Development of Dc-Dc Buck Converter for Cathodic Protection Applications

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***Abstract*: Cathodic protection (CP) is crucial for preventing corrosion in metal structures like pipelines, storage tanks, and marine installations, where a stable DC power supply is vital for long-term effectiveness. This paper presents the design of a DC-DC buck converter specifically developed for CP applications. The converter steps down a 200V input to a regulated 50V output using an buck converter, ensuring low ripple and high efficiency. At the heart of the design is a Pulse Width Modulation (PWM)-controlled buck topology with a high-speed MOSFET for switching and feedback control to maintain constant voltage under varying load conditions. The buck converter smooths the output voltage, eliminating noise and providing stable, noise-free DC power, which is essential for reliable corrosion protection in CP systems. The converter achieves over 90% efficiency, reducing power losses while maintaining steady output, making it ideal for high-voltage CP applications. Its rugged design ensures reliable performance in harsh environments, including underground and marine settings, where CP systems are commonly used. Overall, this DC-DC buck converter offers a compact, efficient, and reliable power conversion solution, helping to extend the lifespan of metal structures exposed to corrosive environments while reducing maintenance costs. By providing a stable, regulated DC output, the converter enhances the overall effectiveness and durability of CP systems, ensuring long-term corrosion resistance and protection.**

***Keywords*: DC-DC Converter, Buck Converter, Cathodic Protection, Power Electronics, Corrosion Prevention.**

1. Introduction

Corrosion is a major concern for metal structures exposed to harsh environments such as seawater, underground soil, and industrial atmospheres. Cathodic protection (CP) is a well-established technique for mitigating corrosion using either sacrificial anodes or impressed current cathodic protection (ICCP) systems.[3] ICCP requires a stable and efficient DC power source, making power electronics an integral component of corrosion prevention strategies.

Traditional CP systems rely on transformer-rectifier units, which are often bulky and inefficient. A DC-DC buck converter offers a more efficient, compact, and precise voltage regulation alternative.[1] This paper presents the development and performance evaluation of a buck converter designed specifically for CP applications.

2. Methodology

The proposed DC-DC buck converter is designed to step down a 200V DC input to a regulated 50V DC output. The system architecture includes:

- *Switching Circuit*: A high-speed MOSFET controlled by PWM ensures efficient switching.
- *Inductor and Capacitor Design*: Optimized for minimal ripple and high efficiency.
- *Feedback Control*: A closed-loop control system maintains voltage stability under varying load conditions.
- *Simulation Setup*: MATLAB/Simulink is used for performance analysis before hardware implementation.

3. Topology

A. Working of Interleaved Buck Converter

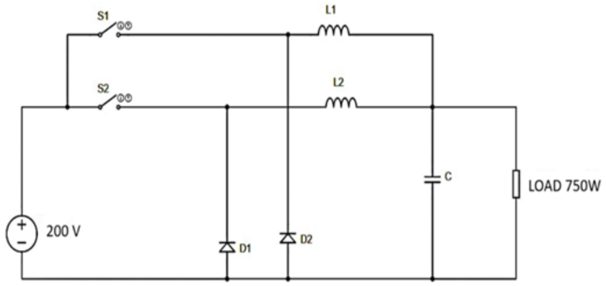

Fig. 1. Interleaved Buck Converter

1) Mode 1: Switch Q1 Turns ON, Q2 Turns OFF

In Mode 1, switch S1 is activated by applying a gate pulse, while switch S2 remains off. Diode D1 is reverse biased while diode D2 is forward biased. As a result, current flows through S1, inductor L1, and the load, causing the current in L1 to rise as long as S1 remains on. Meanwhile, the current in inductor L2 decreases linearly during this period.

2) Mode 2: Both Switch Q1 and Q2 Turns OFF

Since the Interleaved Boost Converter (IBC) operates with a duty cycle below 0.5, both switches remain OFF in this mode. During this time, diodes D1 and D2 conduct. The corresponding equivalent circuit is shown in Fig.4 The energy stored in inductors L1 and L2 is transferred to the load via the forward-biased diodes, causing the currents iL1 and iL2 to decrease linearly.

3) *Mode 3: Both Switch Q1 and Q2 Turns ON*

During T3, switch Q2 is turned on while Q1 is turned off, as shown in the equivalent circuit. When Q2 is activated, inductor L2 gets charged, whereas inductor L1 discharges its stored energy to the load due to Q1 being off.

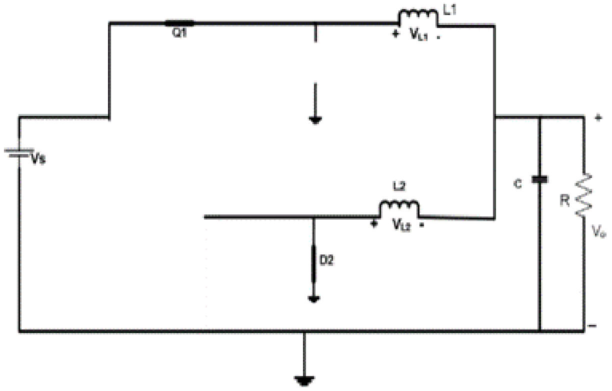

Fig. 2. Equivalent circuit of buck converter -Mode 1

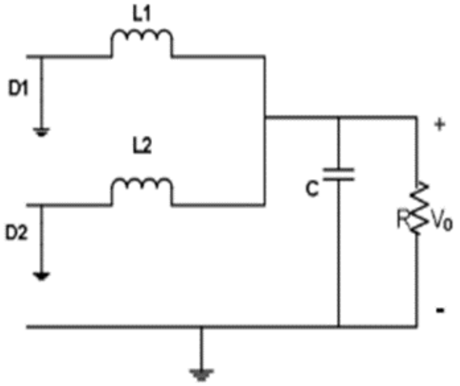

Fig. 3. Equivalent circuit of buck converter-Mode2

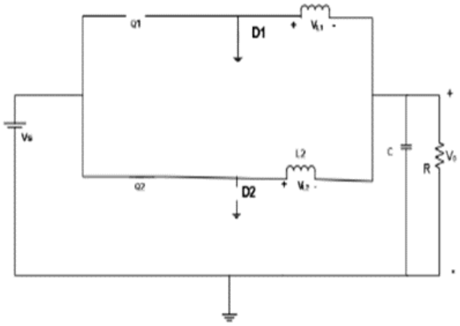

Fig. 4. Equivalent circuit of buck converter-Mode 3

B. *Mode 4: The Operating Mode is Same as Mode 2*

The given waveform represents the inductor current characteristics of an Interleaved Buck Converter (IBC), illustrating the switching sequence of Q1 and Q2 and their impact on inductor currents iL1 and iL2. The first graph shows the gate pulses for Q1 and Q2, which operate in an interleaved manner with a phase shift. When Q1 is ON (T1), inductor L1 charges, causing iL1 to increase, while L2 discharges, making iL2 decrease. Conversely, when Q2 is ON (T3), L2 charges, increasing iL2, while L1 discharges, decreasing iL1. This alternating pattern ensures that at least one inductor is always supplying current to the load, maintaining a continuous power flow. The triangular shape of the inductor currents results from the charging and discharging cycles of each inductor.[6]

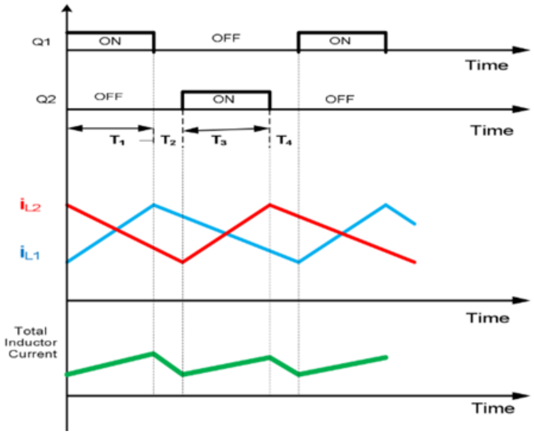

Fig. 5. Inductor current waveform

The third graph represents the total inductor current (iL1 + iL2), which exhibits a lower ripple compared to a single inductor buck converter. Since the two inductors share the current load, the overall current ripple is minimized, improving efficiency and reducing stress on components. This interleaved operation helps achieve better thermal performance, lower electromagnetic interference (EMI), and improved output voltage regulation, making IBCs ideal for high-power applications requiring smooth and efficient power conversion.

C. *Design of Buck Converter*

The design of the buck converter is critical in ensuring efficient voltage step-down while maintaining the required current for cathodic protection. Here, the design is done in such a way that a prototype of the original model is being implemented, due to design limitations of the original model, as high rated inductors will be needed which causes saturation leading to power losses so here by converting DC voltage (20V) to a lower level (5V), the buck converter enables precise control over the protection current.Key design considerations include selecting appropriate components for switching frequency, efficiency, and thermal management. A well-designed buck converter enhances system reliability, ensuring optimal protection for metal structures while minimizing power losses and operational costs.

$$V_{in} = 20V \quad V_O = 5V \quad F_S = 25KHz$$

Duty Cycle, 2D = $\frac{2\times T_{on}}{T}$

Inductance , $L = \frac{(Vin-Vo)D}{\Delta Il\times 2\times Fs} = 750\mu F = 3.3\mu F$

$$\text{Capacitance, } C = \frac{(1-2)D}{8L(\frac{\Delta Vo}{Vo})\times 2Fs^2}$$

$$\text{Load Resistance, } R = \frac{V_0}{I_0} = 10\ \Omega$$

4. Simulation and Results

A. Simulation Circuit

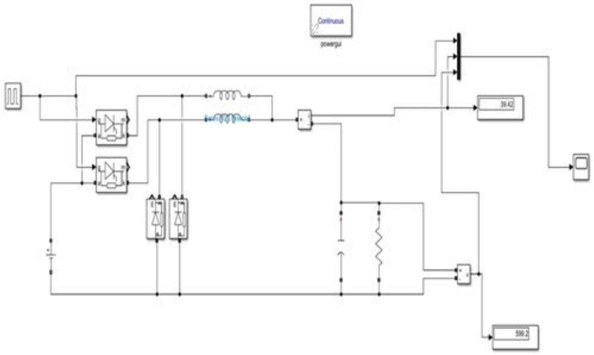

Fig. 6. MATLAB circuit

A MATLAB Simulink model of a buck converter circuit simulates the step-down con version of DC voltage, making it ideal for power electronics applications. The model typically includes components such as a power source, MOSFET switch, diode, inductor, capacitor, and load. It enables the analysis of the converter's behavior, including output voltage regulation, switching dynamics, and current waveforms. Simulink's graphical environment allows for easy visualization and tuning of system parameters, helping engineers design and optimize the buck converter's performance effectively.

B. Simulation Result

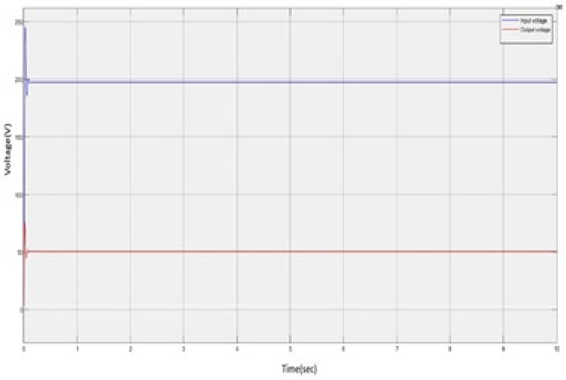

Fig. 7. Simulation result

Simulink model of a buck converter efficiently reduces a 200V DC input to a stable 50V DC output, demonstrating effective voltage regulation with minimal ripple. A MOSFET is employed for high-speed switching, controlling energy transfer through an inductor. This switching mechanism enables the converter to periodically store energy in the inductor and release it at a lower voltage to the load. The inductor current follows a sawtooth waveform, while the output capacitor smooths the voltage, minimizing fluctuations and ensuring a steady 50V DC output.

The Pulse Width Modulation (PWM) signal regulates the MOSFET's duty cycle, adjusting the on-off ratio to achieve the required output voltage. Here, the duty cycle is tuned to create an approximate 4:1 step-down ratio, converting 200V to 50V. Throughout the simulation, the converter consistently maintains the target voltage with minimal ripple, improving power quality and stability. The inductor and load currents behave as expected, confirming the converter's effectiveness. Additionally, the simulation validates that modifying the duty cycle allows output voltage adjustment, as demonstrated when stepping the input down from 200V to 40V.

Table 1
Simulation parameters

Parameters	Values
Input Voltage	20
Frequency	25KHz
Load Current	0.1
Inductance	750 µH
Capacitance	3.3 µF
Load Resistance	10Ω

The given graph represents the input and output voltage waveforms of an Interleaved Buck Converter over a simulation period of 10 seconds. The blue line corresponds to the input voltage, which starts with a small transient and then stabilizes at 200V, indicating a steady DC supply. The red line represents the output voltage, which also exhibits an initial transient but quickly settles at approximately 50V. Since the circuit is a buck converter, it steps down the input voltage, and based on the observed output, the duty cycle of the converter is estimated to be around 25%. The small oscillations at the start are due to transient effects, including inductor charging and switching dynamics, but the system quickly stabilizes, demonstrating effective voltage regulation. The stable output suggests that the converter operates efficiently, maintaining a smooth DC output suitable for a 750W load. This confirms the proper functioning of the converter, with well-tuned control and filtering components ensuring minimal voltage ripples and steady-state operation.

5. Hardware Prototype and Results

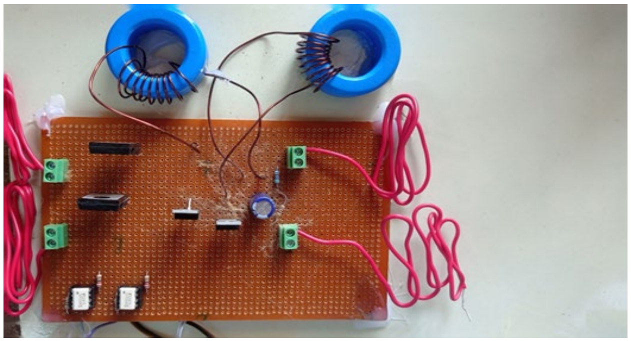

Fig. 8. Hardware circuit

A. Hardware Model

The hardware model shown in the image corresponds to the interleaved buck converter circuit depicted in the schematic diagram. The setup consists of multiple sections: the control circuit, driver circuit, power circuit, and passive components.

1) The control circuit, seen on the left side of the hardware model, features a DSPIC30F2010 microcontroller. This microcontroller is responsible for generating the necessary PWM (Pulse Width Modulation) signals required for driving the MOSFET switches (IRFP250) in the interleaved buck converter. The microcontroller operates at a specific clock frequency, which is stabilized using a crystal oscillator (6.144 MHz) along with capacitors (22 pF each) for precise timing.
2) The driver circuit, located adjacent to the control circuit, includes optocouplers (TLP250F). These optocouplers provide electrical isolation between the low-power control circuit and the high-power switching circuit. They amplify the PWM signals and drive the gate terminals (G1 and G2) of the IRFP250 MOSFETs, ensuring efficient switching operation.
3) The power circuit, which is the central section of the hardware model, consists of two MOSFET switches (SW1 and SW2) arranged in an interleaved configuration. These MOSFETs regulate the power transfer from the DC source to the load by alternately turning on and off. Inductors (L1 and L2), visible as blue toroidal coils, store energy and release it gradually, reducing ripples and improving efficiency. The circuit also includes Schottky diodes (MBR20200) for freewheeling current, ensuring continuous conduction mode (CCM) operation.
4) The load section, visible at the output terminals, consists of a resistive load. A capacitor (C0) at the output smooths the voltage, ensuring a stable DC output. The hardware model effectively implements the schematic circuit, demonstrating the working principle of the interleaved buck converter for stepping down the input voltage while improving efficiency through phase interleaving.

B. Hardware Result

Fig. 9. Hardware output

The interleaved buck converter utilizes parallel MOSFETs and dual LC filters (L1, L2, C0) to step down the input voltage while minimizing ripple. By employing the interleaving technique, the PWM signals controlling the MOSFETs are phase-shifted, effectively increasing the switching frequency at the output filter. The inductors (L1, L2) regulate the current by storing and releasing energy, while the capacitor (C0) smooths the voltage, resulting in a stable 5V DC output, as observed on the oscilloscope. The flat waveform indicates low ripple, highlighting the benefits of interleaving in enhancing efficiency and reducing electromagnetic interference (EMI).

6. Applications

Corrosion of metal structures exposed to electrolytic environments, such as soil, water, or concrete, leads to material degradation. Cathodic protection (CP) mitigates this by supplying a controlled DC current to counteract oxidation. The DC-DC buck converter in this circuit ensures a stable impressed current cathodic protection (ICCP) system by stepping down a high DC voltage to a regulated low-voltage supply.

The microcontroller (DSPIC30F201) generates a PWM signal to regulate the MOSFET (IRFP250), adjusting the output voltage and current. Inductors (L1, L2) and diodes (MBR2020) smooth the DC output, preventing fluctuations that could compromise protection. Different metals require different levels of protection, and the system dynamically adjusts current based on the metal type and environmental conditions. This prevents overprotection, which can cause hydrogen embrittlement, and under-protection, which allows corrosion to persist.

This system ensures long-term corrosion prevention, significantly extending the lifespan of metal infrastructure. The integration of a microcontroller enables real-time monitoring and adaptive control, making it a highly efficient and cost-effective solution for industrial CP applications.

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