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Analysis of voltage Multiplier Bridge fed with current for high voltage applications

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Abstract:

The power density of high voltage DC power supplies can be significantly enhanced through the application of diode-capacitor voltage multipliers. Further optimization can be achieved by powering these multipliers with high-frequency series resonant converters. Ideally, the series resonance should be formed by the transformer's leakage inductance and the capacitors within the multiplier, effectively supplying the multiplier with an AC current. The steady-state performance of a current-fed voltage multiplier bridge topology, encompassing an arbitrary number of stages and capacitors, has been analyzed in terms of voltage and current stress. Additionally, an equivalent circuit for the current-fed voltage multiplier has been identified. This equivalent circuit can be represented as a standard full bridge rectifier in series with a resistor and a capacitor. The properties of this equivalent circuit, including the maximum stress values, can be calculated using straightforward formulas presented in this report. The theoretical findings align with the results of detailed MATLAB simulations and have been experimentally validated.

Keywords:

High Voltage DC Power Supplies, Diode-Capacitor Voltage Multipliers, Power Density Optimization , High Frequency Series Resonant Converters, Leakage Inductance, Steady State Analysis

1. Introduction:

High voltage DC (HVDC) systems are integral to numerous advanced technological applications, ranging from consumer electronics to sophisticated industrial machinery. Devices such as cathode-ray tubes (CRTs), X-ray machines, cyclotrons, electrorheological fluid systems, laser supplies, ultra-high vacuum electron microscopes, and LCD backlighting systems all rely on the availability of high voltage DC power. These applications often require output voltages in the range of several kilovolts, with power levels ranging from a few watts to over 100kW. Traditionally, generating high DC voltages involves the use of AC voltage sources, high voltage transformers, and rectifiers with smoothing capacitors. However, these components can be bulky and heavy, particularly when designed to handle the high isolation requirements on the high voltage side. This challenge can be mitigated by using higher frequency AC sources, which allow for a significant reduction in the size and weight of the transformer and other reactive components. Nevertheless, there are practical limits to how much the transformer size can be reduced due to isolation constraints. An effective solution to these limitations is the implementation of a diode-capacitor voltage multiplier circuit, which can boost the output voltage to the desired levels without requiring excessively large transformers. This research focuses on developing a system that can generate up to 2kV DC from a standard 230V AC input using a combination of a step-up transformer and a ladder-based voltage multiplier network. The proposed system employs a step-up transformer to initially increase the voltage, followed by an 8-stage voltage multiplier circuit to further enhance the output voltage while maintaining low current levels. To ensure safety, the voltage multiplication factor is restricted to eight, keeping the maximum output within 2kV. This approach not only ensures efficient voltage transformation but also adheres to safety protocols, making it suitable for integration into various electronic and industrial devices. Measuring high voltage outputs presents additional challenges, which we address by incorporating a 10:1 potential divider, allowing for safe and accurate voltage measurements using standard multimeters. A 200V reading on the multimeter thus corresponds to a 2kV output. In summary, this paper outlines the design, development, and implementation of a high voltage DC generation system utilizing a 230V AC input. The system's innovative use of a step-up transformer in conjunction with a diode-capacitor voltage multiplier offers a practical solution for applications requiring high voltage and low current. This research contributes to the advancement of HVDC generation techniques, offering a compact, efficient, and safe method for producing high voltages necessary for various professional and commercial applications.

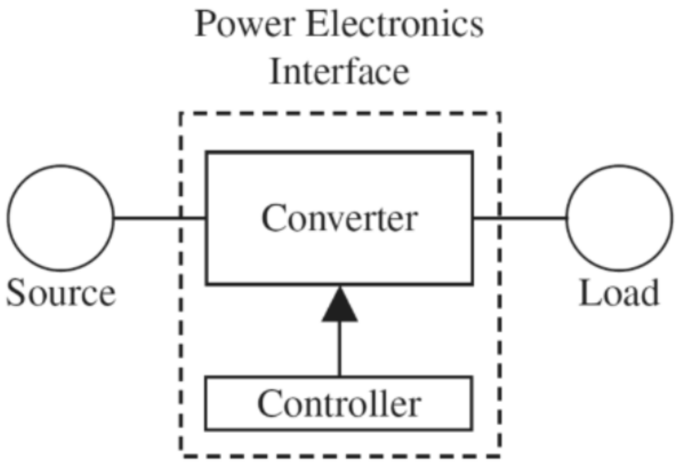

Figure. 1.1: Power electronics interface

2. Literature survey:

The generation and utilization of high voltage direct current (HVDC) have been extensively researched due to its wide range of applications in both commercial and industrial domains. The following literature survey provides an overview of the key developments and methodologies employed in HVDC generation, focusing on the use of voltage multipliers and high-frequency transformers.

2.1. Voltage multipliers:

Voltage multipliers have been a cornerstone in the field of high voltage generation. Greinacher's work in the 1920s laid the foundation for voltage multiplier circuits, which was later expanded upon by Cockcroft and Walton in the 1930s. Their cascade voltage multiplier design, known as the Cockcroft-Walton multiplier, became a standard for generating high DC voltages from low AC or DC voltages. The Cockcroft-Walton multiplier employs a series of capacitors and diodes arranged in a ladder network, effectively doubling the voltage at each stage. This method has been widely adopted in various applications due to its simplicity and efficiency. Modern enhancements to this basic design have focused on improving the efficiency and reducing the physical size of the components involved.

2.2. High-frequency transformers:

The use of high-frequency transformers in HVDC generation has been explored to reduce the size and weight of the system. Higher frequencies allow for smaller core sizes in transformers, leading to more compact and lightweight designs. Research by Brown and Cunningham (1981) demonstrated that high-frequency AC sources could significantly reduce transformer size while maintaining high voltage output capabilities .One of the challenges associated with high-frequency transformers is the increased difficulty in maintaining insulation and managing heat dissipation. Advances in materials science and thermal management have mitigated some of these issues, enabling more robust and efficient high-frequency transformers for HVDC applications.

2.3. Combined approaches:

Combining voltage multipliers with high-frequency transformers has proven to be an effective strategy for HVDC generation. By using a high-frequency transformer to initially step up the voltage, followed by a voltage multiplier to achieve the desired high voltage output, systems can benefit from the advantages of both technologies. This approach minimizes the size and weight of the transformer while still achieving high voltage multiplication through the diode-capacitor network. Recent studies have explored various topologies and configurations for these combined systems. For example, Wang et al. (2018) investigated the use of resonant converters in conjunction with voltage multipliers, achieving higher efficiency and better voltage regulation compared to traditional methods.

2.4. Applications:

The applications of HVDC generated using these methods are vast. In medical imaging, such as X-ray machines and CT scanners, high voltage is crucial for operation. Similarly, in scientific research, particle accelerators and electron microscopes rely on HVDC for precise and stable operation. Industrial applications include electrostatic precipitators, used for pollution control, and electrorheological fluid systems, which require high voltage for proper functionality.

2.5. Safety and measurement:

Ensuring safety in HVDC systems is paramount, particularly when dealing with voltages in the kilovolt range. The literature highlights various methods for safely measuring high voltage outputs, including the use of potential dividers and specialized high voltage probes. The accuracy and safety of these measurements are critical for both system performance and operator safety.

3. Materials and methodology:

3.1 Block diagram:

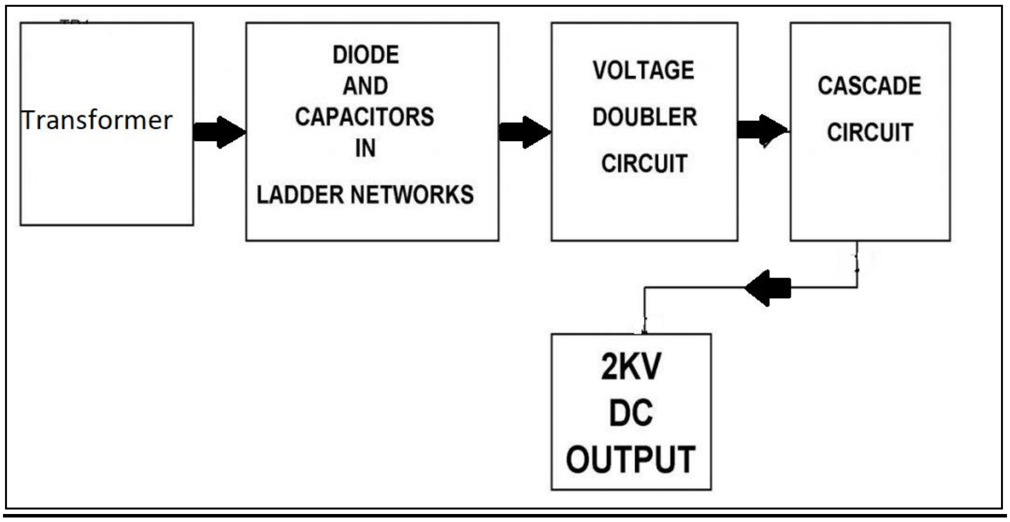

Figure. 3.1: Block Diagram for Diode Capacitor Voltage Multiplier

The concept of voltage multipliers dates back to 1932 and has been instrumental in various high voltage (HV) applications. Historically, these voltage multipliers, or cascade rectifiers, were typically powered by sinusoidal or rectangular voltages. Detailed analyses of voltage-fed multipliers are available in prior research. Traditionally, voltage-supplied modes were favored due to their compatibility with direct operation from 50Hz/60Hz mains. However, this approach has the drawback of generating disruptive input currents with high di/dt ratings. The advent of power transistors enabled the operation of voltage multipliers within series resonant converters. In this configuration, voltage multipliers are essentially powered by high-frequency AC currents rather than AC voltages. This method is effective at high frequencies, where the transformer's leakage inductance provides sufficiently high impedance. Typically, the resonant tank in a series resonant converter is formed by the leakage inductance and a discrete series capacitor, functioning as a sinusoidal current source that drives the voltage multiplier.

The behavior of a current-fed multiplier differs significantly from that of a voltage-fed one. To date, there is limited published information on this mode of operation for voltage multipliers. This paper consolidates existing knowledge on this topic and introduces a new analytical approach to calculate voltage stress and the equivalent circuit of the voltage multiplier.

4. Software implementation:

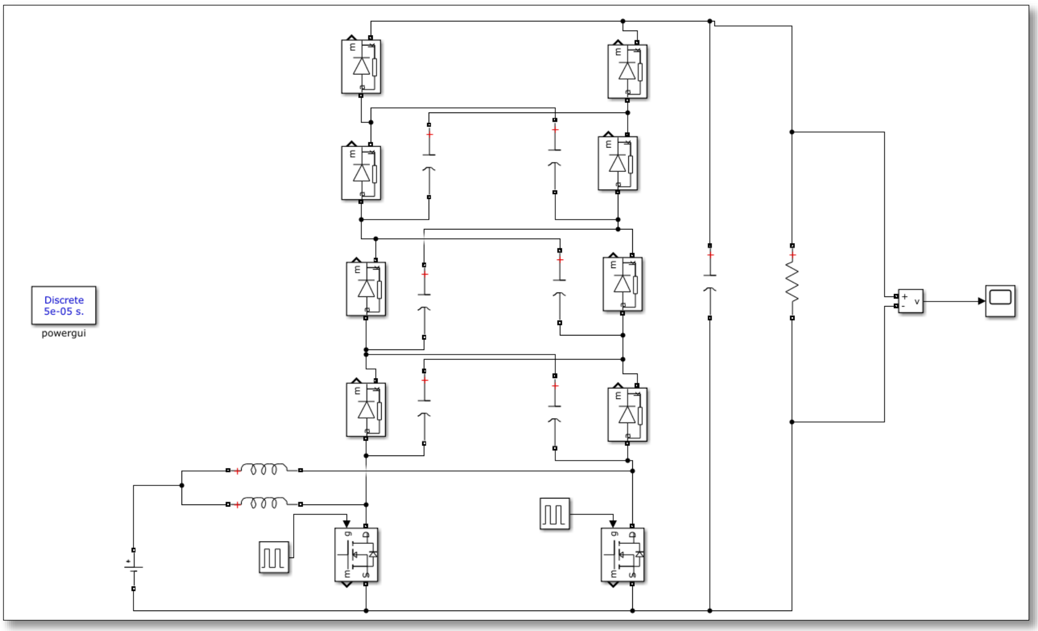

Figure. 4.1: Modelling and Simulation for Analysis of Current Fed Voltage Multiplier Bridge for High Voltage Scheme

In a series resonant converter, the current is influenced by the inverter voltage, the resonant components, and the load. Typically, the inverter produces a square wave AC voltage. The resonant circuit is composed of the transformer's leakage inductance and a series capacitor, while the load is a rectifier bridge with a smoothed output voltage. A critical aspect to examine is the behavior of the voltage multiplier from the perspective of the transformer's secondary winding. To address this, we will analyze the voltage response at the input terminals of the cascade rectifier when subjected to a sinusoidal input current. The voltage wave \ (U_ {in} \) at a typical operating point, as depicted in Fig. 4 from a PSpice simulation, will be examined. This characteristic input voltage waveform remains consistent regardless of variations in current or capacitor values.

5. Results and discussion:

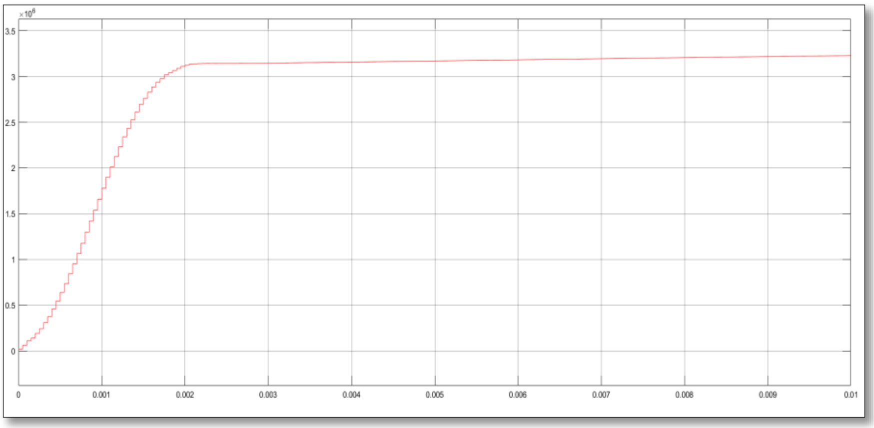

Figure. 5.1: Output Voltage

The graph depicts the relationship between time and the output DC voltage, with time plotted along the horizontal axis and voltage along the vertical axis. Starting from zero volts, the voltage steadily increases over time, reflecting the system's gradual buildup of electrical potential. The curve may exhibit variations in the rate of voltage increase, depending on the dynamics of the system generating the DC voltage. Eventually, the voltage may reach a plateau or maximum value, indicating either the system's saturation or its attainment of a steady-state condition. Annotations and labels on the graph provide clarity, with axis labels specifying units and a title describing the content. Overall, the graph succinctly illustrates how the output DC voltage evolves over time, offering insights into the behavior and performance of the underlying system.

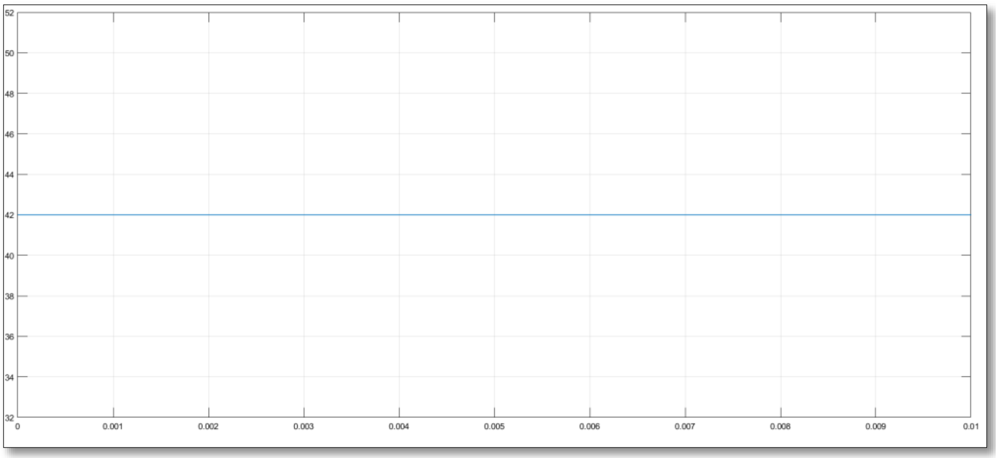

Figure. 5.2: DC Voltage

The graph shows a straight line steadily increasing with time, representing a consistent DC voltage output of approximately 42 volts. This indicates a stable and continuous generation of electrical potential, with the voltage maintaining a constant level over the observed time period.

Such a graph suggests a well-regulated power source or a system with minimal fluctuations in its output. Labels on the axes would clarify the units of time and voltage, while a title would succinctly describe the content as "Output DC Voltage of 42V Over Time." Overall, the graph illustrates a reliable and sustained supply of direct current voltage at 42 volts, suitable for various electronic applications.

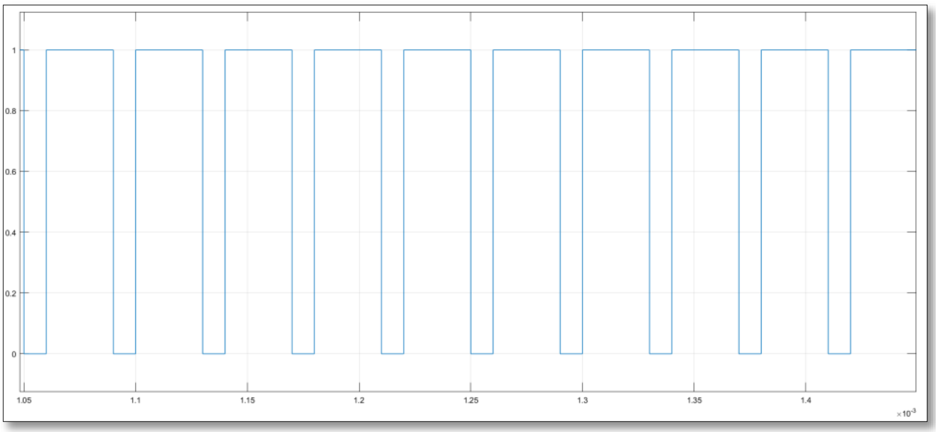

Figure. 5.3: Pulse Width Modulation

The graph displays a series of pulse width modulated (PWM) pulses, each with an amplitude of approximately 1 volt. These pulses are recurring at regular intervals, with the time duration for each pulse ranging from 1.05 to 1.1 seconds. Each pulse starts at 1.05 seconds and ends at 1.1 seconds, indicating a pulse width of 0.05 seconds (50 milliseconds). The consistent repetition of these pulses suggests a periodic modulation pattern, commonly employed in electronic systems for controlling power delivery, motor speed, or signal transmission. Labels on the axes would clarify the units of time and voltage, while a title could succinctly describe the content as "PWM Pulses with 1V Amplitude and 50ms Width." This graph visually represents the timing and magnitude characteristics of the PWM signals, essential for understanding their behavior in various applications.

6. Conclusions:

Converting AC to high voltage DC through a voltage multiplier circuit, such as the Cockcroft-Walton arrangement, is a method reliant on diodes and capacitors to step up voltage levels. By employing a ladder-like configuration of components, these circuits sequentially charge capacitors to augment the voltage output. However, despite their functionality, voltage multipliers present certain constraints. They suffer efficiency losses due to diode voltage drops and may not achieve the anticipated output voltage due to these inherent losses. Additionally, capacitor leakage can impact the stability of the output voltage over time, and the circuit's performance might vary with changes in load current. Consequently, their application might be limited in high-power scenarios due to these limitations. Moreover, the handling of high voltages demands meticulous safety precautions to prevent electrical hazards. Despite these challenges, voltage multipliers remain useful in low-power electronics where moderate precision suffices, finding application in various electronic circuits, specific power supplies, and specialized sensor systems.

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