Optimal PWM of Dual Active Bridge Converters for EV charging Applications

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Introduction

Problem: Variable Loads

- The EV charging stations face a significant challenge: the power demand at each charging port is variable and unpredictable.
- This is influenced by the vehicle's battery state and the station's own power management system.

Solution: The Dual Active Bridge (DAB) Converter

- Conventional DAB converters are designed for fixed power levels and lose efficiency under the variable loads of a real-world charging environment.
- Our Objective: To develop an optimal Pulse-Width Modulation (PWM) control strategy/optimizing algorithm that ensures the DAB converter operates at maximum efficiency across all possible power demands, ensuring optimal Irms and making EV charging efficient.

Why a Dual Active Bridge (DAB) Converter?

The DAB converter is a preferred topology for isolated, bidirectional DC-DC conversion in EV charging due to several key advantages:

- **High Power Density:** Operates at high frequencies, allowing for smaller, lighter, and more compact components.
- **High Efficiency:** Capable of achieving Zero Voltage Switching (ZVS) over a wide operating range, which significantly reduces power losses.
- **Bidirectional Power Flow:** The symmetric design is essential for Vehicle-to-Grid (V2G) applications, allowing EVs to supply power back to the grid. By changing the lead or lag between voltages power flow can be controlled.
- **Galvanic Isolation:** An integrated transformer provides crucial safety isolation between the electrical grid and the vehicle.
- **Modularity:** The design can be easily scaled by connecting modules in parallel to achieve the high power ratings required for fast chargers.

The Dual Active Bridge (DAB) Converter

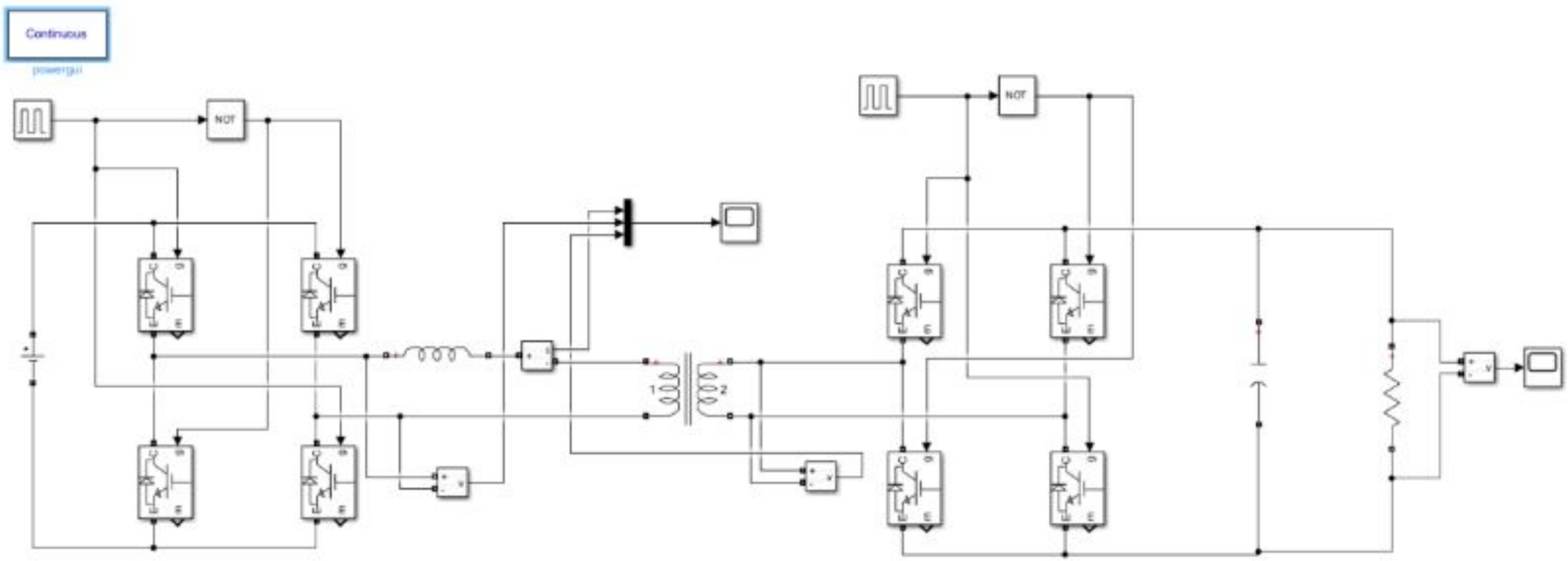

Fig. 1. Circuit Diagram of a Dual Active Bridge (DAB) Converter.

The magnitude and direction of the power flow are controlled by precisely timing the switching of the two bridges. By creating a phase shift between the fundamental components of vp and vs, energy is transferred from the leading bridge to the lagging bridge.

Problem Formulation: Our Optimization Objective

As we know, during the flow of power, there are conduction losses due to high Irms value.

So our main objective is to minimize losses by reducing the Irms value.

Find: The set of control variables (D_1, D_2, ϕ)

To Minimize: $I_{rms}(D_1, D_2, \phi)$

Subject to: $P(D_1, D_2, \phi) = P_{req}(t)$

Control Strategies: From SPS to Triple-Phase-Shift (TPS)

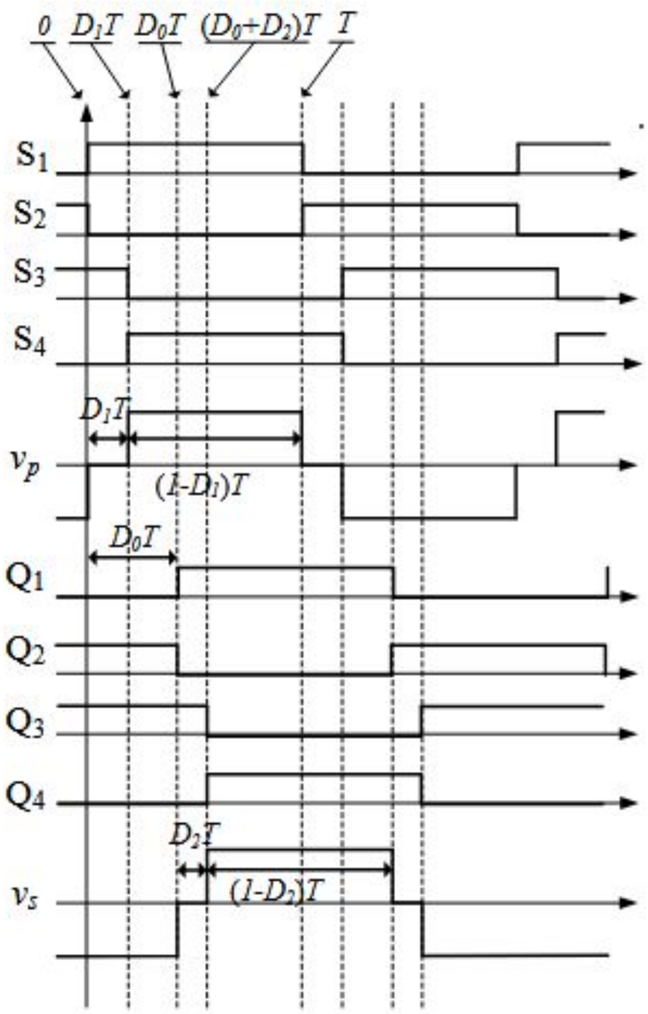

Fig.2 Typical waveform of PWM control

Three available degrees of freedom: the internal phase shifts of each bridge (D1, D2) and the external phase shift (D0). These variables give us flexibility to change the shape of Irms to minimize it by creating more complex, multi-level voltage waveforms.

When D1 and D2 are 0, it just becomes SPS

Analytical Modeling: The 6 Operating Modes

Mode	Rang of D_0, D_1, D_2	
Mode 1	$0<D_1<D_0<1$ && $D_1<D_0+D_2<1$	$P=\frac{-V_1V_2T}{L}(-D_0+D_0^2+0.5D_1-D_0D_1+0.5D_1^2-0.5D_2+D_0D_2-0.5D_1D_2+0.5D_2^2)$ $I_{RMS}^2=\frac{T^2}{L^2}(\frac{0.125}{3}V_1^2+\frac{0.125}{3}V_2^2+\frac{0.5}{3}(0.25-1.5D_1^2+D_1^3)V_1^2-\frac{0.5}{3}(0.25-1.5D_0^2+D_0^3)V_1V_2$ $-\frac{0.5}{3}(0.25-1.5(D_0+D_2)^2+(D_0+D_2)^3)V_1V_2-\frac{0.5}{3}(0.25-1.5(D_0-D_1)^2+(D_0-D_1)^3)V_1V_2$ $-\frac{0.5}{3}(0.25-1.5(D_0+D_2-D_1)^2+(D_0+D_2-D_1)^3)V_1V_2+\frac{0.5}{3}(0.25-1.5D_2^2+D_2^3)V_2^2)$
Mode 2	$0<D_1<D_0<1$ && $1<D_0+D_2<1+D_1$	$P=-\frac{V_1V_2T}{L}(-0.5+0.5D_0^2+0.5D_1-D_0D_1+0.5D_1^2+0.5D_2-0.5D_1D_2)$ $I_{RMS}^2=\frac{T^2}{L^2}(\frac{0.125}{3}V_1^2+\frac{0.125}{3}V_2^2+\frac{0.5}{3}(0.25-1.5D_1^2+D_1^3)V_1^2-\frac{0.5}{3}(0.25-1.5D_0^2+D_0^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(2-D_0-D_2)^2+(2-D_0-D_2)^3)V_1V_2-\frac{0.5}{3}(0.25-1.5(D_0-D_1)^2+(D_0-D_1)^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(D_0+D_2-D_1)^2+(D_0+D_2-D_1)^3)V_1V_2+\frac{0.5}{3}(0.25-1.5D_2^2+D_2^3)V_2^2)$
Mode 3	$0<D_1<D_0<1$ && $1+D_1<D_0+D_2<2$	$P=-\frac{V_1V_2T}{L}(-1+D_0-0.5D_1+1.5D_2-D_0D_2+0.5D_1D_2-0.5D_2^2)$ $I_{RMS}^2=\frac{T^2}{L^2}(\frac{0.125}{3}V_1^2+\frac{0.125}{3}V_2^2+\frac{0.5}{3}(0.25-1.5D_1^2+D_1^3)V_1^2-\frac{0.5}{3}(0.25-1.5D_0^2+D_0^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(2-D_0-D_2)^2+(2-D_0-D_2)^3)V_1V_2-\frac{0.5}{3}(0.25-1.5(D_0-D_1)^2+(D_0-D_1)^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(2-D_0-D_2+D_1)^2+(2-D_0-D_2+D_1)^3)V_1V_2+\frac{0.5}{3}(0.25-1.5D_2^2+D_2^3)V_2^2)$
Mode 4	$0<D_0<D_1<1$ && $0<D_0+D_2<D_1$	$P=-\frac{V_1V_2T}{L}(-D_0+0.5D_1+D_0D_1-0.5D_1^2-0.5D_2+0.5D_1D_2)$ $I_{RMS}^2=\frac{T^2}{L^2}(\frac{0.125}{3}V_1^2+\frac{0.125}{3}V_2^2+\frac{0.5}{3}(0.25-1.5D_1^2+D_1^3)V_1^2-\frac{0.5}{3}(0.25-1.5D_0^2+D_0^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(D_0+D_2)^2+(D_0+D_2)^3)V_1V_2-\frac{0.5}{3}(0.25-1.5(D_1-D_0)^2+(D_1-D_0)^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(D_1-D_0-D_2)^2+(D_1-D_0-D_2)^3)V_1V_2+\frac{0.5}{3}(0.25-1.5D_2^2+D_2^3)V_2^2)$
Mode 5	$0<D_0<D_1<1$ && $D_1<D_0+D_2<1$	$P=-\frac{V_1V_2T}{L}(-D_0+0.5D_0^2+0.5D_1-0.5D_2+D_0D_2-0.5D_1D_2+0.5D_2^2)$ $I_{RMS}^2=\frac{T^2}{L^2}(\frac{0.125}{3}V_1^2+\frac{0.125}{3}V_2^2+\frac{0.5}{3}(0.25-1.5D_1^2+D_1^3)V_1^2-\frac{0.5}{3}(0.25-1.5D_0^2+D_0^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(D_0+D_2)^2+(D_0+D_2)^3)V_1V_2-\frac{0.5}{3}(0.25-1.5(D_1-D_0)^2+(D_1-D_0)^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(D_0+D_2-D_1)^2+(D_0+D_2-D_1)^3)V_1V_2+\frac{0.5}{3}(0.25-1.5D_2^2+D_2^3)V_2^2)$
Mode 6	$0<D_0<D_1<1$ && $1<D_0+D_2<1+D_1$	$P=-\frac{V_1V_2T}{L}(-0.5+0.5D_1+0.5D_2-0.5D_1D_2)$ $I_{RMS}^2=\frac{T^2}{L^2}(\frac{0.125}{3}V_1^2+\frac{0.125}{3}V_2^2+\frac{0.5}{3}(0.25-1.5D_1^2+D_1^3)V_1^2-\frac{0.5}{3}(0.25-1.5D_0^2+D_0^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(2-D_0-D_2)^2+(2-D_0-D_2)^3)V_1V_2-\frac{0.5}{3}(0.25-1.5(D_1-D_0)^2+(D_1-D_0)^3)V_1V_2-$ $\frac{0.5}{3}(0.25-1.5(D_0+D_2-D_1)^2+(D_0+D_2-D_1)^3)V_1V_2+\frac{0.5}{3}(0.25-1.5D_2^2+D_2^3)V_2^2)$

Methodology: A Data-Driven Approach

- **Simulation and Analysis**: A 2-level DAB converter has been simulated to understand the fundamental operating principles and to visualize the voltage and current waveforms under various control inputs. This step was crucial for validating our understanding of the analytical models.
- **Comprehensive Data Generation**: We have developed a script to generate a comprehensive lookup table. This table is populated by systematically iterating through a wide range of possible values for the control variables D0, D1, and D2. For each combination, the corresponding power transfer (P) and inductor RMS current (Irms) are calculated using the analytical equations for all six modes of operation.
- **Mode Mapping**: After generating the complete data set, we have processed it to create a mapping between specific power ranges and the potential operating modes that can achieve them. This pre-analysis significantly narrows down the search space for the subsequent optimization step.

Future Work

Development of Optimization Algorithm: For a given power demand, P1, we will implement an optimization routine. This algorithm will use the “power range vs. possible modes” relationship to limit its search to only the viable operating modes. The values of (D0, D1, D2) from our pre-calculated table will serve as intelligent initial guesses for the optimization algorithm, ensuring faster convergence to the true optimal point that minimizes Irms.

Dataset Generation: The results from the optimization routine will be used to generate a final, streamlined lookup table. This table will directly map a desired power level to the single, optimal set of (D0, D1, D2) that guarantees minimum conduction loss. This table would be suitable for implementation in a real-time digital controller.

Machine Learning Integration: As a potential enhancement, we will investigate the use of machine learning techniques. A trained neural network, for example, could potentially replace the lookup table and optimization algorithm, offering a faster and more adaptive method for determining the optimal control parameters in real-time.

Thank You