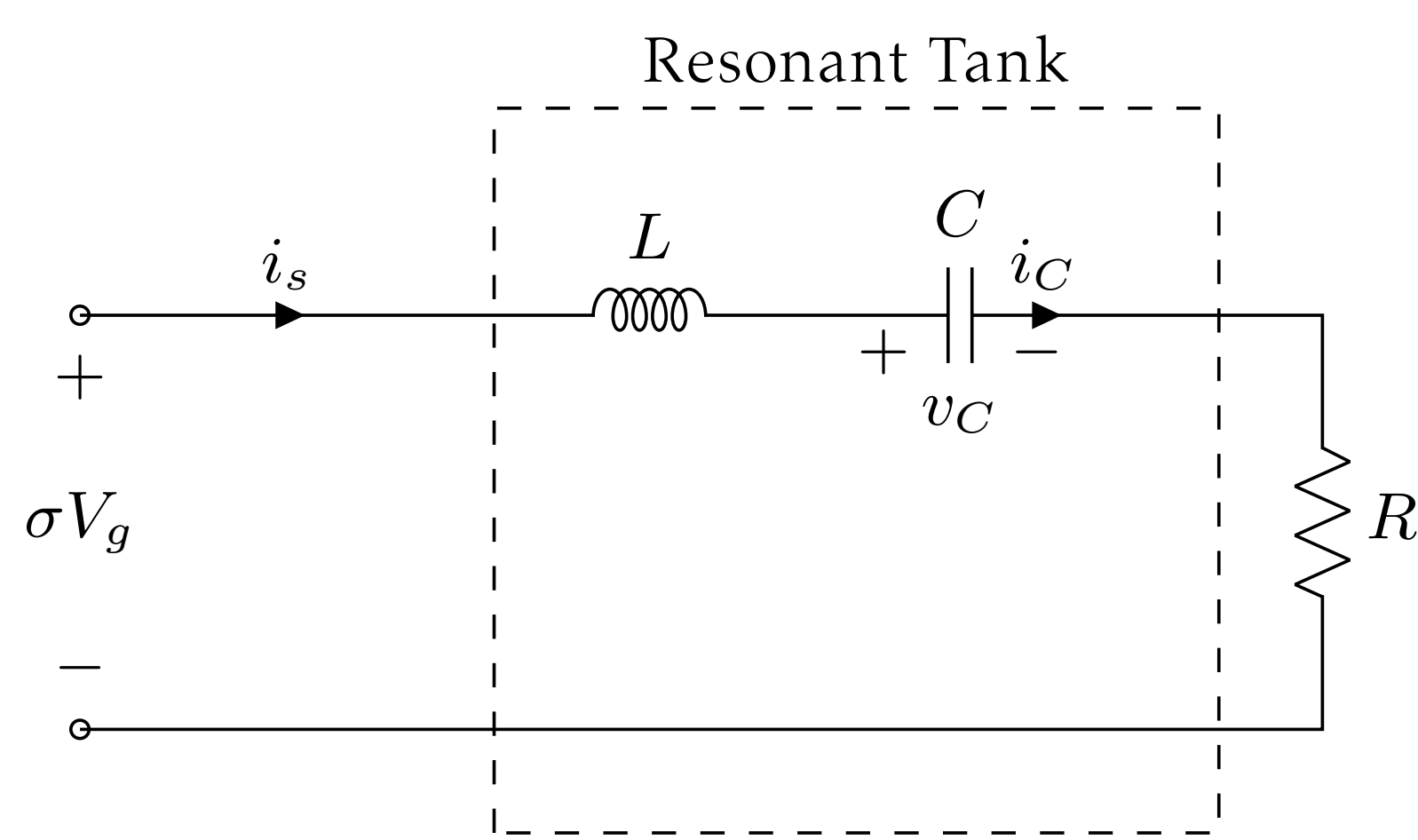
In simple words, the resonant converter transforms a DC voltage into a sinusoidal one taking advantage of the natural oscillation phenomenon – present when there is a network of capacitors and inductors called resonant tank.



The core is the resonant tank that comprises an  $L$ - $C$  network characterized by high-frequency AC waveforms of current and voltage. In the following we consider the series second-order resonant tank.

## Dynamical model

Consider a second-order series resonant converter



described by the following dynamical equations

$$\frac{d^2 v_C}{dt^2} + \frac{R}{L} \frac{dv_C}{dt} + \frac{1}{LC} v_C = \frac{V_g}{LC} \sigma. \quad (1)$$

By defining the resonant frequency  $\omega_0 := \frac{1}{\sqrt{LC}}$  and the damping factor  $\beta := \frac{R}{L}$ , we introduce the set of dimensionless coordinates  $(x_1, x_2)$ :

$$x_1 := \frac{1}{V_g} v_C, \quad x_2 := \frac{1}{V_g} \sqrt{\frac{L}{C}} i_C. \quad (2)$$

Therefore, equations (1) in statespace reads as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & \omega_0 \\ -\omega_0 & -\beta \end{bmatrix}}_A \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ \omega_0 \end{bmatrix}}_B \sigma. \quad (3)$$

In simple words, the system corresponds to a second-order harmonic oscillator with parameters  $(\omega_0, \beta)$ .

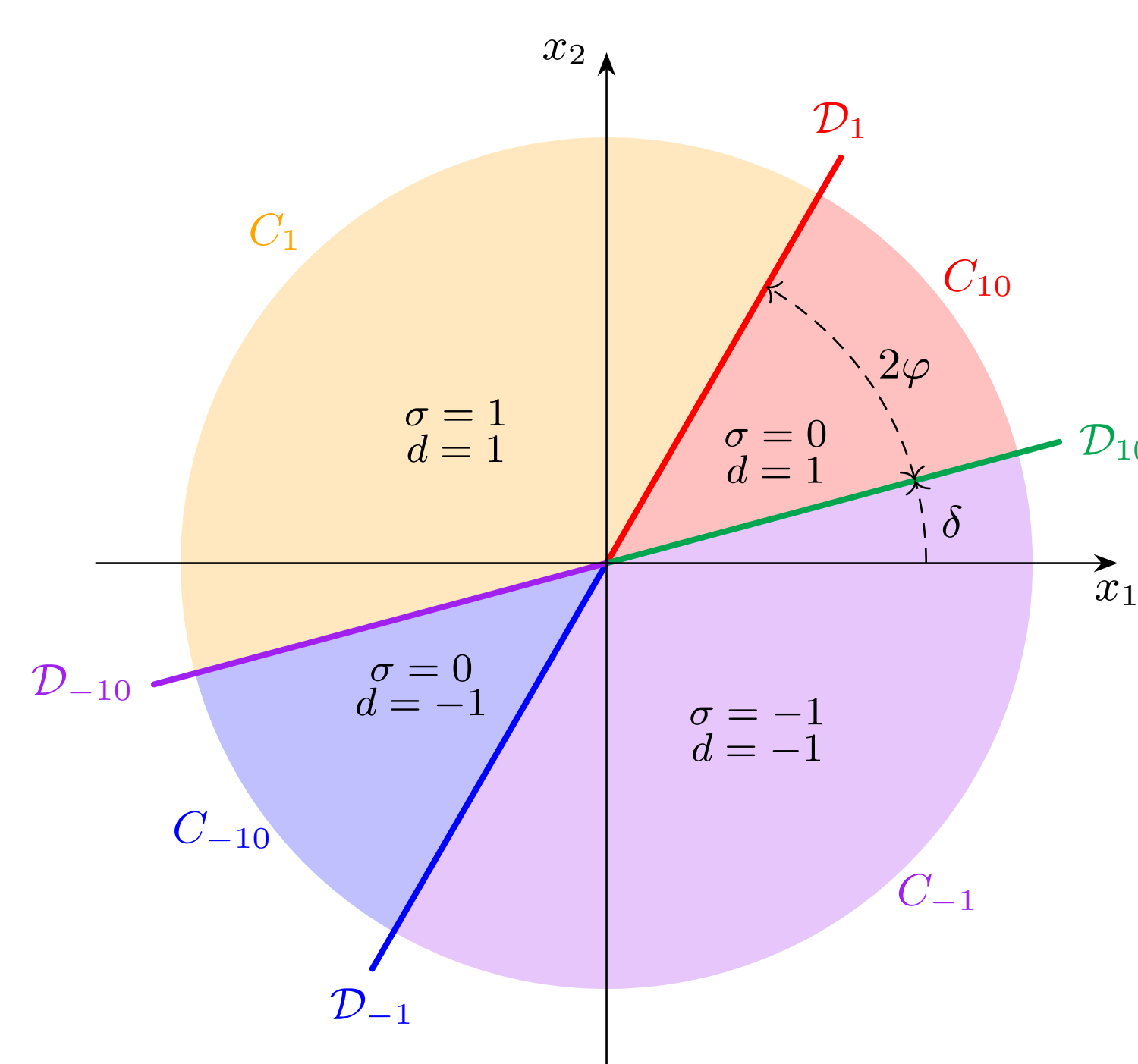
## Zero-Voltage Switching (ZVS)

In few words, ZVS occurs when the input current  $i_S$  is positive when  $\sigma$  is decreasing, and vice versa. Having ZVS ensures a higher switching efficiency.

## Proposed control law: mixed modulation

Hybrid dynamical model with continuous states  $(x_1, x_2)$  and discrete states  $(\sigma, d)$ :

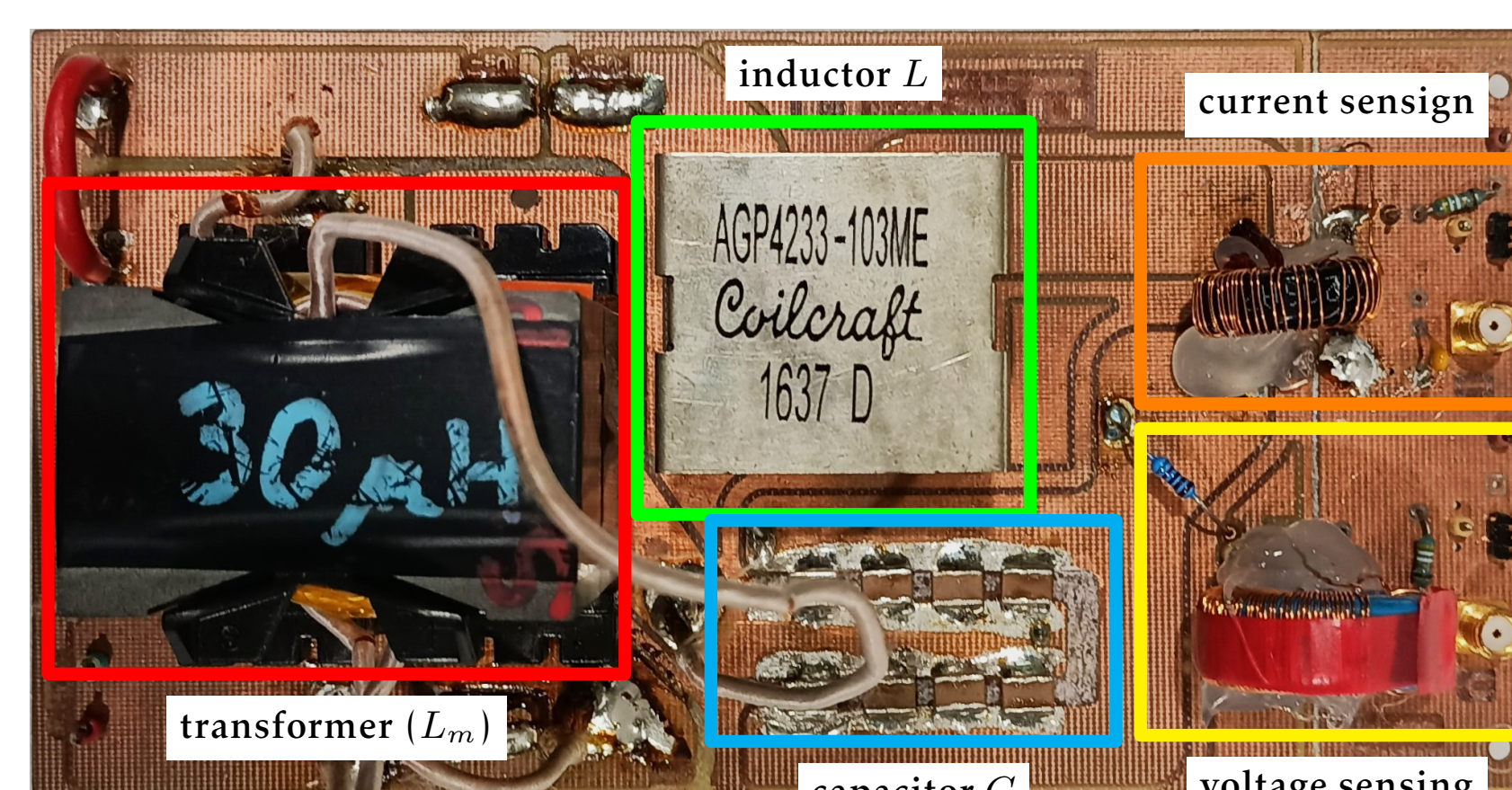
$$\begin{aligned} (\dot{x}_1, \dot{x}_2, \dot{\sigma}, \dot{d}) &= (\omega_0 x_2, -\omega_0 x_1 - \beta x_2 + \omega_0 \sigma, 0, 0), & (x_1, x_2, \sigma, d) &\in \mathcal{C}(\varphi, \delta), \\ (x_1^+, x_2^+, \sigma^+, d^+) &= (x_1, x_2, -d + \sigma, -d + 2\sigma), & (x_1, x_2, \sigma, d) &\in \mathcal{D}(\varphi, \delta). \end{aligned}$$



The discrete dynamics ensures the correct sequence for  $\sigma$ , while the jump set enforces a particular modulation behavior. From an intuitive perspective, four different zones (flow sets) are defined in the  $(x_1, x_2)$  plane corresponding to the  $\sigma$  values in a period:  $\sigma = -1, 0, 1, 0, \dots$ . From a practical point of view:

- increasing the aperture  $\varphi$  of the sets with  $\sigma = 0$  the amplitude decreases (*amplitude modulation*);
- rotating the sets counterclockwise ( $\delta$ ) the frequency increases (*frequency modulation*).

## Experimental setup: LLC resonant converter

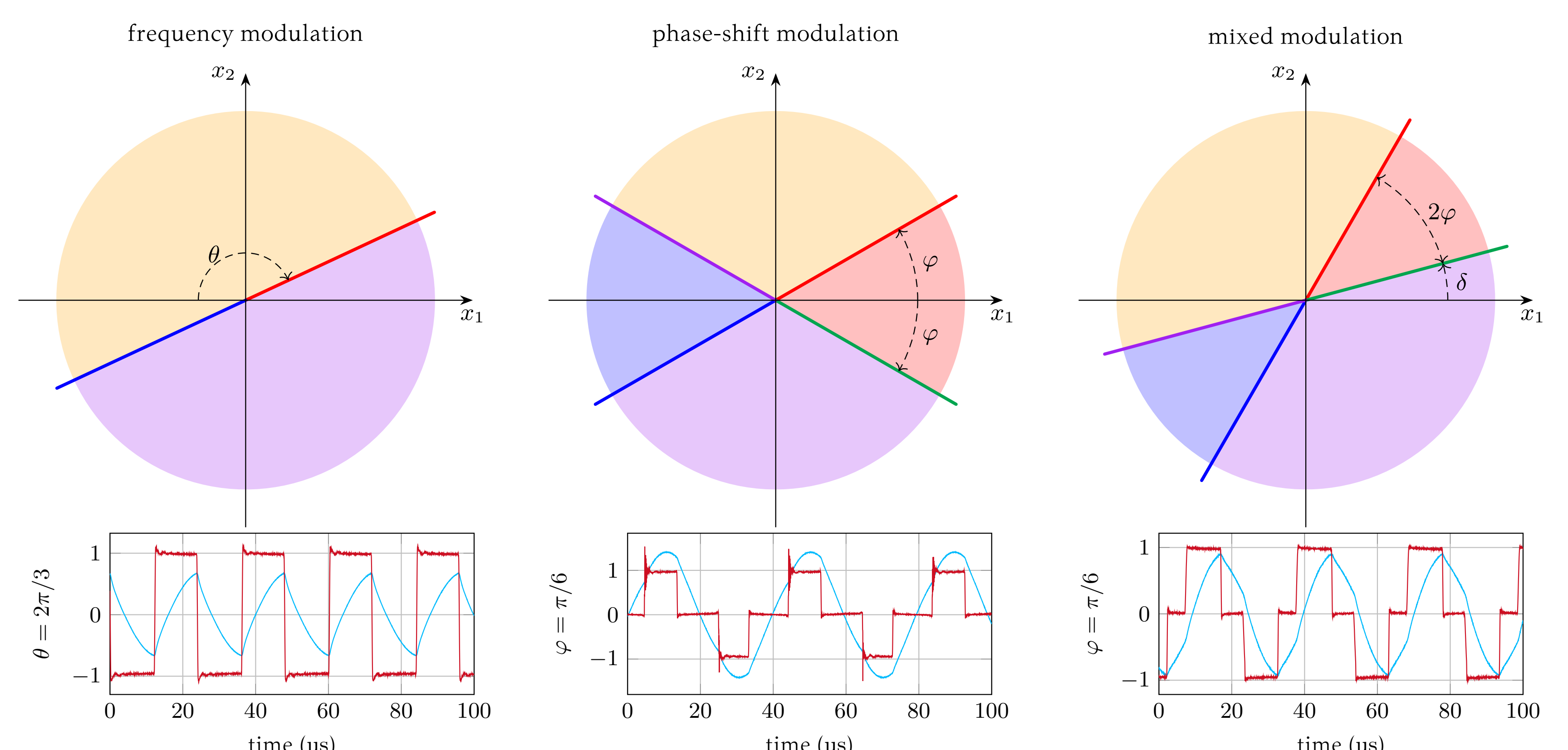


An LLC converter is similar to a series resonant converter with the difference that there is the magnetizing inductance  $L_m$  of the transformer in parallel with the output. Differences:

- boost operation is enabled;
- galvanic isolation.

## Results: a comparison

Typical modulation control laws can be framed in our proposed control law by fixing some parameters. Frequency modulation:  $\delta = \pi - \theta$  and  $\varphi = 0$ . Phase-shift modulation:  $\delta = -\varphi$ .



- |                         |                      |                     |
|-------------------------|----------------------|---------------------|
| ✓ ZVS                   | ✗ No ZVS             | ✓ ZVS               |
| ✗ Large frequency range | ✓ Constant frequency | ✓ Limited frequency |