Virtual Oscillator Control (VOC)

Main Characteristics

The VOC is inspired in the behavior of weakly nonlinear limit-cycle dead-zone oscillators

Main attributes:

- ❑ Global asymptotic synchronization among all parallel connected VOC controlled VSCs
- ❑ Power sharing capacity in islanded mode without directly measurements of powers
- ❑ Programmable Droop behavior in steady-state

B. B. Johnson, S. V. Dhople, A. O. Hamadeh and P. T. Krein, "Synchronization of Parallel Single-Phase Inverters With Virtual Oscillator Control," in IEEE Transactions on Power Electronics, vol. 29, no. 11, pp. 6124-6138, Nov. 2014, doi: 10.1109/TPEL.2013.2296292.

Main Characteristics

Some shortcomings:

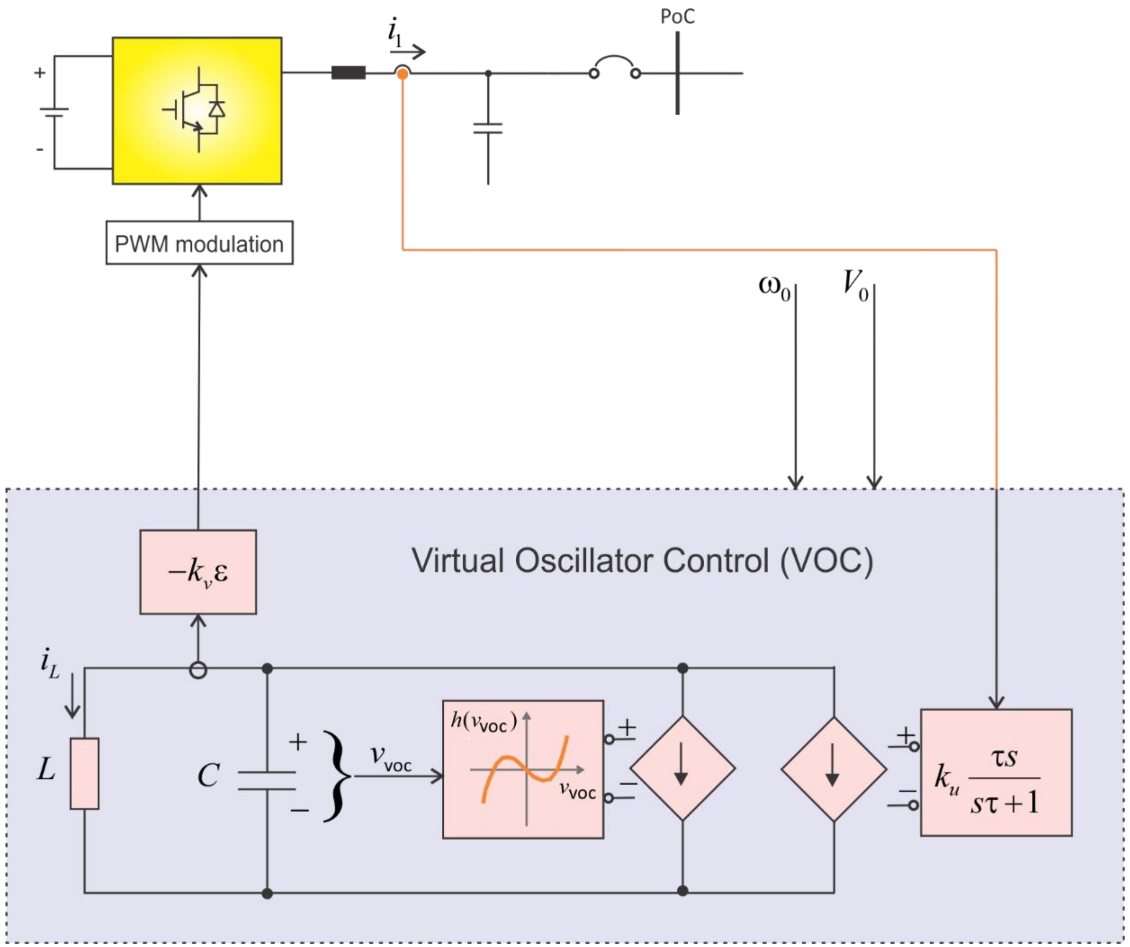
- The application to three-phase systems is not straightforward
- The original VOC is not dispatchable
- The output voltage to the converter presents some (small) harmonic distortions of low order.

Recent advances made the VOC dispatchable and, via filtering, is possible to mitigate the harmonic content

M. A. Awal, H. Yu, H. Tu, S. M. Lukic and I. Husain, "Hierarchical Control for Virtual Oscillator Based Grid-Connected and Islanded Microgrids," in IEEE Transactions on Power Electronics, vol. 35, no. 1, pp. 988-1001, Jan. 2020, doi: 10.1109/TPEL.2019.2912152.

The Virtual Oscillator Control Framework for Grid-Forming Inverters

- Implements VOC the Van der Pol oscillator. It consists of
  - an LC tank which is designed to define de natural frequency $\omega_0 = \frac{1}{\sqrt{LC}}$
  - a current controlled element $h(v_{voc})$ that acts as Source or Dissipative Element to control the amplitude of oscillation
- The input-output pair $(i_1, -k_v \varepsilon i_L)$ is added to interact with the electrical system.



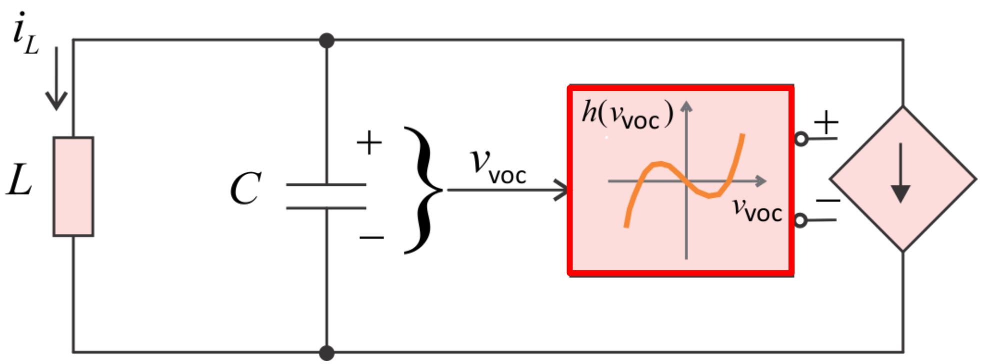
Typhoon HIL

Universidade Federal de Santa Maria 1960

Grupo de Eletrônica de Potência e Controle

The Van der Pol Oscillator

- Circuit for implementation



$$C\dot{v}_{\text{voc}} + h(v_{\text{voc}}) + \frac{1}{L}\int_{-\infty}^{t} v_{\text{voc}}\,dt = 0$$

$$LC\ddot{v}_{\text{voc}} + L\frac{dh(v_{\text{voc}})}{dv_{\text{voc}}}\dot{v}_{\text{voc}} + v_{\text{voc}} = 0 \qquad (1)$$

- Liénard's equation with $f(v_{\text{voc}}) = dh(v_{\text{voc}})/dv_{\text{voc}}$, $\varepsilon = \sqrt{L/C}$ and $\omega_0 = 1/\sqrt{LC}$)

$$\ddot{v}_{\text{voc}} + \omega_0 \varepsilon f(v_{\text{voc}})\dot{v}_{\text{voc}} + \omega_0^2 v_{\text{voc}} = 0 \qquad (2)$$

For

$$h(v_{\text{voc}}) = \frac{v_{\text{voc}}^3 \alpha}{3} - \sigma v_{\text{voc}} \qquad (3)$$

yields the Van der Pol oscillator

$$\Rightarrow \quad \frac{d^2 v_{\text{voc}}}{dt^2} - \varepsilon\omega_0\alpha(\sigma - \alpha v_{\text{voc}}^2)\frac{dv_{\text{voc}}}{dt} + \omega_0^2 v_{\text{voc}} = 0 \qquad (4)$$

Typhoon HIL

Universidade Federal de Santa Maria 1960

Grupo de Eletrônica de Potência e Controle

The Van der Pol Oscillator

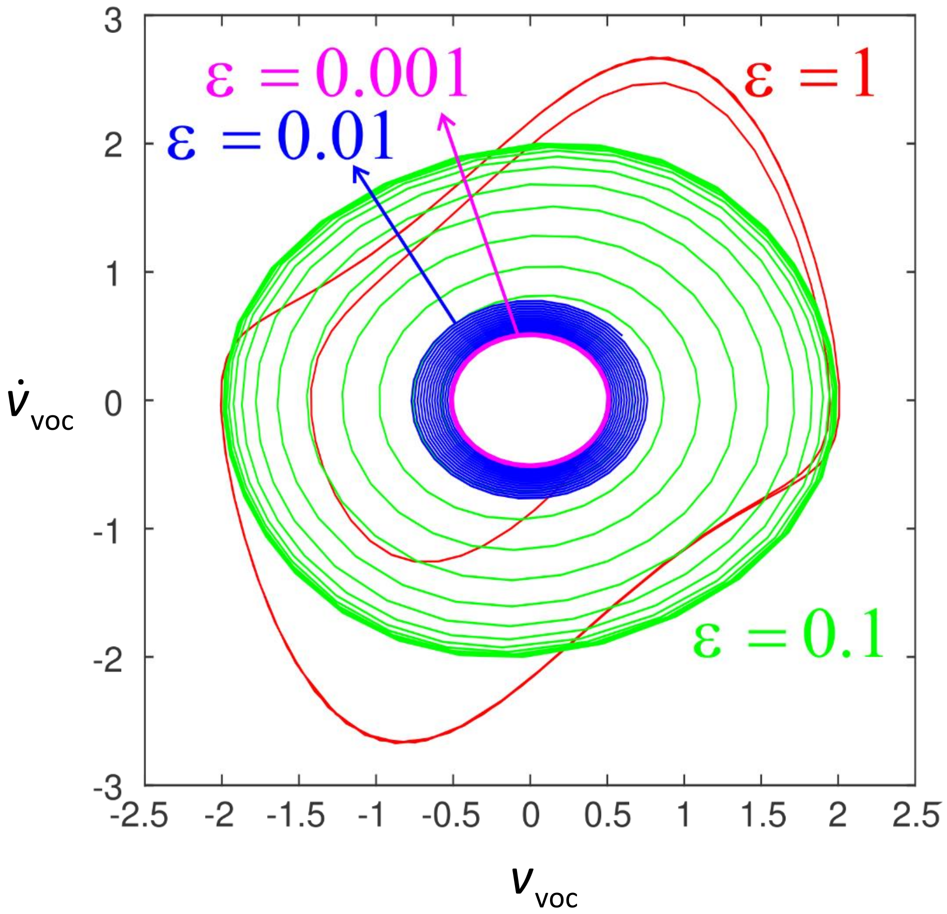
Example: Let's construct the phase portrait of the Van der Pol's Equation with $\sigma = 1,\ \omega_0 = 1$ and $\alpha = 1$, with $v_{voc(0)} = 0.5$ and $\dot{v}_{voc}(0) = 0$, for different values of ε.

$$\frac{d^2 v_{voc}}{dt^2} - \varepsilon\omega_0\alpha\left(\sigma - \alpha v_{voc}^2\right)\frac{dv_{voc}}{dt} + \omega_0^2 v_{voc} = 0$$

$$\Downarrow$$

$$\frac{d^2 v_{voc}}{dt^2} - \varepsilon\left(1 - v_{v_{voc}}^2\right)\frac{dv_{voc}}{dt} + v_{voc} = 0 \qquad (1)$$

✓ The oscillations become more sinusoidal as $\varepsilon \to 0^+$



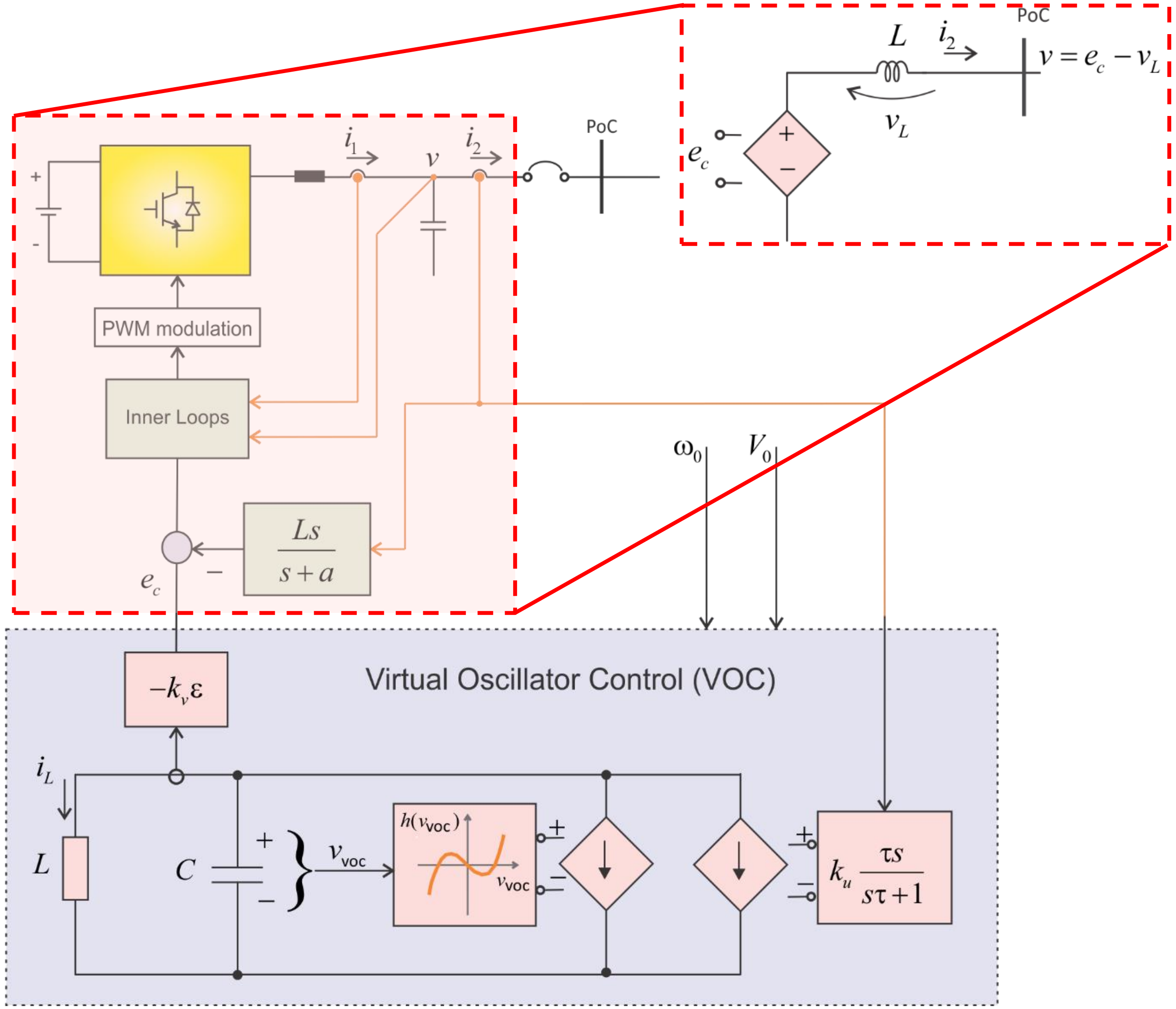
Typhoon HIL

Universidade Federal de Santa Maria 1960

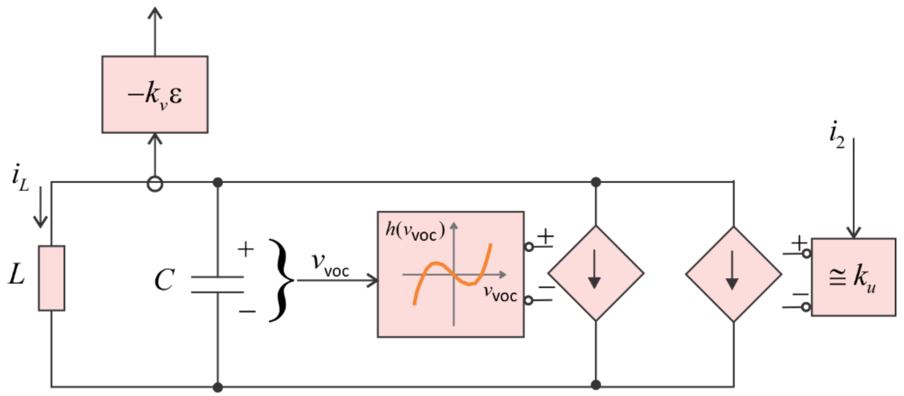
Grupo de Eletrônica de Potência e Controle

VOC Controlled VSC with Inner Loops

- The VOC framework for control of VSCs consists of:
  - LC circuit
  - Nonlinear voltage-controlled current-source $h(v_{\mathrm{voc}})$
  - synchronization input i_2
  - output $-k_v \varepsilon i_L$
- Additional functions:
  - Virtual Inductor
  - Inner voltage and current loops



VOC Model for Inductive Lines



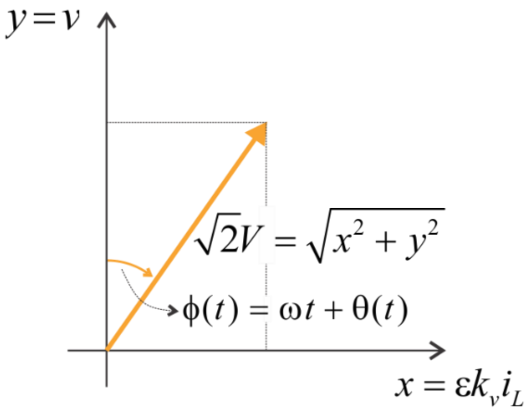
$$\frac{di_L}{dt} = \frac{1}{L} v_{voc}$$
$$\frac{dv_{voc}}{dt} = -\frac{1}{C} i_L - \frac{1}{C}\left(\frac{\alpha}{3} v_{voc}^3 - \sigma v_{voc}\right) - \frac{k_u}{C} i_2 \qquad (1)$$

- State variables: $x = k_v \varepsilon i_L, \quad y = v_{voc}$ (2)
- Model constants: $\omega_0 = \frac{1}{\sqrt{LC}}, \ \beta = \frac{\alpha}{k_v^2 \sigma}, \quad \varepsilon = \sqrt{\frac{L}{C}}$

$$\frac{dx}{dt} = \omega_0 y$$
$$\frac{dy}{dt} = -\omega_0 x + \varepsilon \omega_0 \sigma \left(y - \frac{\beta}{3} y^3 \right) - \varepsilon \omega_0 k_v k_u i_2 \qquad (3)$$

VOC Average Model for Inductive Lines

- VOC in Polar coordinates:



$$x = \sqrt{2} V \sin\phi$$
$$y = \sqrt{2} V \cos\phi$$

- Average model for the (rms) **Voltage Amplitude** and **Phase Offset** (with respect to ω)

$$\dot{\bar{V}} = \frac{\sigma}{2C}\left(\bar{V} - \frac{\beta}{2}\bar{V}^3\right) - \frac{k_v k_u}{2C\bar{V}}\bar{Q}$$
$$\dot{\bar{\theta}} = \omega_0 - \omega - \frac{k_v k_u}{2C\bar{V}^2}\bar{P} \qquad (1)$$

$$\bar{Q} = \frac{\omega_0}{2\pi}\int_0^{2\pi/\omega_0} Q(\tau)d\tau,$$
$$\bar{P} = \frac{\omega_0}{2\pi}\int_0^{2\pi/\omega_0} P(\tau)d\tau \qquad (2)$$
$$P = e_c i_2, \quad Q = -e_{cq} i_2,$$
$$e_c = -x, \quad e_{cq} = -y$$

- No entries for power setpoints … *not suitable for grid-connected applications.*

B. B. Johnson, M. Sinha, N. G. Ainsworth, F. Dörfler and S. V. Dhople, "Synthesizing Virtual Oscillators to Control Islanded Inverters," in IEEE Transactions on Power Electronics, vol. 31, no. 8, pp. 6002-6015, Aug. 2016, doi: 10.1109/TPEL.2015.2497217