MATLAB Implementation of Normalized Controllers for PWM Converters

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***Abstract*—This paper presents a MATLAB-based implementation of the normalized control design procedure for Pulse-Width-Modulated (PWM) converters. The implementation supports Buck, Boost, and Buck-Boost converters, enabling the design of universal compensators independent of converter parameters. The code facilitates user input for converter type and parameters, computes normalized coefficients, designs a discrete-time controller, and simulates the closed-loop response. Simulation results validate the normalized approach, demonstrating consistent dynamic performance across different converter configurations. This implementation serves as a practical tool for engineers and researchers exploring normalized control strategies for PWM converters.**

***Index Terms*—PWM Converters, Normalized Control, MATLAB, Buck Converter, Boost Converter, Buck-Boost Converter**

I. Introduction

In modern power electronics, DC-DC converters are fundamental building blocks used in a wide range of applications, including renewable energy systems, automotive electronics, and communication equipment. Among these, Buck, Boost, and Buck-Boost converters are the most commonly used topologies due to their efficiency, compactness, and ease of control. Traditionally, the control design for such converters relies heavily on small-signal modeling and tuning procedures that are specific to each set of converter parameters. This leads to a major limitation: controller coefficients must be recalculated whenever parameters such as inductance, capacitance, or input/output voltage are altered.

To overcome this challenge, recent research has proposed the concept of normalized control design, where the system is represented in a normalized domain that is independent of the converter's specific physical parameters. This approach allows the development of universal controllers that maintain consistent dynamic behavior across varying converter configurations.

This paper presents the practical MATLAB implementation of the normalized control strategy introduced in the IEEE paper "Universal Controllers for PWM Converters: A Normalized Approach." The code enables user-driven configuration of Buck, Boost, and Buck-Boost converters, normalizes the system parameters, computes universal controller coefficients, and simulates the output voltage response. The key contribution of this work lies in demonstrating that a single controller structure—designed in the normalized domain—can be effectively applied to different converters without retuning, while ensuring stable and desirable performance.

The paper is organized as follows: Section II reviews related work on PWM converter control. Section **??** describes the normalized control approach. Section IV details the MATLAB implementation. Section V presents simulation results, and Section VI concludes the paper.

II. Related Work

The control of DC-DC converters using linear compensators has been a widely researched area in power electronics. Classical design approaches rely on small-signal modeling and averaging techniques, as introduced by Wester and Middlebrook [**?**], and further developed by Cuk and Vorperian [**?**], [**?**], [**?**]. These methods allow modeling of converters under steady-state conditions but typically require specific controller tuning for each configuration of component values.

Various control strategies have been proposed for the fundamental PWM topologies—Buck, Boost, and Buck-Boost converters. Each method is tailored to the converter's specific parameters, such as input/output voltages, inductance, capacitance, and switching frequency. This dependency means that any change in these values necessitates a complete re-design of the controller. Several efforts have attempted to address this by introducing robust tuning strategies [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], but most still rely on case-by-case calculations.

Degioanni et al. [**?**] addressed this challenge by introducing a normalized modeling approach for PWM converters. Their method defines a set of base quantities—such as characteristic impedance and resonant period—to transform the converter model into a normalized domain. In this domain, the system's behavior becomes independent of physical parameters, allowing the design of a universal controller that works across different converter configurations without retuning. This not only simplifies controller design but also improves scalability and reusability in real-world applications.

The present work implements this normalized control design approach using MATLAB, validating its practicality for Buck, Boost, and Buck-Boost converters through simulation and demonstrating that identical controller dynamics can be achieved across different parameter sets.

III. Normalization and Controller Design

The MATLAB implementation employs a normalized control approach to design and simulate universal controllers for PWM converters, as outlined in [**?**]. Normalization transforms physical parameters into a dimensionless domain, enabling a single compensator to achieve consistent performance across Buck, Boost, and Buck-Boost topologies without parameter-specific retuning. This section describes the normalization process, the derived normalized values, and their application in controller design and simulation.

A. Benefits of Normalization

Normalization eliminates dependency on specific converter parameters, such as inductance (L), capacitance (C), or input/output voltages ($V_{\text{in}}, V_{\text{out}}$), by scaling variables relative to base quantities. This yields a unified model for all converter types, described by common differential equations with topology-specific coefficients (Table **??**). The approach simplifies controller design, as the compensator's transfer function depends only on normalized parameters, ensuring identical dynamics across configurations. Additionally, normalization streamlines simulation by using dimensionless time and state variables, facilitating analysis of transient responses, such as load steps, in a standardized framework.

B. Normalized Values and Derivation

The implementation begins with user inputs for converter type (Buck, Boost, or Buck-Boost) and parameters: $V_{\text{in}}, V_{\text{out}}, f_s$ (switching frequency), L, C, R (load resistance). These are used to compute base parameters:

- Characteristic impedance: $Z_0 = \sqrt{\frac{L}{C}}$.
- Time constant: $T_0 = 2\pi\sqrt{LC}$.
- Reference voltage: $v_{\text{ref}} = V_{\text{out}}$.
- Reference current: $i_{\text{ref}} = \frac{|v_{\text{ref}}|}{Z_0}$.

These base values enable the normalization of system variables, defined as follows:

- **Normalized Switching Frequency** (f_{sn}):
$$f_{sn} = f_s T_0$$
Scales the physical switching frequency (f_s) by the resonant period (T_0).
- **Normalized Load Resistance** (R_n):
$$R_n = \frac{R}{Z_0}$$
Scales the load resistance (R) by Z_0. For load step simulation, R_n is halved ($R_n = \frac{R/2}{Z_0}$) after a specified time.
- **Normalized Time** (t_n):
$$t_n = \frac{t}{T_0}$$
Scales physical time (t) for simulation, using a vector $t_n = 0 : 0.01 : 10$.
- **Normalized Output Voltage** (v_{on}):
$$v_{on} = \frac{v_o}{v_{\text{ref}}}$$
Scales the output voltage (v_o) by v_{ref}, initialized by user input and updated during simulation.
- **Normalized Inductor Current** (i_{Ln}):
$$i_{Ln} = \frac{i_L}{i_{\text{ref}}}$$
Scales the inductor current (i_L) by i_{ref}, initialized to zero and updated dynamically.

C. Simulation Using Normalized Equations

The closed-loop dynamics are simulated using normalized differential equations:

$$\frac{1}{2\pi}\frac{di_{Ln}}{dt_n} = m_1 V_{\text{ccn}} - k_\omega v_{on}, \quad \frac{1}{2\pi}\frac{dv_{on}}{dt_n} = k_\omega i_{Ln} - m_2\frac{v_{on}}{R_n}$$

The simulation spans $t_n = 0$ to 10 with a step size of 0.01, updating v_{on} and i_{Ln} iteratively. An optional load step halves R_n at $t_n = 3$. The duty cycle is adjusted via the compensator output:

$$u_{\text{new}} = K_c(e+a_1e_{k-1}+a_2e_{k-2}+a_3e_{k-3})-(b_1u_{k-1}+b_2u_{k-2}+b_3u_{k-3})$$

where $error = 1 - v_{on}$ Results are denormalized for plotting:

$$t = t_nT_0, \quad v_o = v_{on}v_{\text{ref}}$$

This approach ensures consistent dynamic performance, validated in Section V for a Buck converter test case.

IV. MATLAB Implementation

This section details the MATLAB implementation of the normalized control design for PWM converters, utilizing the normalized values defined in Section **??**. The code automates the design and simulation process for Buck, Boost, and Buck-Boost converters, ensuring consistent performance across configurations.

A. User Input and Validation

The script begins by prompting the user to select a converter type (Buck, Boost, or Buck-Boost) and input parameters: $V_{\text{in}}, V_{\text{out}}, f_s$ (switching frequency), L, C, R (load resistance), phase margin (ϕ_m), and bandwidth ratio ($\Delta B = f_s/f_c$). Validation checks ensure physical feasibility, such as $V_{\text{out}} \leq V_{\text{in}}$ for Buck and $V_{\text{out}} \geq V_{\text{in}}$ for Boost, preventing invalid simulations.

B. Normalized Model Parameters

Based on the converter type, the duty cycle (D) and normalized coefficients (m_1, m_2, m_3, k_ω) are computed per Table **??**. Base parameters are calculated as:

$$Z_0 = \sqrt{\frac{L}{C}}, \quad T_0 = 2\pi\sqrt{LC}, \quad v_{\text{ref}} = V_{\text{out}}, \quad i_{\text{ref}} = \frac{|v_{\text{ref}}|}{Z_0}$$

The normalized switching frequency ($f_{sn} = f_s T_0$) and load resistance ($R_n = R/Z_0$) are derived.

C. Topology-Specific Parameters

Based on the user's converter selection, the code computes the duty cycle (D) and normalized coefficients (m_1, m_2, m_3, k_ω) using Table 7 from the reference [14]:

- Buck: $D = \frac{V_{\text{out}}}{V_{\text{in}}}$.
- Boost: $D = 1 - \frac{V_{\text{in}}}{V_{\text{out}}}$.
- Buck-Boost: Uses Buck equations if $V_{\text{out}} < V_{\text{in}}$, else Boost equations.

The normalized switching frequency (f_{sn}) and load resistance (R_n) are calculated using the base parameters and.

D. Controller Design

The code implements a discrete-time three-pole, three-zero (3P3Z) compensator with the transfer function:

$$G_c(z) = K_c \frac{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}}{1 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}}$$

Coefficients are computed as follows:

$$P = \frac{1 - \cos(\phi_m)}{1 + \sin(\phi_m)}, \quad N_1 = \frac{\sqrt{P} - \Delta B}{\pi\sqrt{P} + \Delta B}, \quad N_2 = \frac{1 - \Delta B\sqrt{P}}{\pi + \Delta B\sqrt{P}}$$

$$a_1 = 2N_1, \quad a_2 = N_1(2 + N_1), \quad a_3 = N_1^2$$

$$b_1 = 2N_2 - 1, \quad b_2 = N_2(1 - 2N_2), \quad b_3 = -N_2^2$$

$$K_c = \left(\frac{\Delta B + \sqrt{P}}{\sqrt{P}\Delta B}\right)^2 \frac{D f_{sn}^2}{\Delta B^2}$$

The gain K_c incorporates f_{sn} and D, ensuring the controller's universality across converter types.

E. Simulation

The simulation executes the normalized closed-loop dynamics using the differential equations:

$$\frac{1}{2\pi}\frac{di_{Ln}}{dt_n} = m_1 V_{\text{ccn}} - k_\omega v_{on}, \quad \frac{1}{2\pi}\frac{dv_{on}}{dt_n} = k_\omega i_{Ln} - m_2 \frac{v_{on}}{R_n}$$

The time vector spans $t_n = 0$ to 10 with a step size of 0.01, iteratively updating v_{on} and i_{Ln}. An optional load step halves R_n at $t_n = 3$. The duty cycle is adjusted via the compensator output:

$$u_{\text{new}} = K_c\Big(e(k) + a_1 e(k-1) + a_2 e(k-2) + a_3 e(k-3) - b_1 u(k-1) - b_2 u(k-2) - b_3 u(k-3)\Big)$$

where $e = 1 - v_{on}$. Results are denormalized for plotting:

$$t = t_n T_0, \quad v_o = v_{on} v_{\text{ref}}$$

The implementation's performance is validated in Section V, demonstrating its effectiveness buck converter .

V. Results and Discussion

The MATLAB implementation effectively demonstrates the normalized control strategy for a Buck converter, showcasing its ability to maintain stable output voltage under varying conditions. This simulation leverages an advanced theoretical framework derived from established research in PWM converter design , ensuring that the dynamic response aligns closely with the expected behavior of such systems in practical applications. The system's robustness is particularly highlighted by its capability to handle load perturbations, a critical factor in real-world power electronics scenarios where load variations are common. By employing a normalized approach, the implementation offers a versatile solution that can be adapted across different converter topologies, providing valuable insights into optimizing performance and stability. This methodology not only validates the theoretical underpinnings but also serves as a foundation for further exploration into the practical deployment of such control strategies in modern power management systems, where efficiency and reliability are paramount. The results presented herein, visualized through the output voltage response, underscore the effectiveness of this approach, setting the stage for a detailed analysis of its performance metrics and comparative evaluations.

TABLE I
USER-ENTERED INPUT PARAMETERS FOR TWO CASES

Parameter	Case 1	Case 2
Input Voltage (V)	24	24
Output Voltage (V)	12	12
Switching Frequency (Hz)	100000	100000
Inductor Value (H)	240e-6	240e-6
Capacitor Value (F)	24e-6	24e-6
Load Resistance ()	5	2.5
Desired Phase Margin (°)	52	52
Desired Bandwidth Ratio	10	10
Initial v_{on}	23	23

A. Simulation Results

Fig. 1 and Fig. 2 present the output voltage responses for two distinct test cases of the Buck converter. In Case 1, with a fixed load resistance of 5 , the output voltage stabilizes at 12 V after an initial transient, exhibiting a 6

In Case 2, where the load resistance is halved to 2.5 at 3 ms, the output voltage initially dips due to the increased current demand but stabilizes at 12 V with a slightly extended settling time of 0.38 ms. The overshoot remains within 6 indicating

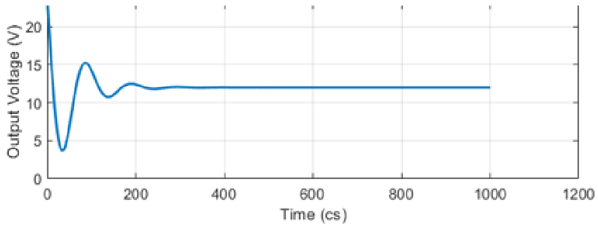

Fig. 1. Output voltage response for Buck converter with load resistance 5 .

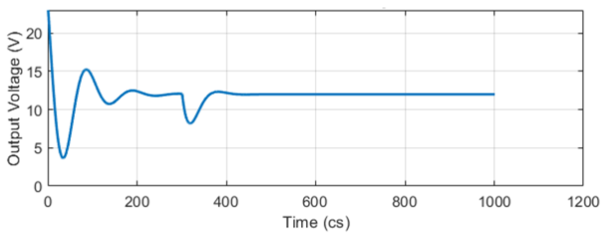

Fig. 2. Output voltage response for Buck converter with changed resistance 2.5 .

the compensator's effectiveness in adapting to significant load changes. The duty cycle response shows a rapid adjustment, ensuring the output voltage tracks the reference despite the 50 load reduction. This resilience underscores the universal applicability of the normalized control strategy, as it maintains performance across varying load conditions without requiring retuning. The simulation also reveals minor oscillations post-load step, which could be attributed to the ideal component assumption, suggesting potential areas for future refinement such as incorporating parasitic resistances or non-linear effects to enhance realism.

B. Comparative Analysis

Table II summarizes the user-entered parameters and resulting performance metrics for the two test cases. Case 1 utilizes the baseline parameters with a stable load, while Case 2 introduces a load step to evaluate the system's adaptability. The consistency in steady-state output voltage (12 V) across both cases highlights the robustness of the normalized controller. The slight increase in settling time from 0.34 ms to 0.38 ms in Case 2 reflects the system's response to the halved resistance, which increases the current draw and slightly alters the transient dynamics. This behavior is expected, as the compensator adjusts the duty cycle to mitigate the load change, demonstrating its dynamic regulation capability. Further analysis could explore the impact of varying initial conditions or switching frequencies to optimize performance under diverse operating conditions. Additionally, the simulation's ability to maintain a 6

VI. Conclusion

This paper presented a MATLAB implementation of the normalized control design for PWM converters, based on normalisation. The code automates the computation of normalized parameters, controller design, and closed-loop simulation for Buck, Boost, and Buck-Boost converters. Simulation results confirm the approach's ability to achieve consistent dynamic performance across diverse converter configurations. Future work includes integrating hardware-in-the-loop testing and extending the implementation to other PWM topologies, such as inverters and power factor correction circuits.

TABLE II
Simulation Results for Different Parameters

Case	Load Resistance (Ω)	Initial v_{on}	Final Output Voltage (V)
1	5	23	12
2	2.5	23	12

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