אוניברסיטת בן-גוריון בנגב
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Nonlinear Controller Design for Resonant Inverter Driving Time-Varying RLC Load

Ohad Akler, Alon Kuperman

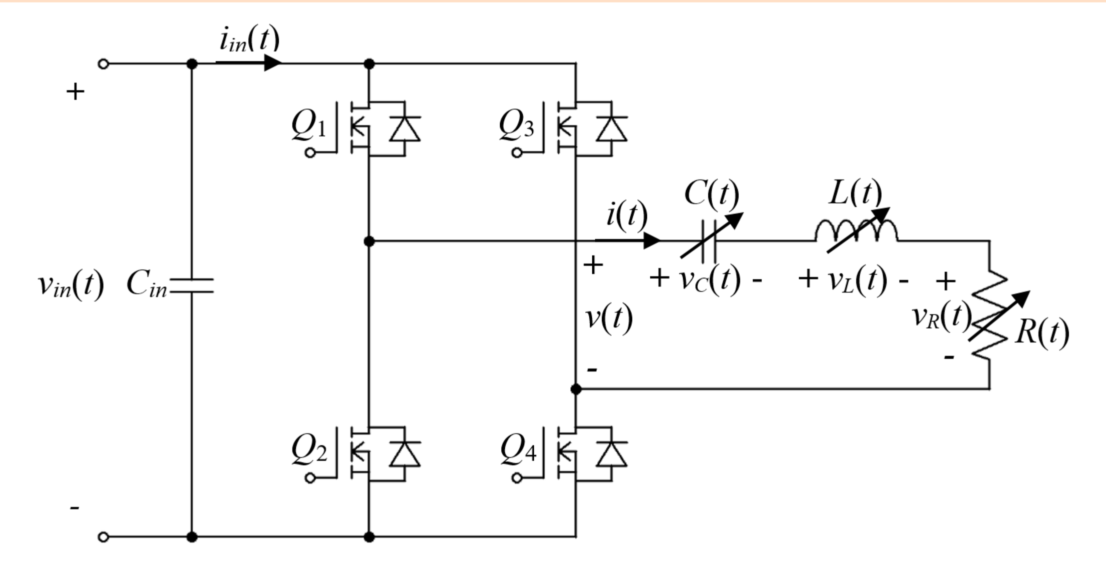
Applied Energy Laboratory, Ben-Gurion University of the Negev, Israel, in collaboration with nT-tao.

1. Introduction

Resonant converters are widely used in applications such as induction heating, wireless charging, and pulsed-power fusion systems. In the latter, phasor and small-signal models fail to predict system behaviour due to large operating point variations during short, high-intensity pulses.
Envelope modelling approach captures large-signal amplitude and phase dynamics while ignoring fast switching dynamics. Nonlinear controller is designed based on a reduced-order envelope model of a resonant inverter driving time-varying RLC load.

2. System Under Consideration

Full-bridge inverter feeding series-connected resistor-inductor-capacitor (RLC) network with time-varying component values.



$$v(t)=\begin{cases} v_{in}(t), \ 0\le t\le \frac{T_s(t)}{2} \\ -v_{in}(t), \ \frac{T_s(t)}{2}\le t\le T_s(t) \end{cases} \qquad (1)$$

$T_s(t)$ - switching period

$$v_C(t)=V_M(t)\sin\left(\int \omega_s(t)dt+\varphi_v(t)\right) \qquad (2)$$

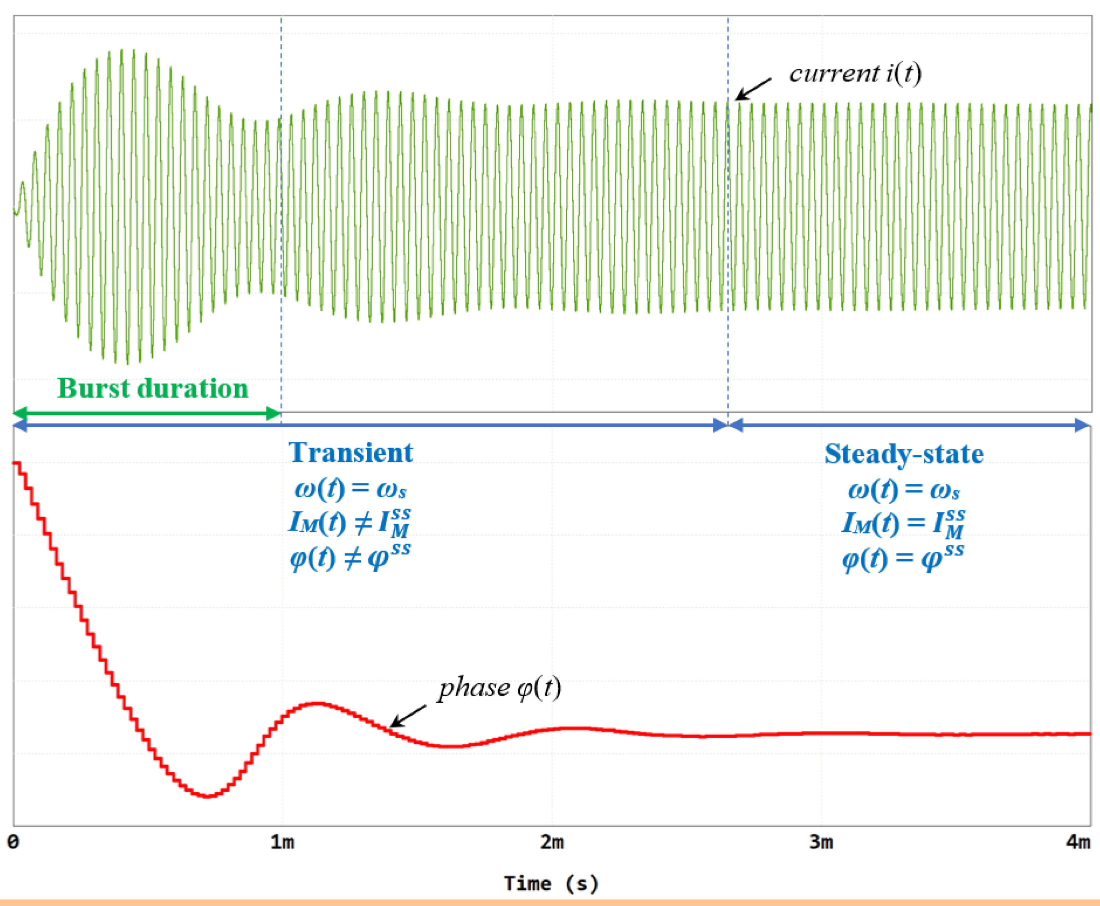
$$i(t)=I_M(t)\sin\left(\int \omega_s(t)dt+\varphi_i(t)\right) \qquad (3)$$

$$V_M(t)\cos\left(\varphi_v(t)\right)\triangleq v_C^s(t), \quad V_M(t)\sin\left(\varphi_v(t)\right)\triangleq v_C^c(t) \qquad (4)$$

$$I_M(t)\cos\left(\varphi_i(t)\right)\triangleq i^s(t), \quad I_M(t)\sin\left(\varphi_i(t)\right)\triangleq i^c(t), \qquad (5)$$

3. Main Challenge

During short bursts, the system may never reach steady-state during operation. Hence, classical phasor analysis considering steady-state is irrelevant for analyzing system behavior within power burst duration period.



Typical System Step Response

4. Envelope Model

Full order plant model

$$\frac{di^s(t)}{dt}=\omega_s(t)i^c(t)+\frac{1}{L(t)}\left[\frac{4v_{in}(t)}{\pi}-\left(R(t)+\frac{dL(t)}{dt}\right)i^s(t)-v_C^s(t)\right], \quad i^s(0)=I_0^s \qquad (6)$$

$$\frac{di^c(t)}{dt}=-\omega_s(t)i^s(t)-\frac{1}{L(t)}\left[\left(R(t)+\frac{dL(t)}{dt}\right)i^c(t)+v_C^c(t)\right], \quad i^c(0)=I_0^c \qquad (7)$$

$$\frac{dv_C^s(t)}{dt}=\frac{1}{C(t)}i^s(t)+\omega_s(t)v_C^c(t)-\frac{dC(t)}{dt}v_c^c(t), \quad v_C^s(0)=V_{C0}^s \qquad (8)$$

$$\frac{dv_C^c(t)}{dt}=\frac{1}{C(t)}i^c(t)-\omega_s(t)v_C^s(t)-\frac{dC(t)}{dt}v_C^c(t), \quad v_C^c(0)=V_{C0}^c \qquad (9)$$

$$\frac{d\overline{v}_{in}(t)}{dt}=-\frac{R(t)}{2\overline{v}_{in}(t)C_{in}}\left(I_M(t)\right)^2, \ \overline{v}_{in}(0)=V_0 \qquad (10)$$

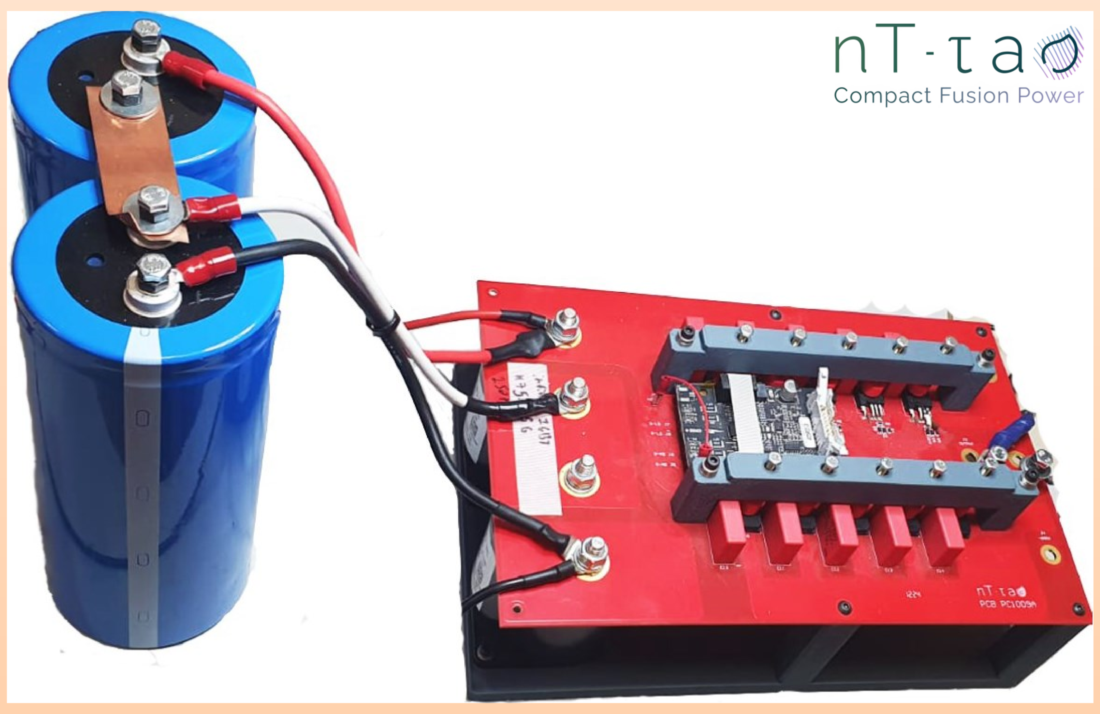
Reduced order AC-side model

$$\begin{aligned}\frac{dI_M(t)}{dt}&=\frac{C(t)L(t)\omega_s^2(t)\left(\omega_s(t)-\frac{1}{C(t)L(t)\omega_s^2(t)}\right)\tan\left(\varphi_i(t)\right)-C(t)L(t)\omega_s^2(t)\frac{R(t)}{L(t)}}{\frac{1}{i^s(t)}\left(C(t)L(t)\omega_s^2(t)+1\right)\sqrt{1+\tan^2\left(\varphi_i(t)\right)}}\\&+\frac{C(t)L(t)\omega_s^2(t)\left(\frac{4\overline{v}_{in}(t)}{\pi L(t)}\right)\frac{1}{i^s(t)}}{\frac{1}{i^s(t)}\left(C(t)L(t)\omega_s^2(t)+1\right)\sqrt{1+\tan^2\left(\varphi_i(t)\right)}}\\&-\frac{\tan\left(\varphi_i(t)\right)\left[C(t)L(t)\omega_s^2(t)\left(\omega_s(t)-\frac{1}{C(t)L(t)\omega_s^2(t)}\right)+C(t)L(t)\omega_s^2(t)\frac{R(t)}{L(t)}\tan\left(\varphi_i(t)\right)\right]}{\frac{1}{i^s(t)}\left(C(t)L(t)\omega_s^2(t)+1\right)\sqrt{1+\tan^2\left(\varphi_i(t)\right)}}.\end{aligned} \qquad (11)$$

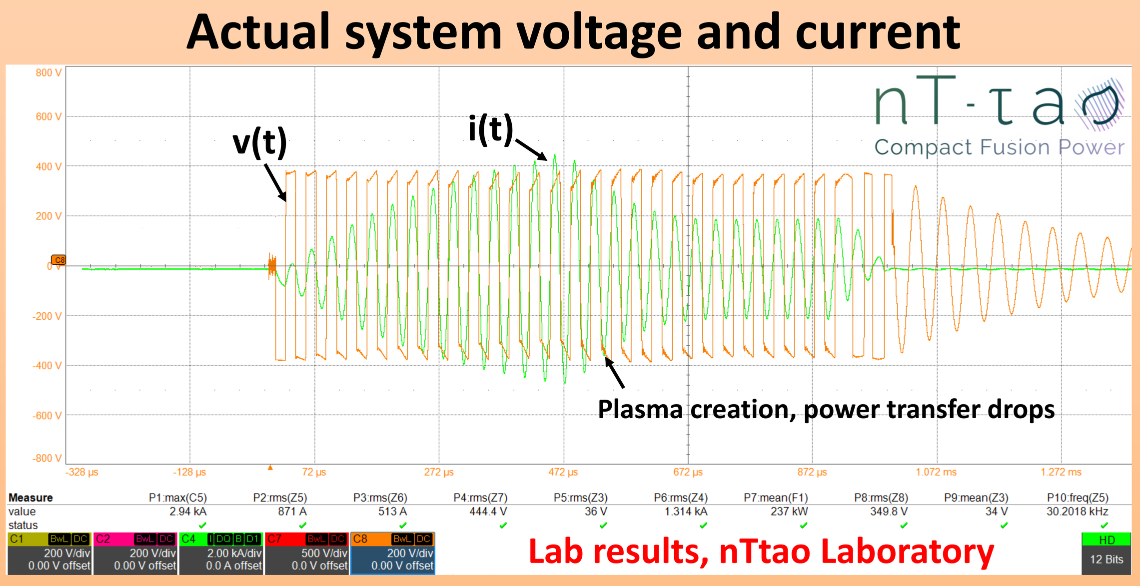
$$\begin{aligned}\frac{d}{dt}\tan\left(\varphi_{ir}(t)\right)&=-\frac{C(t)L(t)\omega_s^2(t)\left(\omega_s(t)-\frac{1}{C(t)L(t)\omega_s(t)}\right)\left(1+\tan^2\left(\varphi_{ir}(t)\right)\right)}{C(t)L(t)\omega_s^2(t)+1}\\&-\frac{\sqrt{\frac{1+\tan^2\left(\varphi_{ir}(t)\right)}{I_{Mr}^2(t)}}\cdot\frac{4\overline{v}_{inr}(t)}{\pi L(t)}C(t)L(t)\omega_s^2(t)\tan\left(\varphi_{ir}(t)\right)}{C(t)L(t)\omega_s^2(t)+1}\end{aligned} \qquad (12)$$

5. Prototype

Capacitor-fed, IGBT based half-bridge inverter

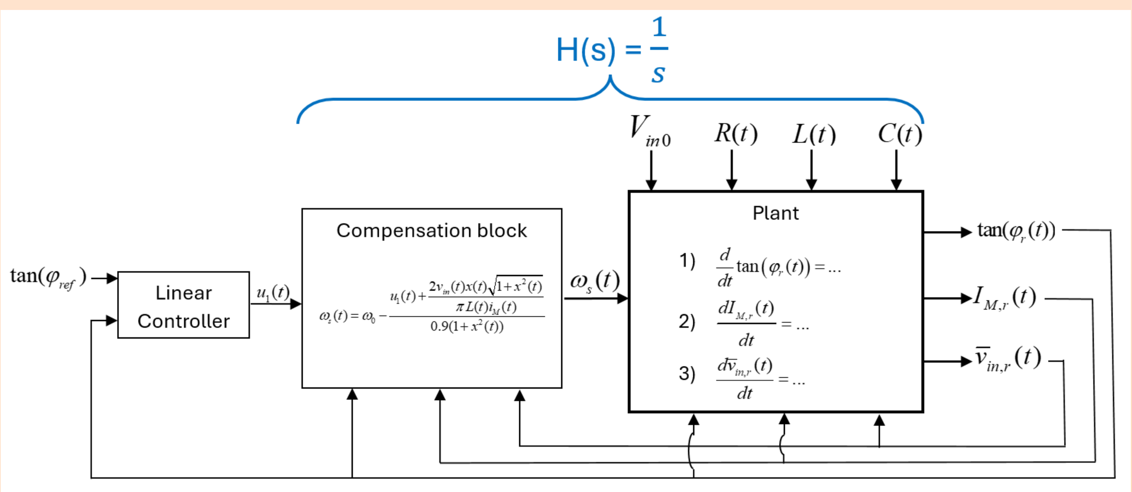


Actual system voltage and current

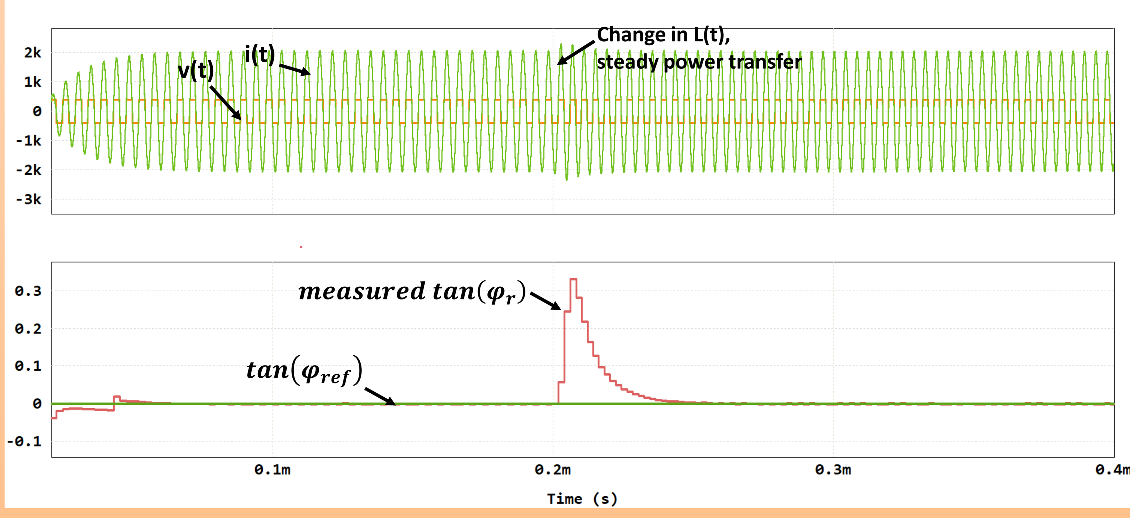


6. Control loop & results

Closed loop system



Closed-loop system response



7. Conclusions

- **High-order envelope model** was established, capturing both DC-side and AC-side dynamics of a pulsed powered resonant inverter.
- **Nonlinear, reduced-order envelope model** was derived from the high-order model, providing a simplified plant for the power-transfer dynamics of a pulsed powered resonant inverter driving time-varying RLC load.
- **The proposed model was shown to accurately track large-signal amplitude and phase** dynamics during transient bursts, outperforming small-signal and phasor-domain approaches in pulsed power scenarios.
- **Non-linearity compensation block** was derived, allowing feedback linearization-based control adoption.
- **Experimental prototype** has been constructed, controller implementation and validation are currently in progress.

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