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Implementation and Calibration of Fractional order PID Controller for DC to DC Boost Convertor

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Abstract- This study focuses on the development of a fractional-order PID controller tailored for a boost converter. Using the values of output capacitance and input inductance, the research derives integer-order PID controller gains that approximate the closed-loop transfer function to a first-order system with a unit DC gain and a specified time constant, τ. The paper introduces a methodology to determine the design parameters for a fractional-order PID controller and describes a discretized control algorithm optimized for DSP implementation. The proposed algorithm is implemented in real-time using a floating-point DSP, with experimental results validating the practical feasibility and enhanced performance of the fractional-order PID controller under various operating conditions. The results also demonstrate its superior performance compared to a conventional integer-order PID controller.

Key Words: EV System, PID control, fractional order system, DC-DC converter.

1. INTRODUCTION

DC-DC converters are widely utilized in various industrial applications, such as power supplies and motor drives, owing to their versatility and efficiency. These converters operate in multiple modes and are modeled using nonlinear, continuous-time dynamical equations. Such equations exhibit complex behaviors, including chaos, bifurcation, periodic patterns, and multiple equilibrium states. The input is typically restricted to discrete values {0, 1} or lies within the interval [0, 1], with the inductor current state constrained to non-negative values. These nonlinear characteristics, coupled with input and state variable constraints, present significant challenges in designing high-performance control systems for DC-DC converters.

Moreover, variations in parameters or load conditions can adversely affect system performance. To address these challenges, advanced control strategies for DC-DC converters have been developed. Model Predictive Control (MPC) is one such approach, where the control input is optimized by minimizing a cost function that balances multiple performance criteria through carefully chosen weighting factors as shown in Figure 1. MPC offers the advantage of naturally incorporating input and state constraints into its design process.

Nonlinear control techniques have also been explored to manage the inherent nonlinearities and constraints. Sliding mode control, in particular, has demonstrated robust performance for uncertain nonlinear systems by effectively managing bounded uncertainties and enhancing feedback robustness. In renewable energy systems and electric vehicles, DC-DC boost converters play a crucial role by increasing the voltage from sources like photovoltaic (PV) arrays to levels suitable for charging batteries. This ensures efficient energy transfer while minimizing conversion losses. Integrating boost converters with advanced controllers, such as Proportional-Integral-Derivative (PID) controllers, enhances energy harvesting efficiency and overall system reliability as shown in Figure 2. This synergy facilitates the effective utilization of solar energy in powering electric vehicles while offering benefits such as reduced energy wastage, lower environmental impact, and improved system stability. Designing controllers for boost converters necessitates addressing load variations and mitigating transient effects to achieve stable power conversion. Emphasizing system components, such as state-space analysis and addressing characteristics like Right Half Plane Zero (RHPZ) dynamics, ensures optimal performance. Applications of boost converters are particularly prevalent in solar and wind energy systems, as well as electric vehicles, where achieving higher output voltages than the input is essential for system functionality.

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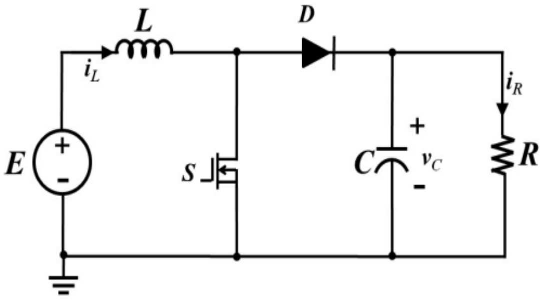

Figure 1: Topology of boost DC-DC converter.

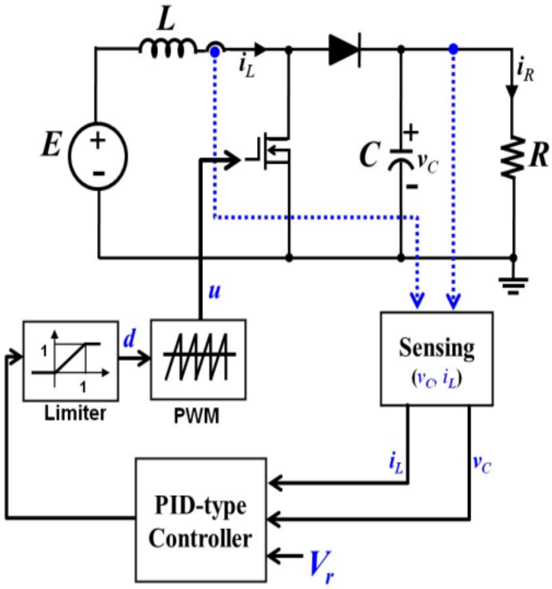

Figure 2: Block diagram of Pid controller for boost DC-DC converter.

1.1 Research Objective

The primary objective of this research is to enhance the stability and efficiency of Boost Converter designs for EV by addressing challenges related to load variations and transient responses. The specific goals include:

Stability Improvement: Investigate methods to enhance the stability of Boost Converters, particularly under varying load conditions, to ensure consistent and reliable performance.

Transient Response Reduction: Develop strategies to minimize transient responses in Boost Converters, especially during abrupt changes in load or input voltage, aiming for faster recovery times.

Controller Optimization: Design and optimize control algorithms, with a focus on Integer Order PID to regulate the Boost Converter under dynamic conditions.

Load Variation Management: Propose innovative techniques for effective load variation management, allowing the Boost Converter to maintain stable output voltage levels with minimal deviations.

2. METHODOLOGY

Mathematical Modelling: Utilize simulation tools such as Simulink to model Boost Converter for vehicle dynamics in different operational modes, considering continuous and discontinuous modes.

Controller Design: Implement Integer Order PID controllers and FOPID controllers, systematically tuning and optimizing their parameters using established methods like Ziegler-Nichols or optimization algorithms.

Simulation Studies: Conduct extensive simulation studies to analyse the performance of Boost Converters with different controllers under various scenarios, including load variations and input voltage changes.

Optimal Tuning: Investigate optimal tuning parameters for controllers, considering both integer and fractional-order approaches, to achieve the best compromise between stability and dynamic response.

Case Studies: Present case studies illustrating the behaviours of the Enhanced Stability Boost Converter under different operating conditions, showcasing its robustness and efficiency.

Documentation: Compile research findings, analyses, and outcomes into a comprehensive report, providing a detailed understanding of the Enhanced Stability Boost Converter design.

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3. Model Description and Problem Formulation

A boost DC-DC converter of Figure 1 can be represented by the following nonlinear continuous-time dynamic equation.

$$iL = -\frac{1}{L}\text{vC}\,\zeta + \frac{1}{L}\text{vC u} + \frac{E}{L}\zeta$$

$$\text{v}^{\cdot}\text{C} = \frac{1}{C}\text{iL}\zeta - \frac{1}{RC}\text{vC} - \frac{1}{C}\text{iLu}$$

where iL, iR, vC , u are the input inductor current, the output capacitor voltage, the output load resistor current, the discrete-valued control input confined in the set {0, 1}, and E, R, L, C represent the external source voltage value, the output load resistance, the inductance of the input circuit, the capacitance of the output filter, respectively. S and D of Figure 2 are an active controllable switch and a diode. The symbol ζ means the auxiliary binary variable defined by

ζ= 1 If u = 1, or u = 0 and iL > 0
ζ= 0 If u = 0 and iL = 0

It should be noted that the converter operates in continuous conduction mode in case of ζ = 1 whereas the converter is in discontinuous conduction mode when ζ = 0. This paper will use the following assumptions:
A1 : iL and vC are available.
A2 : The inductor current can never be zero, i.e. the converter is in continuous conduction mode.

4. Result and Discussion with Simulink

4.1 Boost converter parameter

Boost converter parameter for simulation source voltage E=50V, 25V sampling frequency 50 kHz, load resistance 100$\boldsymbol{\Omega}$, consider the load is electrical vehicle, Input inductance 300$\boldsymbol{\mu}$H, Output capacitance 300$\boldsymbol{\mu}$F and Proportional gain K_P=.04, Integral gain K_I=29, Derivative gain K_D=4e^{-6}

4.2 Open-loop control of a boost converter in Simulink

Designing the open-loop control of a boost converter in Simulink involves creating a model that represents the behaviour of the boost converter without feedback control.
Here are the general steps to design the open-loop control of a boost converter using Simulink as shown in Figure 3 and Figure 4:

Step 1: Create a New Simulink Model
Open MATLAB and Simulink.
In Simulink, create a new model.

Step 2: Add Components to the Model
Drag and drop the necessary blocks from the Simulink Library Browser onto the model canvas.
Voltage Source (Vin): Representing the input voltage.
Inductor (L): Representing the boost inductor.
Switch (S): Representing the power switch (MOSFET or BJT).
Diode (D): Representing the diode.
Capacitor (C): Representing the output capacitor.
Load (R): Representing the output load.

Step 3: Connect the Components
Connect the components according to the boost converter circuit topology.
Pay attention to the direction of current flow and voltage polarities.

Step 4: Define Component Parameters
Double-click on each component to set its parameters.
Specify the values for the input voltage, inductor value, capacitor value, etc.

Step 5: Add Control Signals
Include a signal source to control the switch.
For open-loop, you might use a constant signal or a simple waveform generator to control the switch.

Step 6: Simulate the Model
Configure the simulation parameters (e.g., simulation time, solver options).
Run the simulation to observe the behaviour of the boost converter without feedback.

Step 7: Analyse Results
Observe the waveforms of key variables such as input voltage, inductor current, output voltage, and switch control signal.
Check if the boost converter operates as expected in open-loop conditions.

Step 8: Parameter Tuning (Optional)

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If needed, adjust component values and control signals to optimize the performance of the boost converter.

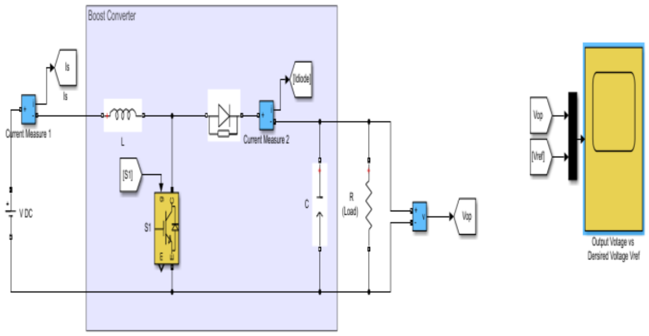

Figure 3: Open loop boost converter design

4.3 Closed Loop of Boost Converter Design

Model Setup: Create a Simulink model with a boost converter circuit.
Feedback Controller: Integrate a Proportional-Integral (PI) controller to regulate output.
Error Sensing: Add error calculation by comparing the reference and output voltages.
Comparator: Utilize a comparator to generate an error signal for the controller.
PWM Signal Generation: Develop a Pulse Width Modulation (PWM) signal to control the switch.
Simulation: Run simulations to validate closed-loop performance.
Tuning: Adjust PI controller parameters for optimal response.
Analysis: Evaluate the closed-loop boost converter's stability and transient response.

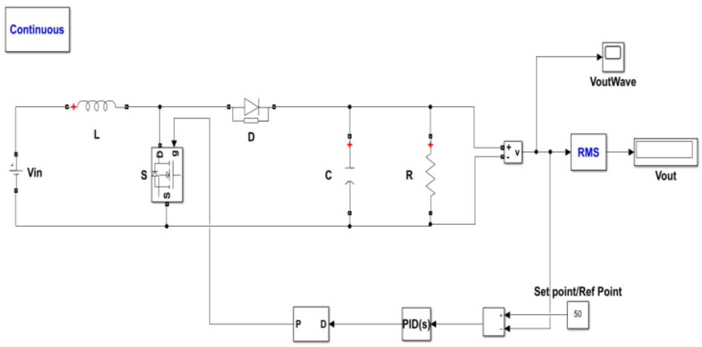

Figure 4: Closed loop boost converter design

Considering Figure 3 and Figure 4, during the double-loop DC-DC boost converter design, the output voltage and inductor current have to be measured. Therefore, the open-loop transfer functions ‘‘G1(s)’’ and ‘‘G2(s)’’ are derived, respectively, in the following equations
The transfer function G1(s) between inductor current and duty ratio.

$$\boldsymbol{G_1(s) = \frac{i_L(s)}{d(s)} = \frac{VoCs + 2(1-D)IL}{LCs^2 + \frac{L}{R}s + (1-D)^2}}$$

$$G_2(s) = \frac{\widetilde{v_u}(s)}{\widetilde{i_L}(s)} = \frac{(1-D)V_0 - LILS}{VoCs + 2(1-D)IL}$$

By using this formula, we generate double loop PI controller.

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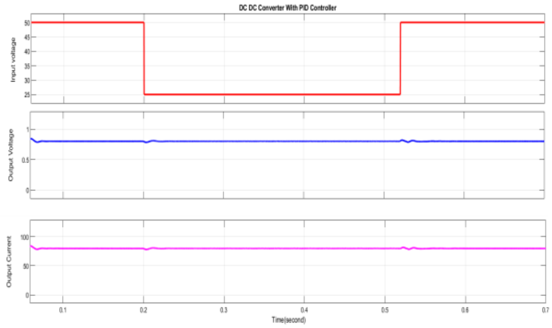

Figure 5: Simulink Result of Boost Converter Design with PID Controller.

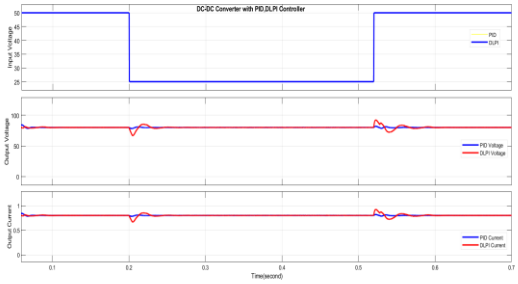

Figure 6: Simulink Result of Boost Converter Design with PID and DLPI Controller

In Figure 5 and Figure 6 voltage change 50v to 25v and 25v to 50v and that instant we checked transient Response got PID more accurate. By simulation performance demonstrates the effectiveness of the PID control algorithm in enhancing the efficiency and stability of boost DC-DC converters in electric vehicles. we introduced and validated a PID control algorithm tailored for a boost DC-DC converter in electric vehicles. Through simulation, we examined the performance of the system when the source of boost converter voltages changed abruptly, while also subjecting it to instant transient changes in electrical vehicle load. Our findings indicate that the PID controller demonstrated greater efficiency compared to the double-loop PI (DLPI) controller under these dynamic conditions. By mitigating the impact of voltage and load variations, the PID controller contributes to the seamless integration of renewable energy sources into electric vehicle systems, ultimately advancing the sustainability and reliability of future transportation technologies.

CONCLUSION

In this study, we developed and validated a PID control algorithm specifically designed for a boost DC-DC converter used in electric vehicles. By combining simulation and experimental analysis, we demonstrated the efficiency and practicality of the proposed control system under various operational conditions. The experimental results consistently highlighted the advantages of the PID controller, including reduced overshoot and faster recovery times, particularly in response to sudden load or input voltage fluctuations. Simulation results further confirmed the reliability and robustness of the algorithm, reinforcing its suitability for real-world applications. The observed enhancements in overshoot and recovery times are critical performance indicators, reflecting improved stability and responsiveness of the control system. Additionally, the versatility of PID controllers was emphasized, with suggestions that similar approaches could be adapted for buck and buck-boost converters, showcasing the algorithm's potential for broader applications in DC-DC converter systems. A comparative analysis revealed that the PID controller outperformed a traditional double-loop PI controller, particularly under dynamic conditions such as abrupt changes in load or input voltage. This robustness is especially important in electric vehicles, where rapidly changing operating conditions demand precise and efficient control to maintain optimal performance. Overall, this research not only presented an optimized PID control algorithm for boost DC-DC converters but also provided empirical evidence of its superiority over conventional controllers in handling dynamic variations. Furthermore, the findings underscore the potential to extend this approach to other converter types, broadening its applicability in power electronics and enhancing its relevance in the evolving landscape of electric vehicles.

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