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Performance Evaluation of Dual Active Bridge DC-DC Boost Converter

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Abstract

This research presents a detailed performance analysis of a Dual Active Bridge (DAB) DC-DC converter, focusing on the impact of MOSFET on-resistance (Rds(on)) on converter efficiency and output characteristics. Using MATLAB simulink model, this work implements proportional-integral (PI) controllers for improved output current and voltage stability and pulse width modulation (PWM) for voltage regulation. To assess their impact on converter losses and overall performance, simulations are run using different MOSFET Rds(on) values. The results highlight the relationship between Rds(on) and efficiency, demonstrating how lower MOSFET on-resistance leads to lower losses and better converter performance. To measure the improvements, losses are computed, and the output voltage and current under various Rds(on) situations are displayed. This study offers insightful information for improving the performance and efficiency of power converters. Additionally, it compares the performance of PWM alone and PWM and PI together. The effect of frequency on the converter is then also explained.

A. Introduction

A DC-DC converter is an electronic circuit that converts a direct current (DC) voltage from one level to another. It is frequently used in power electronics to transfer energy efficiently in a variety of applications, such as portable devices, renewable energy systems, and electric cars. The two primary categories of DC-DC converters are isolated and non-isolated. When the input and output share a common ground, non-isolated DC-DC converters are utilized; they do not offer galvanic isolation. Buck converters (step-down converters), boost converters (step-up converters), buck-boost converters, and Cuk converters are the several types of non-isolated DC-DC converters. Through the use of a transformer, isolated DC-DC converters offer electrical isolation between the input and output. Flyback, push-pull, half-bridge, full-bridge, and dual active bridge (DAB) converters are other names for isolated DC-DC converters.

The Dual Active Bridge (DAB) DC-DC converter has emerged as a versatile solution for efficient power conversion in various applications such as electric vehicles, renewable energy systems, and power supplies. Due to its bidirectional power flow capability and high efficiency, it is widely studied and applied. The DAB converter consists of two full-bridge circuits (one on the primary and one on the secondary side) connected via a high-frequency transformer. It efficiently transfers power between two different voltage levels while providing galvanic isolation. By varying the phase shift between the primary and secondary bridge switching signals, the power flow is managed. The DAB DC to DC converter's block diagram is displayed in Figure 1.

However, converter losses, especially those associated with the power switches, significantly affect the overall performance of the system. One of the primary sources of these losses is the MOSFET on-resistance (Rds(on)), which varies with temperature, operating conditions, and device characteristics. This research aims to explore the influence of varying Rds(on) of MOSFETs on the efficiency of a DAB DC-DC converter. Proportional-integral (PI) and pulse width modulation (PWM) controllers are used to control the output voltage and current in the MATLAB/Simulink model of the system. The goal is to quantify the losses in terms of output voltage, current, and efficiency while analyzing the converter's performance with various Rds(on) values. The study offers insights into the design of high-performance power electronic systems by highlighting the impact that MOSFET selection has on the converter's overall efficacy.

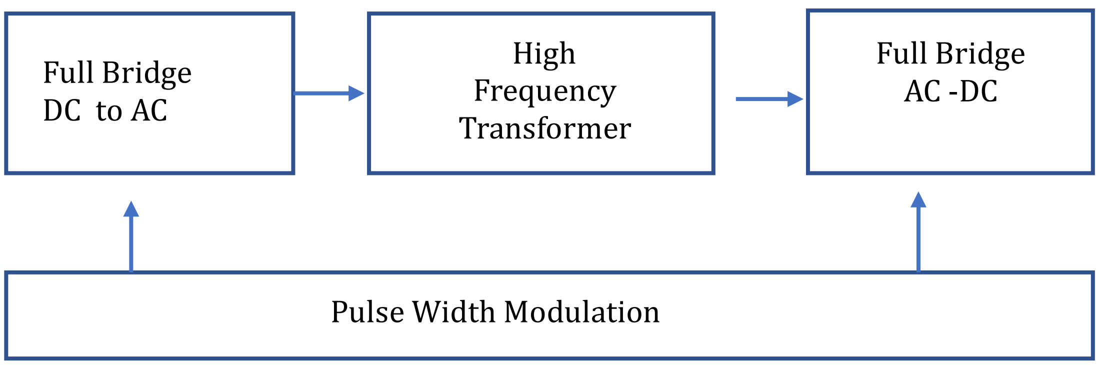

Figure 1. Block Diagram of DAB DC to DC Converter

B. Mathematical Model

Figure 2 displays the DAB DC to DC converter's circuit diagram. A bidirectional isolated converter used in high-power applications is the Dual Active Bridge (DAB) DC-DC Converter. Input full bridge (S1–S4), which transforms DC into high-frequency AC, makes up this system. A high-frequency transformer offers voltage scaling and isolation. The output full bridge (Q1–Q4) transforms AC into DC. The direction and efficiency of power flow are adjusted using phase shift control.

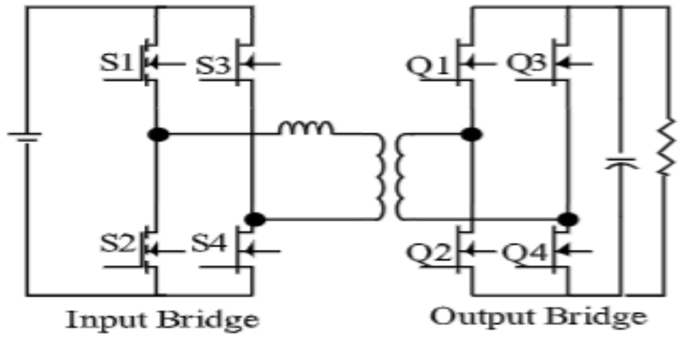

Figure 2. Circuit Diagram of DAB DC to DC Converter

The power transmission properties of a Dual Active Bridge (DAB) DC-DC Converter with phase shift control are described by these equations. The output voltage and output current, which rely on the input voltage, load resistance, switching frequency, and leakage inductance, can be changed using duty cycle (D) and phase shift. Phase shift control regulates power flow in DAB converters to offer maximum efficiency and bidirectional operation.

$$V_2 = \frac{V_1}{2nf_sL_s} R_L \, D\,(1\text{-}\,D\,) \tag{1}$$

$$I_2 = \frac{V_1}{2nf_sL_s} \, D\,(1\text{-}\,D\,) \tag{2}$$

$$P = \frac{V_{in}\,V_{out}}{2nf_sL} D\,(1-D) \tag{3}$$

A significant portion of the conversion is lost due to power switch losses. MOSFETs have two different kinds of losses: switching loss and conduction loss. The power loss or dissipation brought on by the drain current is referred to as conduction loss.

$$P_{conduction,on} = \mathrm{I}^2{}_{rms}.\mathrm{R_{ds(on)}} \tag{4}$$

The total conduction losses of converter can be calculated as:

$$P_{conduction,on} = 4\,[\; I^2{}_{pri,rms}\left(R_{DS(on)}\right) + I^2{}_{sec,rms}\left(R_{DS(on)}\right)\;] \tag{5}$$

where: $I_{pri,rms}$ = the primary winding current of the transformer

$I_{s,rms}$ = secondary winding currents of the transformer

R_{ds}(on) is the on-resistance of the MOSFET.

These losses occur due to the switching action of the MOSFETs (turn-on and turn-off events). While these losses are typically smaller than conduction losses, they depend on switching frequency and the characteristics of the MOSFET. Figure 3. describes “ON” state switching transition.

$$P_{sw} = \frac{1}{2} \text{ x } (t_{rise+} f_{fall)} I_{rms} V_{DS} f_{sw} \tag{6}$$

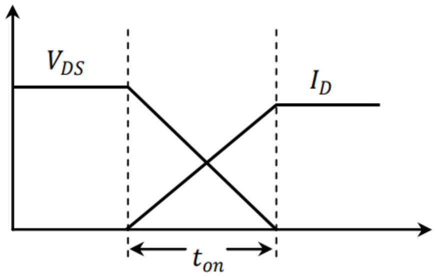

Figure 3. “ON” state Switching Transition

$$t_{on} = t_{off} = \frac{Q_{DS} + Q_{GS}}{I_{driver}} \tag{7}$$

Where:
Q_{DS} = Drain charge (from the MOSFET datasheet)
Q_{GS}= Gate Charge (from the MOSFET datasheet)
I_{driver}= Gate drive current (A, from the gate driver specifications)

The losses in the transformer can be divided into winding resistive losses and magnetic core losses. Winding resistive losses can be calculated as:

$$P = I^2{}_{rms} \, (R_{tr}) \tag{8}$$

Where
I_{rms} is the value of the transformer current .
R_{tr} is the sum of the effective resistance of primary and secondary windings.

The losses in the inductor’s windings due to resistance (R_{coil}) can be expressed as:

$$P_{inductor_{copper}} = I^2{}_{rms} \text{ x } R_{coil} \tag{9}$$

Where;
I_{rms} is the RMS current through the inductor.
R_L is the resistance of the inductor winding.

Continuous switching (on and off) transitions that expose a device to high voltage and current at the same time are the cause of switching losses in semiconductor devices. The DAB only functions in zero voltage switching (ZVS) during the "ON" switching transition, despite the fact that it does so by nature. Conduction losses in DAB can also be categorized as transformer and inductor losses, as well as conduction losses that happen in semiconductor devices (MOSFETs). The contribution of semiconductor devices to switching and conduction losses is the main emphasis of this paper; transformer and inductor losses have not been taken into account. The DAB DC to DC boost converter specification is given in Table 1.

Table 1. Specification of DAB DC to DC Boost Converter

No	Parameters	*Symbol*	*Value*
1	Input voltage	Vin	40 to 60
2	Output voltage	Vout	300
3	Output power	Pout	3000
4	Switching frequency	Fs	5000

C. Research Methodology

The simulation of the Dual Active Bridge (DAB) DC-DC converter was carried out in MATLAB simulink, leveraging its advanced modeling and simulation capabilities for power electronic systems. The Simscape Electrical library in Simulink was employed to simulate the electrical behavior of key components, including the MOSFETs, transformers, and inductors. The simulation environment allows for precise control over system parameters, offering the ability to simulate dynamic behavior under varying operating conditions. Key features include real-time voltage and current measurements, loss calculations, and the ability to visualize performance through Scope and Plot blocks.

There are two complete bridges in the Dual Active Bridge (DAB) DC-DC converter: one on the primary side and one on the secondary side. To achieve electrical isolation between input and output, both bridges are linked to a high-frequency transformer. The converter can both step up and step down the input voltage because it functions with bidirectional power flow. The primary and secondary bridges (MOSFETs), transformer, inductor, capacitor, and load are among the key parts. To efficiently transfer energy, the converter uses phase-shift modulation of the two bridges. Depending on the direction of power transmission, the primary and secondary sides of the bridge run either in-phase or out-of-phase.

The simulation used two control strategies to regulate the DAB converter's output voltage and current. PWM (Pulse Width Modulation) was the primary method for controlling MOSFET switching signals, ensuring stable output voltage despite input voltage variations. An alternative method uses PI (Proportional-Integral) Control with PWM, where the PI controller adjusts the duty cycle based on the error between the measured and reference voltage. The proportional term responds to error magnitude, while the integral term eliminates steady-state errors, ensuring precise voltage and current regulation. This study analyzed the impact of MOSFET on-resistance on the DAB converter's performance, using simulations with various Rds(on) values to understand how MOSFET losses affect the converter's efficiency and performance. Table 2. describe simulink input parameters.

Table 2. Simulink input parameters.

No	Parameters	*Symbol*	*Value*
1	Leakage inductance	L	60 μH
2	Load Resistor	R	30Ω
3	Output Capacitor	C	100 μF
4	Transformer ratio	N	5

Figure 4. represents the Simulink implementation of a Dual Active Bridge (DAB) DC-DC converter, designed to convert 48V DC to 300V DC at 3kW power with a switching frequency of 50kHz. The primary-side full-bridge (left side, Q1-Q4) converts DC to high-frequency AC. Secondary-Side Full-Bridge (Right Side, Q5-Q8) rectifies AC back to DC output (300V, 10A). Control System (Bottom) uses pulse width modulation (PWM), generated through a MATLAB function, to regulate the voltage transfer.

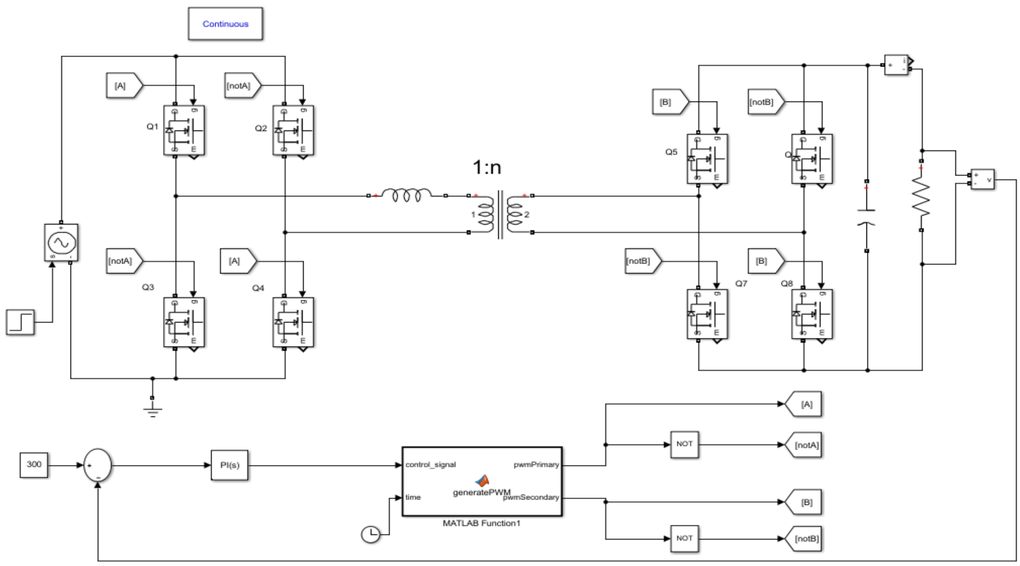

Figure 4. Simulink Model of the Dual Active Bridge (DAB) DC-DC Converter

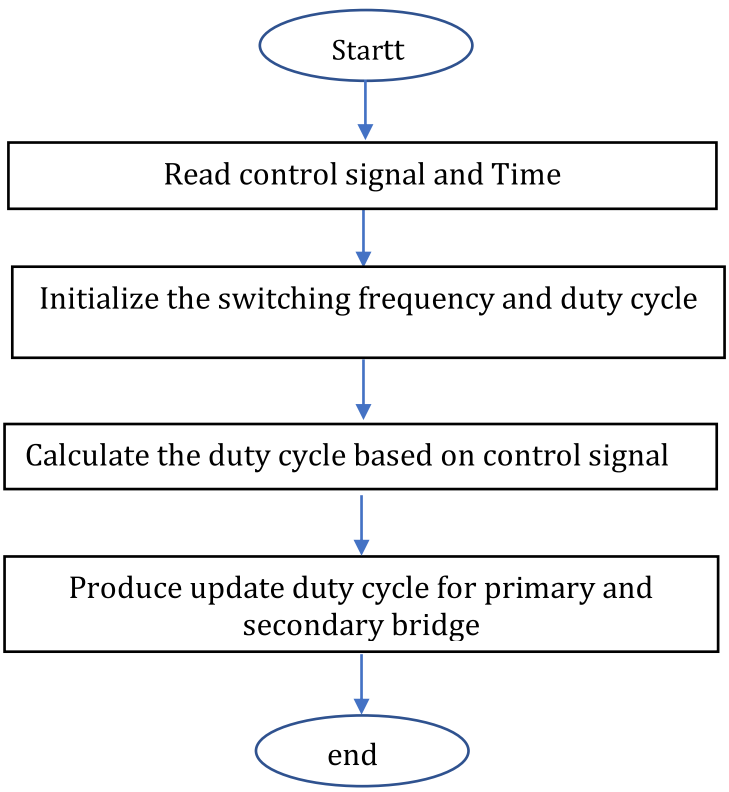

Figure 5. Flowchart of the Phase-Shift Control Algorithm

The flowchart in Figure 5 details the phase-shift control algorithm for the Dual Active Bridge (DAB) DC-DC converter, illustrating the process of generating and updating the duty cycle in response to control inputs. The system calculates the necessary phase shift or duty cycle by reading the control signal—often an error signal from a PI controller—and the current simulation time. This calculated duty cycle is then applied uniformly to both the primary and secondary H-bridges of the converter, ensuring synchronized operation and precise regulation of output voltage and current.

Figure 6. illustrates gate pulses of the primary and secondary H-bridge of MOSFET. The first and secondth plots, labeled ‘pwmPrimary,' represent the gate drive signals for the primary-side H-bridge (48V side). The two signals correspond to the complementary switching of diagonal MOSFET pairs (Q1-Q4 and Q2-Q3). The third and fourth plots, ‘pwmSecondary,’ are the gate drive signals for the secondary-side H-bridge (300V side).

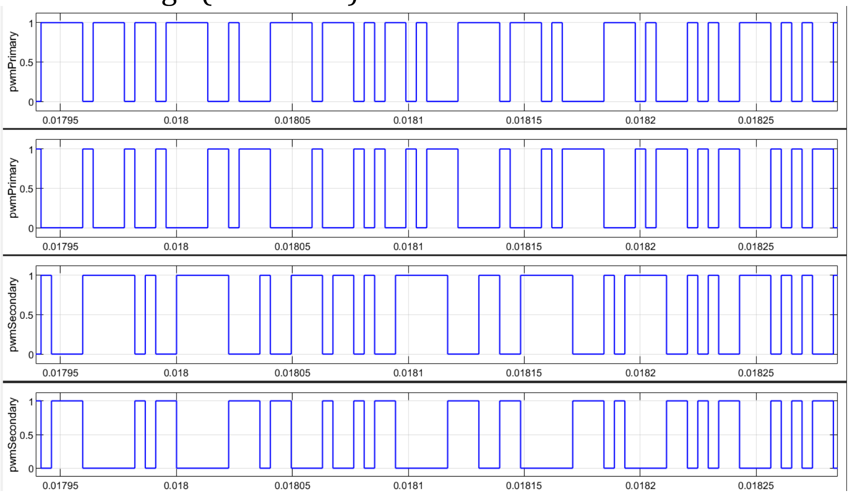

Figure 6. Gate Pulses of the Primary and Secondary H-Bridge MOSFETs

D. Simulation Results

Figure 7 demonstrates the Dual Active Bridge (DAB) converter's output voltage across various MOSFET Rds(on) values. With a low Rds(on) (indicated by the red curve), the converter maintains a stable 300 V output, closely matching the reference voltage with minimal ripple, signifying efficient power transfer. Conversely, the purple curve highlights the adverse effects of higher Rds(on) values, leading to increased conduction losses and reduced performance.

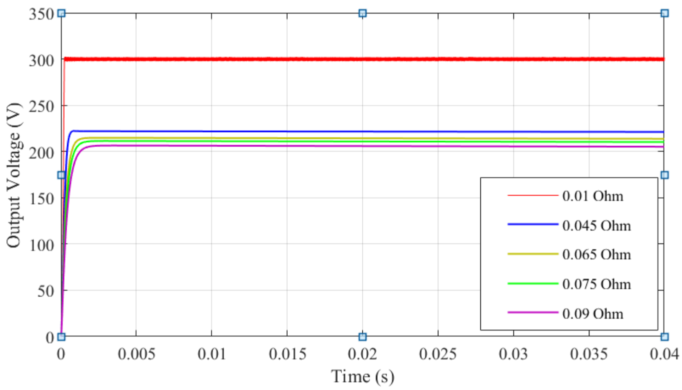

Figure 7. Output Voltage vs. MOSFET On-Resistance (Rds(on))

Figure 8 illustrates the relationship between the Dual Active Bridge (DAB) converter's output current and the MOSFET on-resistance (Rds(on)). The curves demonstrate that as Rds(on) increases, the output current decreases, highlighting the impact of increased conduction losses on the converter's efficiency in delivering power to the load. This underscores the importance of selecting MOSFETs with low Rds(on) to maintain optimal performance and minimize power dissipation in the form of heat.

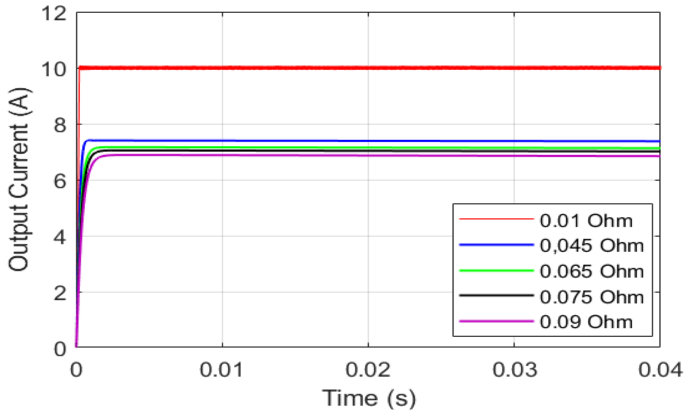

Figure 8. Output Current vs. MOSFET On-Resistance (Rds(on))

Figure 9 displays the input-output relationship of a Dual Active Bridge (DAB) DC-DC converter with Pulse Width Modulation (PWM) control under dynamic input voltage changes. PWM regulates the energy flow between the primary and secondary sides of MOSFETs by altering their on-time. While the input voltage fluctuates, the PWM adjusts the duty cycle to keep the output voltage constant. Specifically, a higher input voltage necessitated a lower duty cycle to keep a constant output, while a lower input voltage necessitated a higher duty cycle. This dynamic adjustment ensures that the converter maintains consistent output performance by adjusting for variations in input voltage.

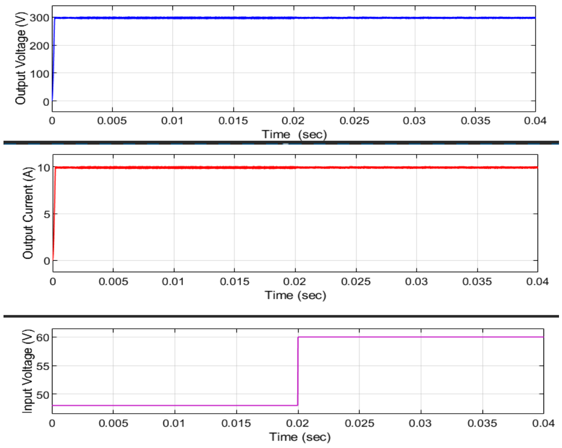

Figure 9. Input-Output Relation with PWM Control Under Dynamic Input Voltage Variations (Normal View)

In typical scenarios, when the input voltage to a Dual Active Bridge (DAB) DC-DC converter is suddenly increased, the output voltage rises to approximately

302 V within a few seconds before stabilizing. Similarly, the output current responds to these input voltage changes, adjusting and stabilizing after a brief period. Figure 10 demonstrates the converter's ability to adapt to dynamic input voltage fluctuations through Pulse Width Modulation (PWM) control, ensuring reliable output performance.

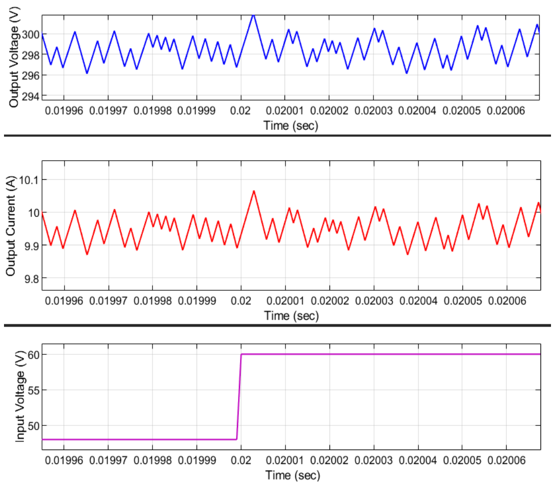

Figure 10. Input-Output Relation with PWM Control Under Dynamic Input Voltage Variations (Zoomed View)

Figures.11 and Figure.12 demonstrate the Dual Active Bridge (DAB) DC-DC converter's response to sudden input voltage increases. Upon a rapid input voltage rise, the output voltage swiftly increases from 301 V to 301.5 V, and the current rises from 10.03A to 10.05A within seconds. The Proportional-Integral (PI) and Pulse Width Modulation (PWM) control system then stabilizes the output, returning both voltage and current to their normal values after the transient response. This behavior illustrates the converter's ability to adapt to rapid input changes while maintaining stability.

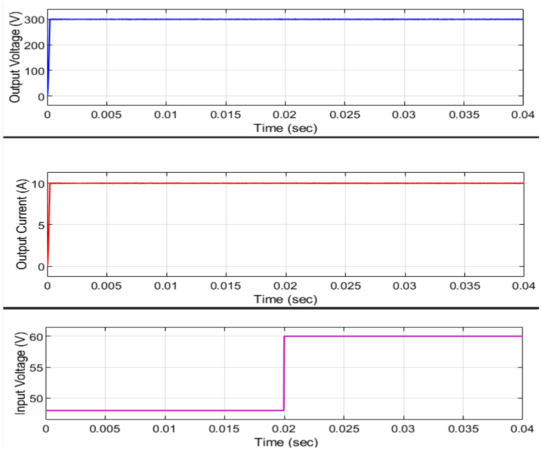

Figure 11. Input-Output Relation with PI and PWM Control During Sudden Voltage Step-Up (Normal View)

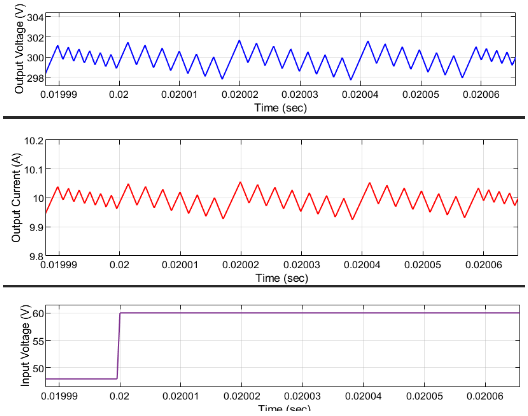

Figure 12. Input-Output Relation with PI and PWM Control During Sudden Voltage Step-Up (Zoomed View)

When the input voltage to a Dual Active Bridge (DAB) DC-DC converter drops from 48V to 45V, the output voltage remains stable, and the output current fluctuates slightly between 9.9A and 10.1A. These minor fluctuations are within acceptable limits, demonstrating the converter's ability to maintain stable performance despite significant input voltage changes. The control system effectively regulates the output, ensuring consistent operation across a wide input voltage range.

Figure 13. consists of three time-domain plots that illustrate the performance of a DC-DC converter. The top plot represents the output voltage, which remains steady at approximately 300V throughout the simulation, indicating effective voltage regulation. The middle plot shows the output current, which remains stable around 10A, confirming that the converter is supplying the expected power to the load. The bottom plot displays the input voltage behavior, which initially starts at 48V but experiences a sudden drop at around 0.022 seconds. Despite this transient in the input voltage, the output voltage and current remain unaffected, demonstrating the converter's ability to maintain a stable output under input variations. This suggests that the Dual Active Bridge (DAB) converter operates efficiently and maintains robust regulation, even when subjected to changes in input conditions.

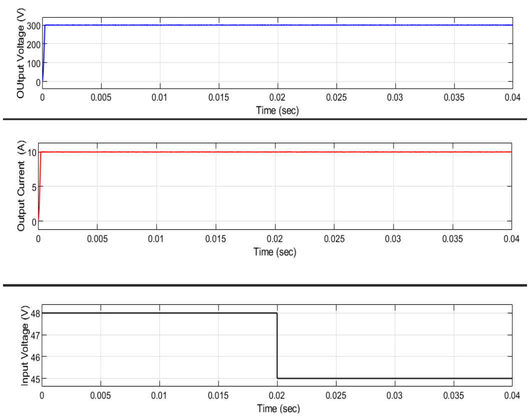

Figure 13. Input-Output Behavior with Input Voltage Changes from 48V to 45V

The drain-source on-resistance (Rds(on)) of a MOSFET is a critical parameter that significantly influences power output. Rds(on) represents the resistance between the drain and source terminals when the MOSFET is in its conducting (on) state. A lower Rds(on) results in reduced conduction losses, thereby enhancing output power.

Table 3 presents the conduction losses of different MOSFETs used in the Dual Active Bridge DC-DC Converter. The results indicate that lower RDS(on) leads to reduced conduction losses, improving overall efficiency. Among the tested MOSFETs, the IMW120R045M1H SiC MOSFET exhibited the lowest conduction loss (4.5W), while the GaN Systems GS66508T had the highest (9W), primarily due to its higher RDS(on).

Table. 3 Conduction Losses of Different MOSFETs

MOSFET Type	Maximum Current Imax (A)	Drain-Source On-Resistance (R_{DS}(on) (mΩ)	Conduction Losses (Pconduction) (W) Per each
SiC MOSFET (IMW120R045M1H)	60	45	16.2W
SiC MOSFETs C3M0065100K	51	65	169 W
SiC MOSFETs (STP75N75M5)	75	75	421W
GaN MOSFETs (GS66508T)	80	90	576 W

Figure 14. illustrate the impact of MOSFET Drain-Source On-Resistance R_{ds}(on) of four MOSFETs on power output from simulation result. Lower Rds(on) MOSFETs help reduce power dissipation and heat generation, leading to better efficiency. Using MOSFETs with ultra-low Rds(on) improves power delivery and system performance. Selecting MOSFETs with lower Rds(on) is critical for maximizing DAB converter output power and efficiency**.**

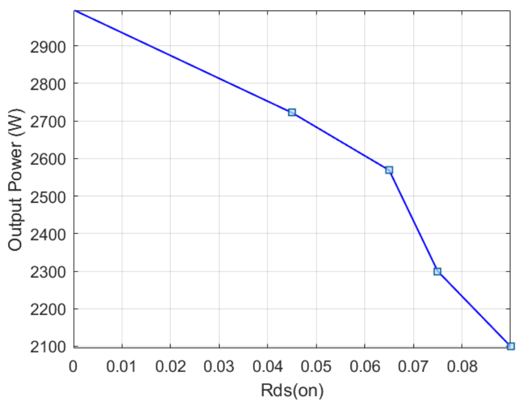

Figure 14. Impact of MOSFET Drain-Source On-Resistance R_{ds}(on) on Power Output

This graph shows the relationship between switching frequency (kHz) and output power (W) in a Dual Active Bridge (DAB) DC-DC converter**.** As the switching frequency increases, output power improves, reaching a peak at around 60 kHz**.** This is because higher frequencies reduce transformer size, improve power transfer, and lower conduction losses. After 60 kHz, output power drops sharply. The relation between switching frequency and output power is shown in Figure.15.

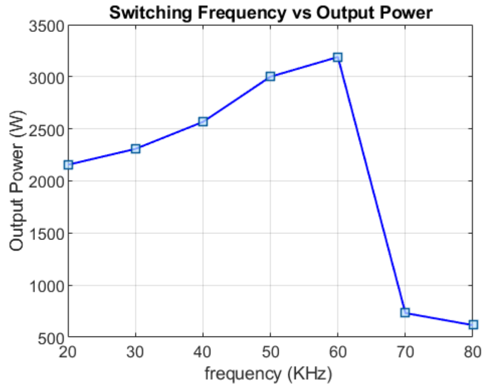

Figure 15. Switching Frequency vs Output Power

E. Result and Discussion

In assessing the performance of the DAB DC-DC converter, PWM control efficiently regulated the output voltage of 300V at a fixed input of 48V. However, slight oscillations occurred when the input voltage varied between 45V and 60V. On the other hand, the addition of PI control improved voltage regulation.

As the Rds(on) increased, the converter's losses also rose, causing a significant drop in output voltage and current. With lower Rds(on) values, the output voltage remained stable, fluctuating between 296V and 300V. However, as Rds(on) values increased, these fluctuations became more pronounced, making it harder to maintain proper output voltage regulation.

During dynamic input voltage variations (45V to 60V), both output current and voltage fluctuated similarly, with the current varying from 9.8A to 10.10A. The study highlights the benefits of using PI control for improved voltage regulation and provides valuable insights into how Rds(on) impacts the efficiency of the DAB converter. The findings highlight that optimizing MOSFET selection and control strategies is crucial for improving converter performance.

While higher switching frequencies offer benefits like smaller transformers and more efficient power transfer, the sharp drop in output power beyond 60 kHz indicates that switching losses and control instability increase. This suggests a trade-off between the advantages of high frequency and the drawbacks of higher losses and instability, requiring careful balance for practical applications.

F. Conclusion

This research highlights the significant impact of MOSFET on-resistance (Rds(on)) on the performance and efficiency of a DAB DC-DC converter. Simulations in MATLAB simulink show that lower Rds(on) values reduce losses, enhance efficiency, and stabilize output characteristics, emphasizing the importance of selecting suitable MOSFETs for optimized converter performance. To achieve optimal power output, it's essential to select MOSFETs with low R_{ds}(on) values suitable for the specific application. This selection helps in minimizing conduction losses, thereby enhancing efficiency and performance.

The combined use of PWM and PI control further enhances the converter's ability to maintain stable voltage and current under changing input voltage conditions. This work provides valuable insights for designing more efficient power converters, especially in applications requiring high efficiency and reliability. The findings also underline the significance of minimizing MOSFET losses in improving the overall performance of the DAB DC-DC converter.

In conclusion, while higher switching frequencies in power converters can improve power transfer efficiency, they also bring drawbacks such as higher switching losses and potential control instability. Careful consideration of these trade-offs is essential to achieve efficient and reliable converter performance in real-world applications. Optimal switching frequency selection is critical to achieving high efficiency and power output. Higher frequency isn't always better due to increasing losses.

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