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Digital Simulation of Buck Converter with Closed Loop Control Method

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Abstract

This paper presents the digital simulation of a closed-loop buck converter using an Artificial Intelligence (AI)-based control method for improved voltage regulation and dynamic performance. The converter is modelled using a mathematical approach and controlled through an ANN-based controller with PWM switching. Python-based simulation is carried out to analyse input voltage, output voltage, inductor current, and switching waveforms. The results demonstrate that the proposed AI controller provides faster response, reduced ripple, and enhanced stability compared with conventional control methods, making it suitable for advanced power electronic applications.

Keywords: Buck Converter, Artificial Intelligence, Artificial Neural Network, Closed-Loop Control, Digital Simulation, PWM, DC-DC Converter, Python Simulation, Intelligent Control, Power Electronics.

1. Introduction

Power electronic converters play a crucial role in modern electrical and electronic systems. The growing utilization of renewable energy systems, electric vehicles, battery management systems, telecommunications equipment, industrial automation, aerospace electronics, and portable consumer devices has significantly increased the demand for highly efficient power conversion techniques. Among various converter topologies, the DC-DC buck converter is one of the most extensively used converters because it provides regulated output voltage lower than the input voltage with high efficiency and compact size. A buck converter operates by rapidly switching a semiconductor device, generally a MOSFET, to transfer energy from the source to the load through an inductor-capacitor filtering network. By varying the duty ratio of the switching pulse, the average output voltage can be controlled effectively. Due to its simplicity, low cost, and high conversion efficiency, the buck converter has become an indispensable component in modern power supplies.

Although open-loop operation can provide basic voltage conversion, practical applications require accurate voltage regulation despite variations in load, input voltage, and component parameters. Therefore, closed-loop control systems are widely adopted in buck converters. Conventional controllers such as Proportional (P), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID) controllers are frequently employed because they are simple and computationally efficient. However, these controllers are designed based on linear approximations and often struggle to maintain optimal performance under nonlinear operating conditions. Power electronic converters inherently exhibit nonlinear characteristics due to switching actions, parameter uncertainties, and changing operating conditions. Variations in load resistance, input supply fluctuations, temperature changes, and component ageing can degrade the performance of conventional controllers. As a result, modern research has focused on intelligent control techniques capable of adapting to varying conditions without requiring accurate mathematical models.

Artificial Intelligence (AI) has emerged as a powerful tool for solving complex control problems. AI techniques such as Artificial Neural Networks (ANN), Fuzzy Logic Controllers (FLC), Reinforcement Learning (RL), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) possess strong nonlinear approximation capabilities. These methods can learn system behaviour from data and provide improved dynamic response compared to classical controllers. Among various AI techniques, Artificial Neural Networks are particularly attractive because they can model nonlinear relationships between input variables and control actions through supervised learning. Once trained, ANN controllers can generate appropriate control signals rapidly and accurately. In DC-DC converter applications, ANN-based controllers have demonstrated reduced settling time, improved voltage regulation, lower overshoot, and enhanced robustness against disturbances.

Digital control has further revolutionized power converter design. The availability of high-speed microcontrollers, DSPs, and FPGAs has enabled sophisticated control algorithms to be implemented in real-time. Digital controllers offer flexibility, programmability, repeatability, and easier integration with AI algorithms compared to analog control circuits. Furthermore, digital simulations allow rapid testing and validation of control strategies before hardware implementation. Python has become an increasingly popular platform for power electronics research because of its extensive scientific computing libraries such as NumPy, SciPy, TensorFlow, Scikit-Learn, and Matplotlib. These libraries provide efficient numerical computation, machine learning capability, and advanced visualization tools, making Python an excellent environment for digital simulation of intelligent power converters. This paper investigates the digital simulation of a buck converter operating under closed-loop AI control. The converter is modelled mathematically in Continuous Conduction Mode and regulated using an Artificial Neural Network controller. The ANN controller continuously estimates the required duty cycle based on voltage error and system conditions. A digital PWM mechanism generates switching pulses that drive the converter. Simulation studies are performed using Python to analyse the transient and steady-state behaviour of the system.

2. Analysis of the AI-Controlled Buck Converter

The system consists of a DC-DC buck converter integrated with a closed-loop AI-based control technique. The converter reduces the input DC voltage to a regulated lower output voltage by controlling the switching duty ratio of the power MOSFET. The complete system consists of a power stage, voltage sensing unit, error calculation block, AI controller, PWM generator, and switching device. The performance of the converter is analysed under steady-state and dynamic operating conditions. The converter is as shown in Fig.1.

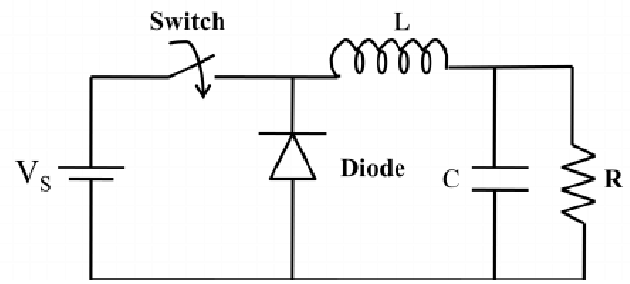


Fig.1 Buck Converter

Buck Converter Operating Principle

A buck converter operates using two switching states:

ON State (MOSFET ON):

During the ON period, the input source is connected to the inductor through the MOSFET. The inductor stores energy and its current increases. The diode remains reverse biased, and energy is supplied to the load through the inductor-capacitor network.

The inductor voltage is:

$$V_L = V_{in} - V_o$$

The inductor current variation is:

$$\Delta I_L = \frac{(V_{in} - V_o)DT_s}{L}$$

where:

- V_{in}= input voltage
- V_o= output voltage
- D= duty ratio
- T_s= switching period
- L= inductance value

OFF State (MOSFET OFF):

During the OFF period, the stored energy in the inductor is transferred to the load through the freewheeling diode. The inductor current decreases while maintaining continuous energy flow.

The inductor voltage becomes:

$$V_L = -V_o$$

The current ripple is:

$$\Delta I_L = \frac{V_o(1 - D)T_s}{L}$$

Voltage Conversion Ratio

For an ideal buck converter operating in Continuous Conduction Mode (CCM), the average output voltage is controlled by the duty ratio.

$$V_o = DV_{in}$$

Therefore,

$$D = \frac{V_o}{V_{in}}$$

Mathematical Model of Buck Converter

The state variables are selected as:

- Inductor current (i_L)
- Capacitor voltage (V_o)

The state-space equations are:

$$\frac{di_L}{dt} = \frac{V_{in}D - V_o}{L}$$

$$\frac{dV_o}{dt} = \frac{i_L - \frac{V_o}{R}}{C}$$

where:

- R= load resistance
- C= output capacitance

These equations describe the dynamic behaviour of the converter and are used for digital simulation.

Closed Loop Control Analysis

The closed-loop control system continuously compares the reference voltage with the actual output voltage.

The error signal is:

$$e(t) = V_{ref} - V_o(t)$$

This error is provided to the AI controller.

The controller generates the required duty cycle:

$$D = f(e, \Delta e)$$

where:

- e = voltage error
- Δe= change in error

The generated duty cycle controls the PWM switching signal applied to the MOSFET.

The key waveforms of the converter operation is as shown in Fig.2.

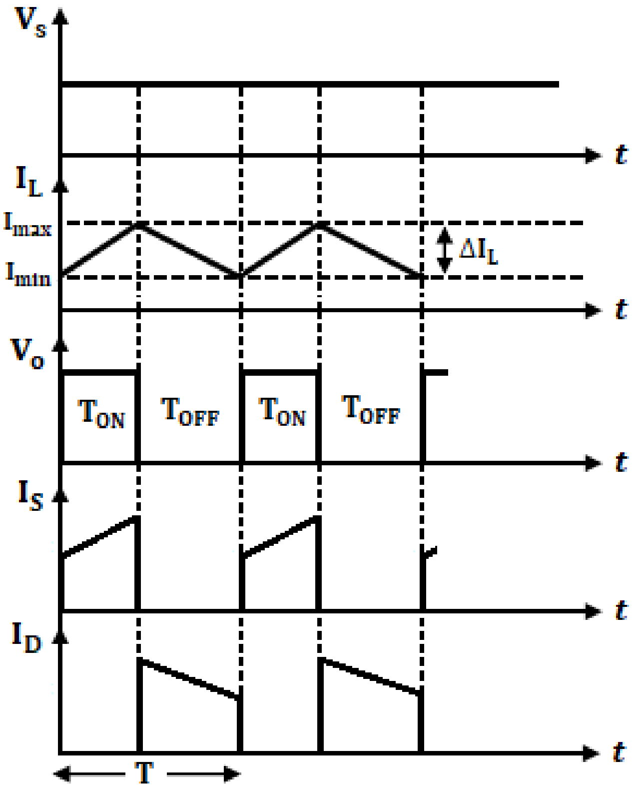
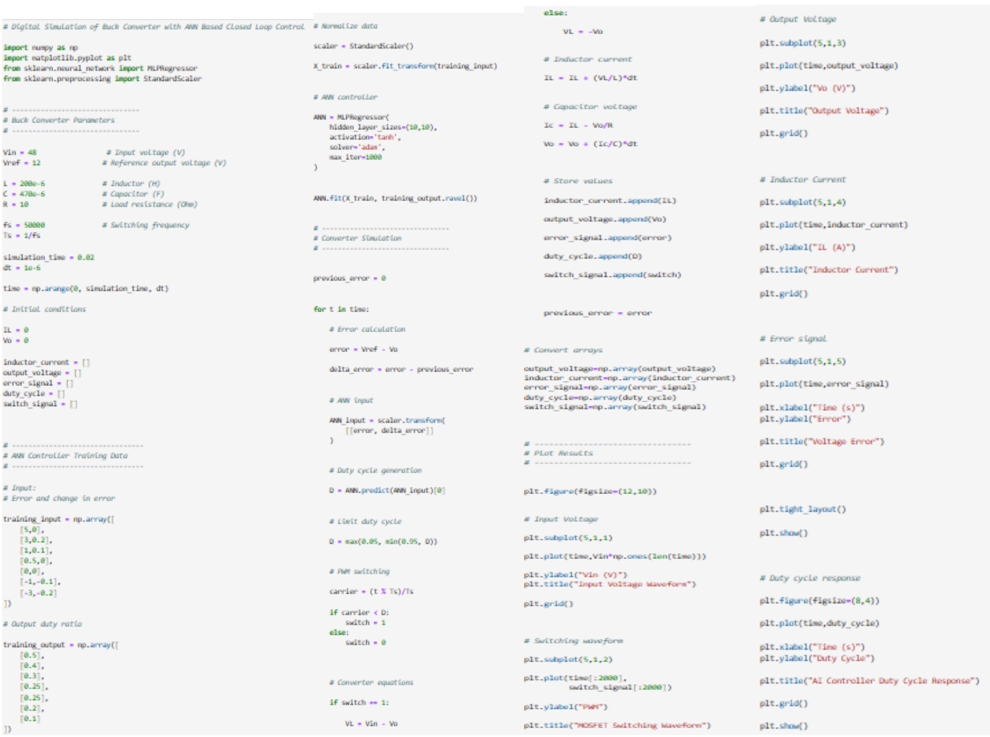


Fig.2. Key Waveforms

The python program code for this is as shown in Fig.3



```python
# Digital Simulation of Buck Converter with ANN Based Closed Loop Control

import numpy as np
import matplotlib.pyplot as plt
from sklearn.neural_network import MLPRegressor
from sklearn.preprocessing import StandardScaler


# -------------------------------
# Buck Converter Parameters
# -------------------------------

Vin = 48                # Input voltage (V)
Vref = 12               # Reference output voltage (V)

L = 200e-6              # Inductor (H)
C = 470e-6              # Capacitor (F)
R = 10                  # Load resistance (Ohm)

fs = 50000              # Switching frequency
Ts = 1/fs

simulation_time = 0.02
dt = 1e-6

time = np.arange(0, simulation_time, dt)

# Initial conditions

IL = 0
Vo = 0

inductor_current = []
output_voltage = []
error_signal = []
duty_cycle = []
switch_signal = []


# -------------------------------
# ANN Controller Training Data
# -------------------------------

# Input:
# Error and change in error

training_input = np.array([
    [5,0],
    [3,0.2],
    [1,0.1],
    [0.5,0],
    [0,0],
    [-1,-0.1],
    [-3,-0.2]
])

# Output duty ratio

training_output = np.array([
    [0.5],
    [0.4],
    [0.3],
    [0.25],
    [0.25],
    [0.2],
    [0.1]
])
# Normalize data

scaler = StandardScaler()

X_train = scaler.fit_transform(training_input)


# ANN controller

ANN = MLPRegressor(
    hidden_layer_sizes=(10,10),
    activation='tanh',
    solver='adam',
    max_iter=1000
)


ANN.fit(X_train, training_output.ravel())


# -------------------------------
# Converter Simulation
# -------------------------------


previous_error = 0


for t in time:

    # Error calculation

    error = Vref - Vo

    delta_error = error - previous_error


    # ANN input

    ANN_input = scaler.transform(
        [[error, delta_error]]
    )


    # Duty cycle generation

    D = ANN.predict(ANN_input)[0]


    # Limit duty cycle

    D = max(0.05, min(0.95, D))


    # PWM switching

    carrier = (t % Ts)/Ts

    if carrier < D:
        switch = 1
    else:
        switch = 0


    # Converter equations

    if switch == 1:

        VL = Vin - Vo
    else:

        VL = -Vo

    # Inductor current

    IL = IL + (VL/L)*dt

    # Capacitor voltage

    Ic = IL - Vo/R

    Vo = Vo + (Ic/C)*dt


    # Store values

    inductor_current.append(IL)

    output_voltage.append(Vo)

    error_signal.append(error)

    duty_cycle.append(D)

    switch_signal.append(switch)


    previous_error = error


# Convert arrays

output_voltage=np.array(output_voltage)
inductor_current=np.array(inductor_current)
error_signal=np.array(error_signal)
duty_cycle=np.array(duty_cycle)
switch_signal=np.array(switch_signal)


# -------------------------------
# Plot Results
# -------------------------------


plt.figure(figsize=(12,10))

# Input Voltage

plt.subplot(5,1,1)

plt.plot(time,Vin*np.ones(len(time)))

plt.ylabel("Vin (V)")
plt.title("Input Voltage Waveform")

plt.grid()


# Switching waveform

plt.subplot(5,1,2)

plt.plot(time[:2000],
         switch_signal[:2000])

plt.ylabel("PWM")

plt.title("MOSFET Switching Waveform")
# Output Voltage

plt.subplot(5,1,3)

plt.plot(time,output_voltage)

plt.ylabel("Vo (V)")

plt.title("Output Voltage")

plt.grid()


# Inductor Current

plt.subplot(5,1,4)

plt.plot(time,inductor_current)

plt.ylabel("IL (A)")

plt.title("Inductor Current")

plt.grid()


# Error signal

plt.subplot(5,1,5)

plt.plot(time,error_signal)

plt.xlabel("Time (s)")
plt.ylabel("Error")

plt.title("Voltage Error")

plt.grid()


plt.tight_layout()

plt.show()


# Duty cycle response

plt.figure(figsize=(8,4))

plt.plot(time,duty_cycle)

plt.xlabel("Time (s)")
plt.ylabel("Duty Cycle")

plt.title("AI Controller Duty Cycle Response")

plt.grid()

plt.show()
```

Fig.3 Program for the Closed control of Buck Converter

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The input, pulse and output waveforms are as shown in Fig. 4, Fig.5 and Fig.6

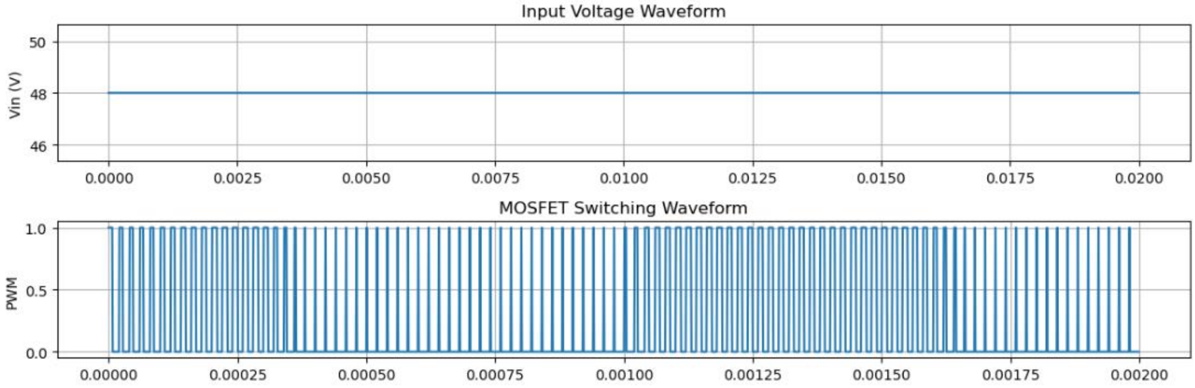

Fig.4 Input and Pulse

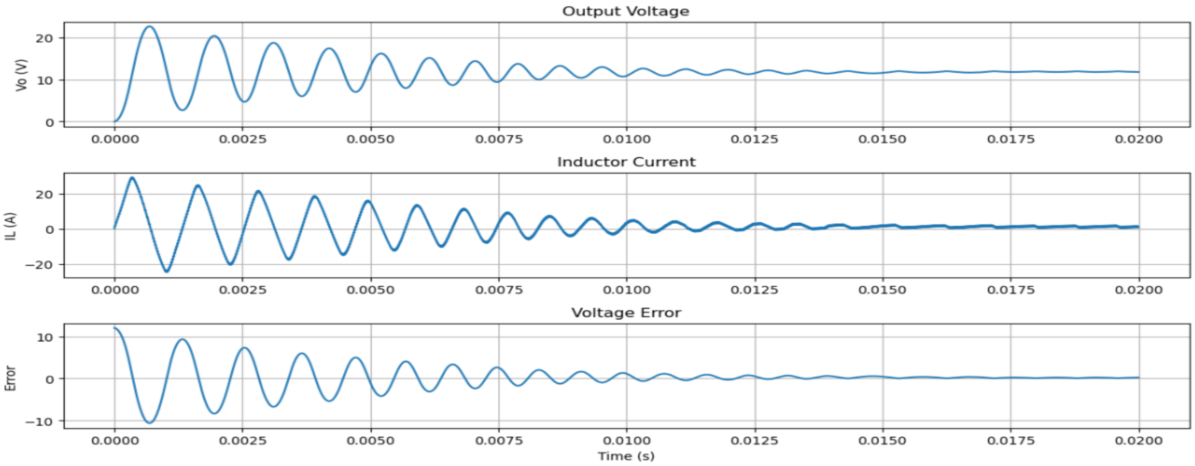

Fig.5 Output voltage, Inductor current and error

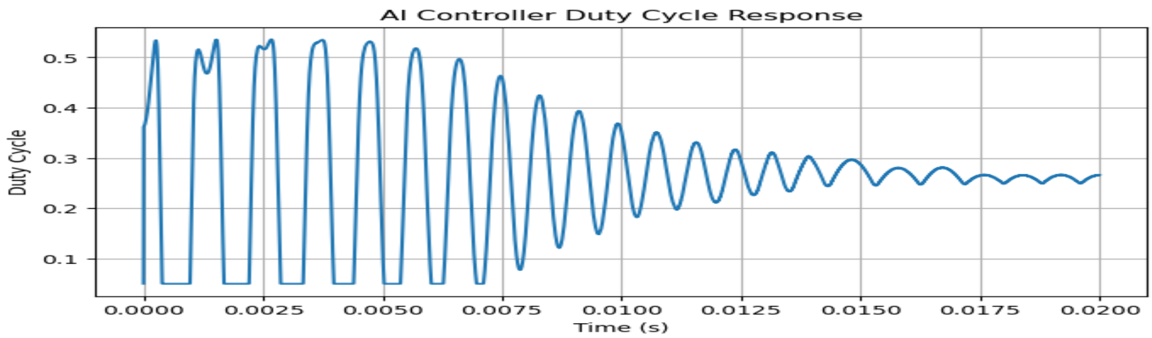

Fig6. AI controlled Duty cycle response

Conclusion:

The closed loop controller was employed to generate an adaptive PWM duty cycle for maintaining the desired output voltage. The simulation results demonstrated that the proposed AI-controlled buck converter provides improved voltage regulation, faster dynamic response, reduced output voltage ripple, and enhanced stability under varying operating conditions. The generated input voltage, switching pulse, output voltage, and inductor current waveforms verified the effective operation of the converter in Continuous Conduction Mode (CCM). The AI controller successfully minimized the voltage error by continuously adjusting the switching duty ratio according to system requirements. The proposed intelligent control method offers better performance compared with conventional fixed-parameter controllers and provides a promising solution for advanced power electronic applications such as renewable energy systems, electric vehicles, and smart power management systems.

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