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Mitigating Constant Power Load-Induced Instability Using Fractional Order Buck Converter and Backstepping Control

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Mitigating Constant Power Load-Induced Instability Using Fractional Order Buck Converter and Backstepping Control

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Abstract

Constant power loads (CPLs), widely present in modern electronic systems and renewable energy applications, are known to cause instability due to their negative incremental impedance (INI) behavior. This phenomenon leads to a reduction in system damping, resulting in voltage oscillations and potential failure of power converters. To overcome this challenge, this work proposes a robust control solution based on a fractional order (FO) buck converter combined with a nonlinear FO backstepping controller. The FO behavior of inductors and capacitors is captured using the Oustaloup Recursive Approximation (ORA), which provides more accurate frequency-domain representation than classical integer-order models. The dynamic model of the FO converter supplying a CPL is developed using the averaging method, and an incommensurate FO backstepping controller is designed to ensure output voltage stability. The system's stability is analytically verified using a FO Lyapunov function. Simulation results under multiple disturbance scenarios confirm that the FO controller ensures fast settling time, better robustness, and improved voltage regulation compared to integer-order approaches. This study demonstrates that fractional calculus offers a powerful framework for addressing the complex instability issues caused by CPLs in DC systems.

Introduction

Constant power loads present major challenges in power electronic systems due to their negative incremental impedance, which can lead to instability and performance degradation. This poster presents a robust control approach based on fractional-order calculus to address this issue [1]. By integrating FO modeling and a FO backstepping control strategy, the proposed method effectively mitigates the destabilizing effects caused by CPLs. The focus is on ensuring stable and accurate output voltage regulation in DC-DC buck converters, making the system more resilient under dynamic load conditions and wide CPL variations.

Fractional Order Buck Converter Modeling

For a general applied voltage on a real capacitor [3], with fractional time derivative, the current is

$$i_C(t) = C\frac{d^{\beta_1}v_c}{dt^{\beta_1}} \tag{1}$$

where β_1 (order) is another constant related to capacitor losses and C is the capacitance.

For a passing current in a real inductor , with fractional time derivative, the voltage is

$$v_L(t) = L\frac{d^{\beta_2}i_L}{dt^{\beta_2}} \tag{2}$$

where β_2 (order) is a constant related to the proximity effect and L is the inductance.

According to the linear models proposed by Westerlund as well as the fact that the converter is assumed to be operating in CCM [2], the dynamic equations of the FO buck converter feeding a CPL and a resistive load is expressed bellow

$$\begin{cases} \frac{d^{q_1}v_C}{dt^{q_1}} = \frac{i_L}{C} - \frac{i_R}{C} - \frac{i_P}{C} \\ \frac{d^{q_2}i_L}{dt^{q_2}} = \frac{v_{in}}{L}d - \frac{v_C}{L} \end{cases} \tag{3}$$

Construction of the Proposed Nonlinear Control Scheme

- The control input of DC-DC buck converter is

$$\boldsymbol{d} = \frac{1}{v_{in}}\begin{bmatrix} \boldsymbol{e_1} + \tilde{v}_C + \boldsymbol{LD^{q_2}\beta} - \frac{L}{C}\boldsymbol{e_2\, sign(D^{q_1-\alpha}e_1)} \\ \boldsymbol{sign(D^{q_2-\alpha}e_2) - LK_2D^{q_2-\alpha}e_2} \end{bmatrix} \tag{4}$$

For $K_1 > 0$ and $K_2 > 0$, the system (3) is globally asymptotically stable,
In which the tracking error dynamics e_1 and e_2 are chosen as

$$e_1 = v_C - \tilde{v}_C. \tag{5}$$

$$e_2 = i_L - \beta. \tag{6}$$

In addition, the virtual controller is as

$$\beta = -CK_1D^{q_1-\alpha}e_1 + CD^{q_1}\tilde{v}_C + i_R + i_P. \tag{7}$$

Impedance-induced instability (INI), commonly caused by a constant power load, is a well-known issue that can significantly impact the stability of DC microgrids. The most critical situation arises when the DC load behaves as a pure CPC, which drastically reduces the system's damping and makes it highly susceptible to oscillations and instability. Proper control strategies are essential to mitigate these adverse effects and ensure reliable operation.

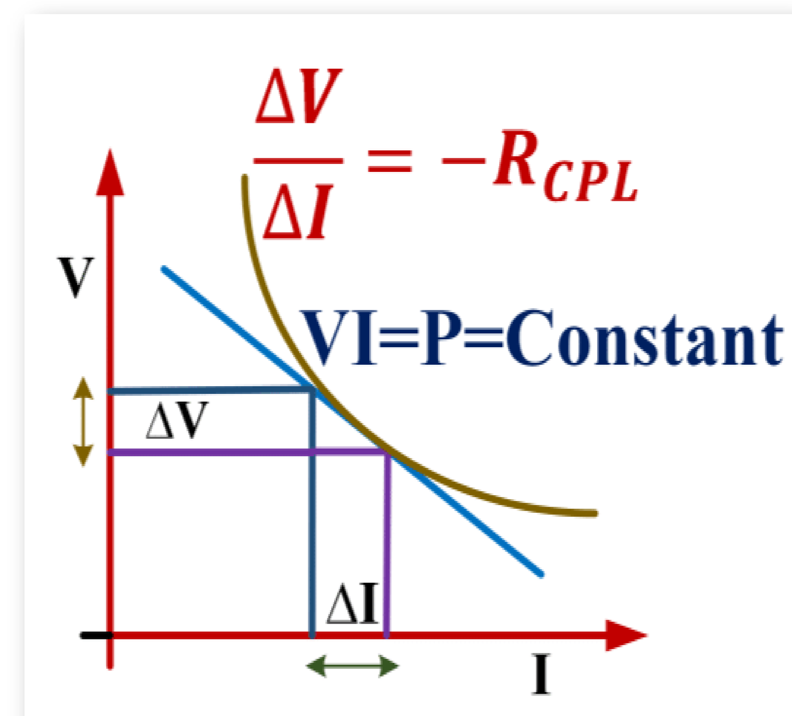

Fig. 1: Graphical Representation of Constant Power Load Characteristics.

Results

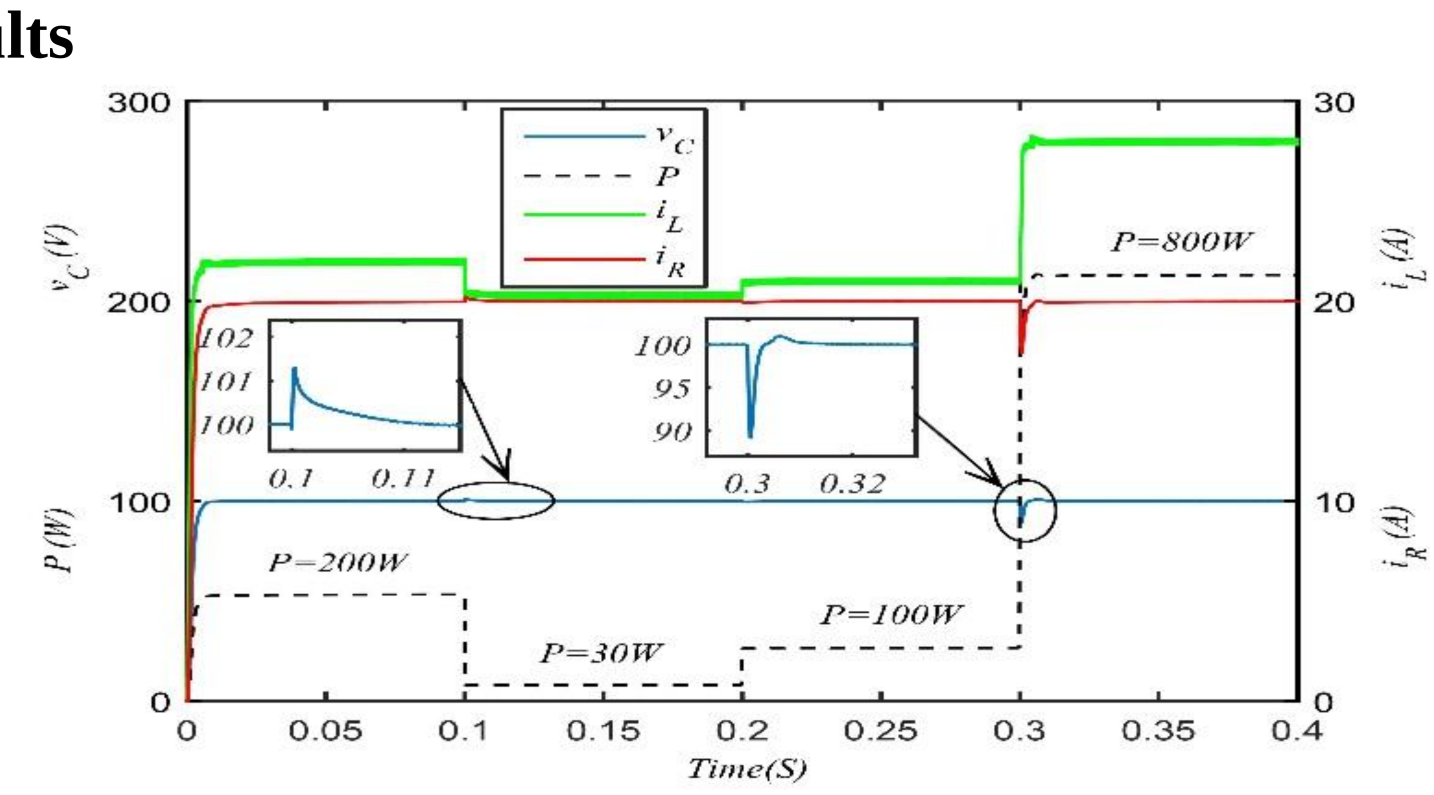

Fig. 2: Simulation Results with a Changing constant power load.

In the first scenario, the test evaluates the impact of sudden variations in constant power load on the DC bus voltage. As shown in Figure 2, the CPL initially starts at 200 W. The FO backstepping controller regulates the voltage effectively, reaching the reference within 8.4 ms without overshoot. At 0.1 s, a decrease from 200 W to 30 W is applied. The controller mitigates the disturbance, maintaining voltage stability. At 0.2 s, a rise from 30 W to 100 W occurs, and the voltage continues tracking the reference. Finally, a jump to 800 W at 0.3 s is introduced. Despite the large variation, the FO-controlled converter remains stable, showing strong disturbance rejection and confirming its robustness under wide CPL changes.

Conclusion

The proposed fractional-order control strategy effectively mitigates the destabilizing effects of constant power loads. By integrating precise fractional-order modeling with nonlinear control, the system ensures voltage stability and surpasses integer-order solutions. This approach is particularly well-suited for robust power management in sensitive DC applications, offering enhanced performance and reliability, making it a highly effective solution for addressing challenges posed by CPL-induced instability.

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