Frequency-Dependent Impedance Variation in Multilevel Converters with Parallel Connectivity

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Background

Multilevel converters like Cascaded Bridge Converters (CBC) and Modular Multilevel Converters (MMC) play a vital role in diverse power applications, from HVDC systems to motor drives. Their scalability and adaptability make them essential in modern power electronics, extending beyond energy sectors to medical devices and neuroscientific instrumentation.

Traditionally, CBC and MMC converters faced energy inefficiency due to inactive submodules. To address this, parallel connectivity in multilevel circuits was introduced[1], offering advantages such as reduced impedance and sensorless ideal voltage sharing among modules. These innovations enhance efficiency and performance in multilevel converters.

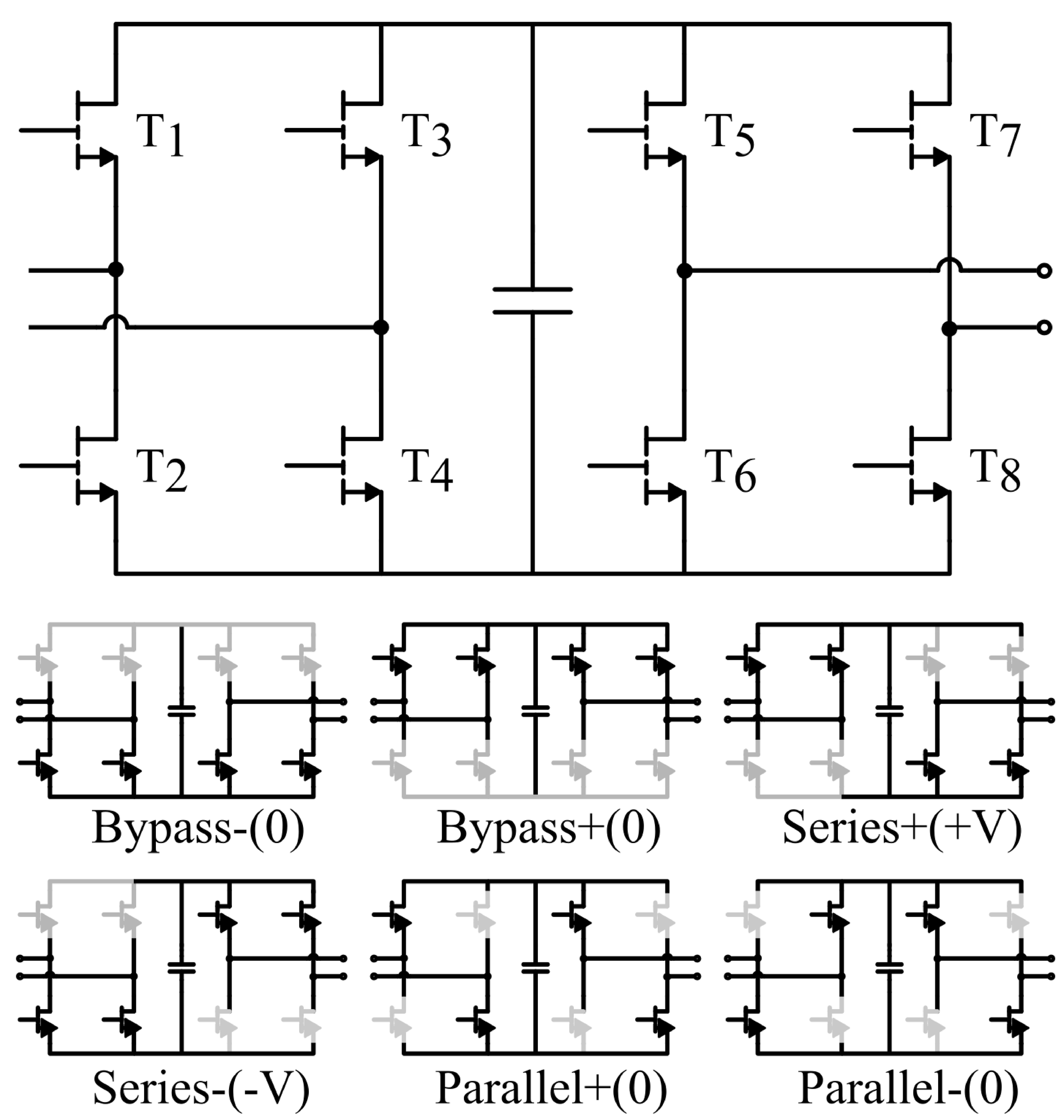

Figure 1. Topology and working principle of CH2B circuit.

Critical Review

The latest research integrates parallel connectivity into CBC/MMC converters, introducing a parallel mode that enables traditionally non-contributing submodules to form logic submodules by paralleling with neighboring modules. This dynamic formation allows logic modules to collectively possess the total capacitance of all paralleled submodules, ensuring even load current distribution and reducing voltage ripple. This approach optimizes the performance and efficiency of multilevel converters across various applications by facilitating ideal voltage sharing and significantly lowering impedance.

While existing research assumes linear reverse proportionality of impedance to the quantity of paralleled submodules, our findings reveal the inadequacy of this assumption, particularly at high and variable output frequencies.

Solution

To address this discrepancy, we conducted an in-depth study of cascaded double-H bridge (CH2B) submodules—a prevalent parallel-connectivity-enabled MMC circuit—while considering its complex stray parameters.

Our research led to the derivation of a novel analytical expression for the impedance of paralleled submodules, ensuring accuracy across the entire output frequency spectrum. Validation was performed through comprehensive SPICE-based simulations and experimental testing.

We modeled the circuit by extracting strays and employed the Delta-Y transform, a circuit transform approach, to obtain a complex description of the impedance of paralleled submodules. This analytical approach enhances the precision of impedance characterization in parallel-connected converters.

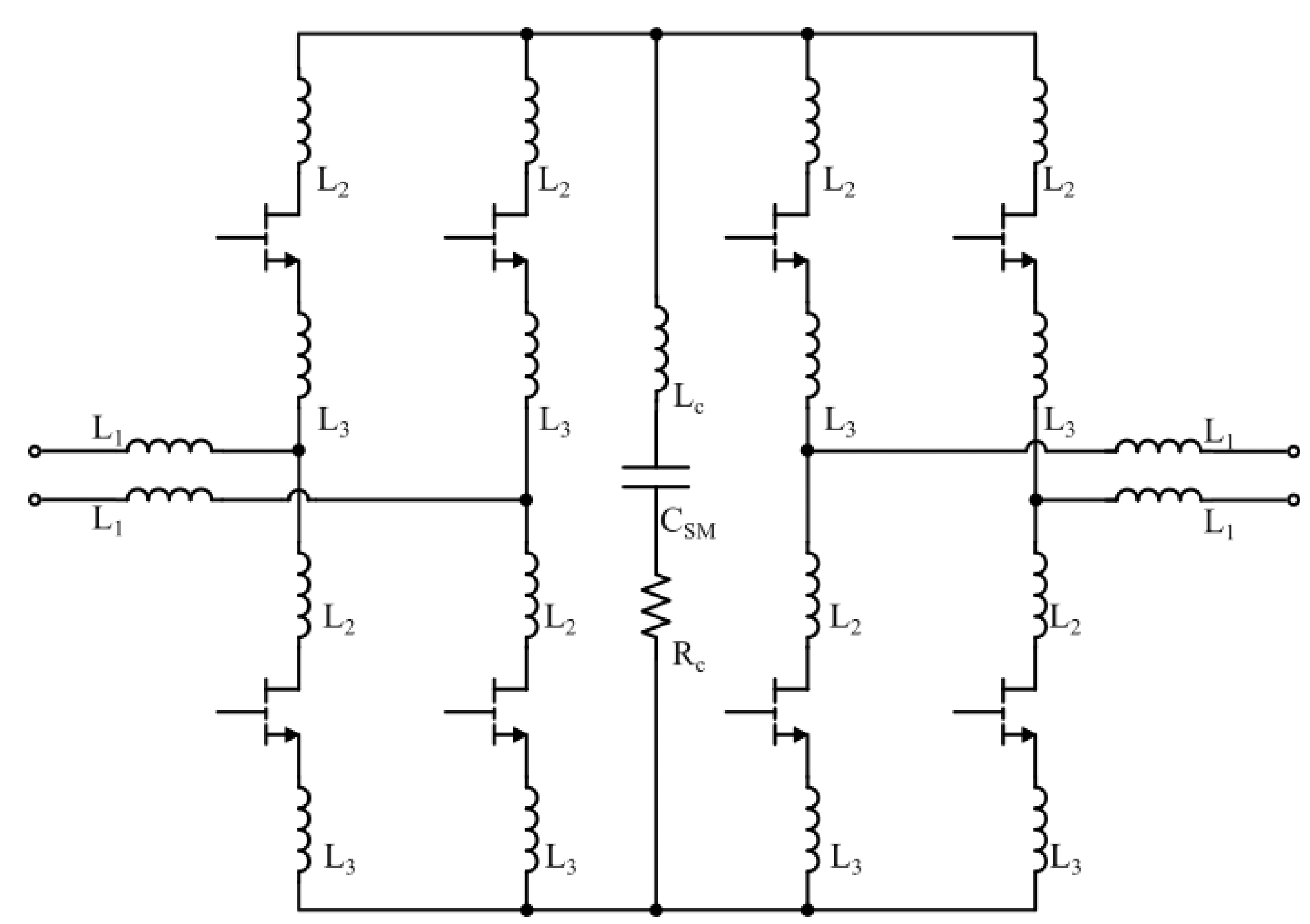

Figure 2. Model of CH2B circuit with stray parameters.

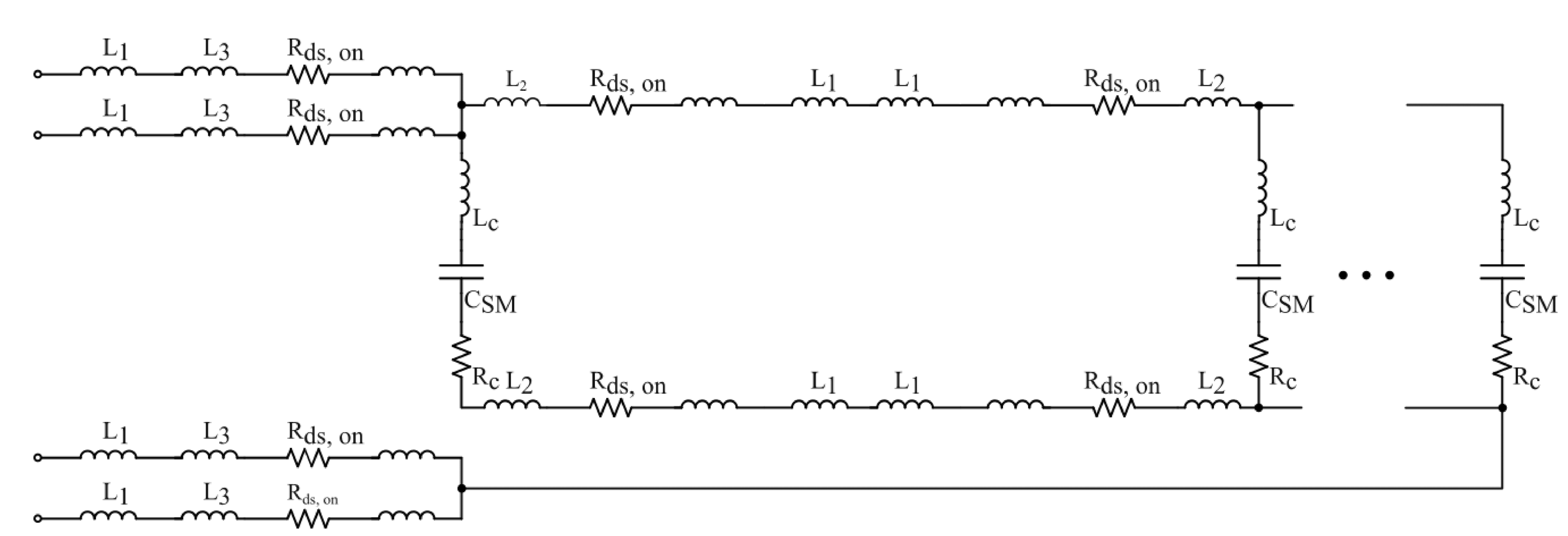

Figure 3. Model of paralleled CH2B circuits.

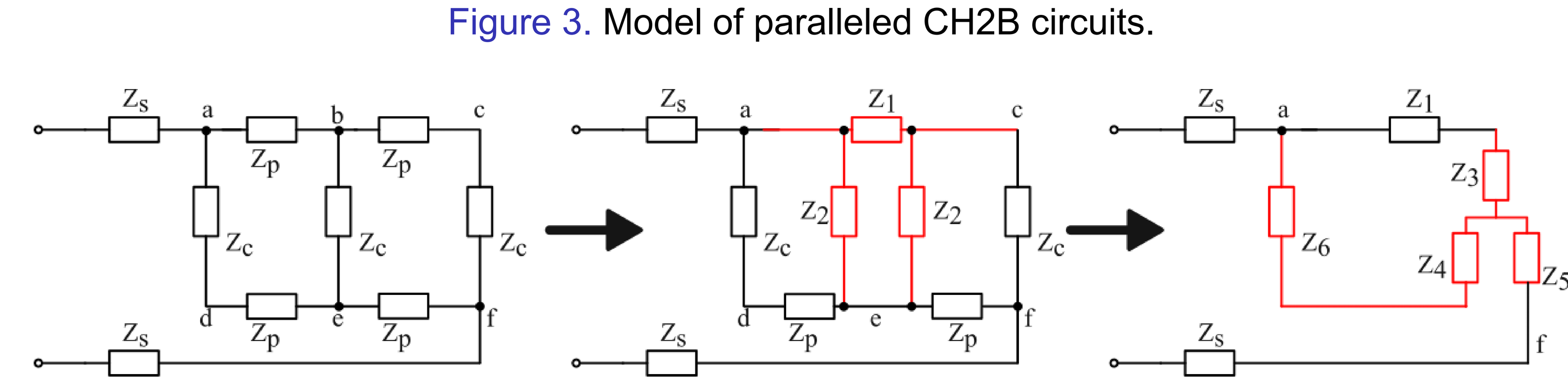

Figure 4. Delta-Y transform of the paralleled CH2B circuit.

Results

We validated our analytical model through SPICE-based simulations and experiments, predicting an increase in conduction loss—a result consistent with our theory and simulations.

Figure 5 compares the analytical expression with SPICE simulation for three parallel CH2B circuits, showing a perfect alignment. Figure 6 shows the measured conducting loss on a three-submodule experimental prototype. An increase in conducting loss, particularly in the 1k to 10 kHz range, aligns with both theory and simulation.

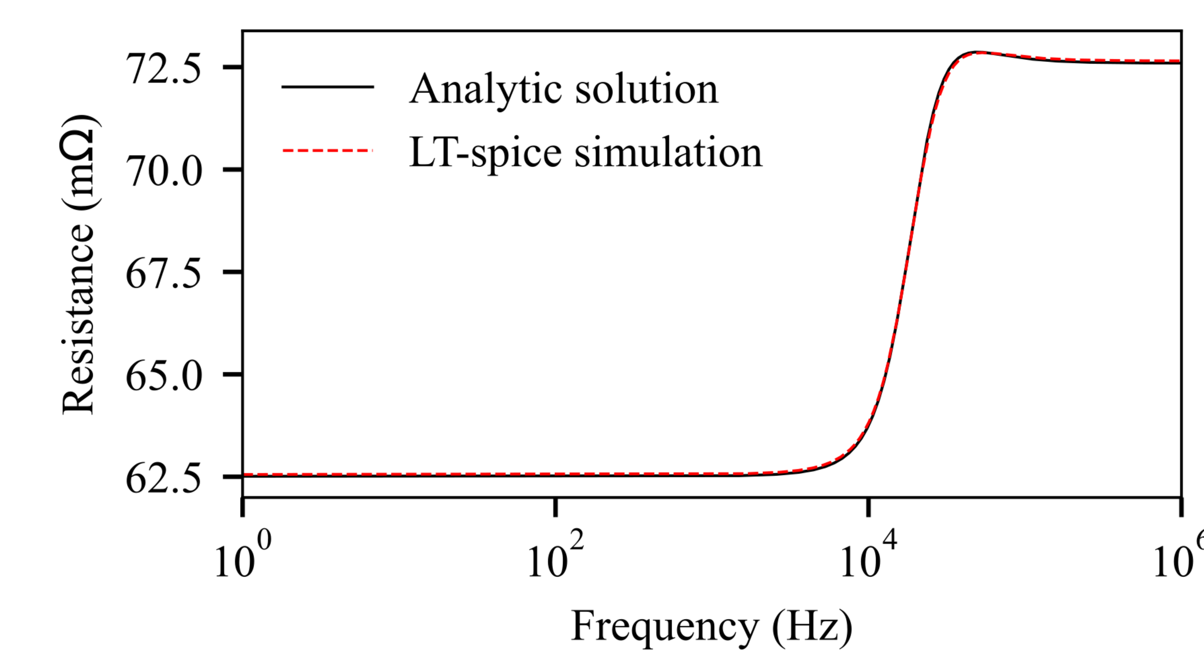

Figure 5. Validation of the frequency sweeping results of impedance of three parallel CH2B submodules.

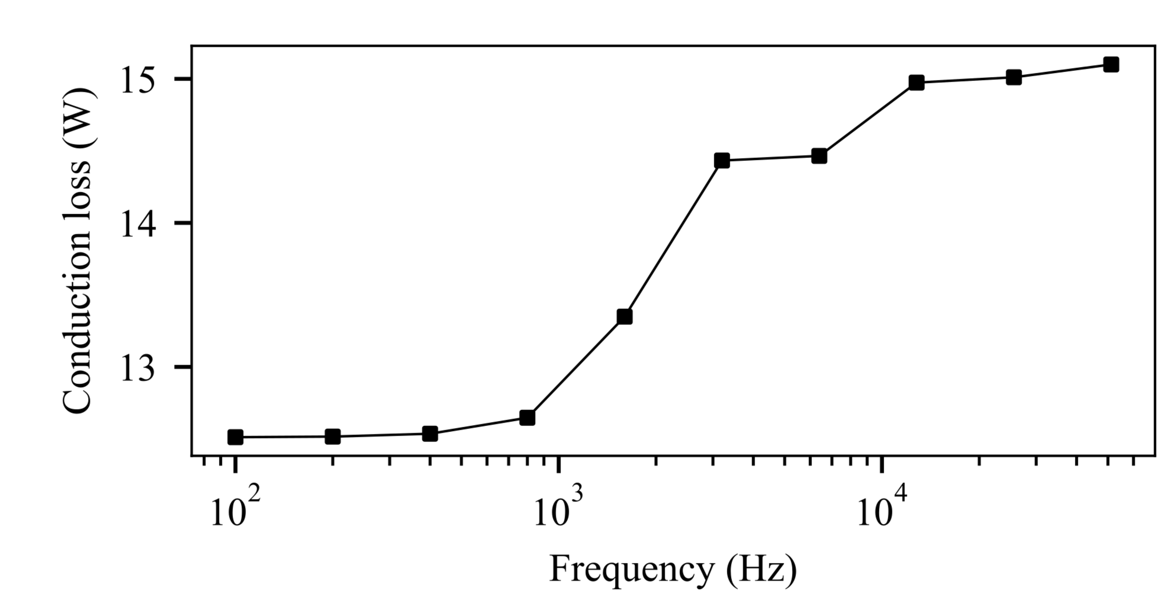

Figure 6. Conduction loss increase as the output current frequency.

Conclusion

In our study, we discovered a phenomenon in multilevel converters with parallel connectivity: the impedance of the logic submodule deviates from the ideally inverse proportional value with the output frequency. We proposed an analytic solution using $\Delta \leftrightarrow Y$ circuit transforming techniques. Results align with simulations and experiments, offering crucial insights into the impedance behavior of parallel-connected submodules. Interestingly, the variation in impedance observed in paralleled CH2B circuits mirrors uneven current distribution, akin to the "skin effect" observed in conductors.

References

[1] Stefan M. Goetz, Angel V. Peterchev, and Thomas Weyh. Modular multilevel converter with series and parallel module connectivity: Topology and control. *IEEE Transactions on Power Electronics*, 30(1):203–215, 2015.