Sensitivity Characterization of Zeta DC-DC Converter to Coupling Capacitance Deviations

Plamen Stanchev
CoE "National Center of Mechatronics and Clean Technologies
Department of Information technology in industry
Faculty of Computer Systems and Technologies
Technical University of Sofia
Sofia, Bulgaria
p.stanchev@tu-sofia.bg

Nikolay Hinov
CoE "National Center of Mechatronics and Clean Technologies
Department of Computer Systems, Faculty of Computer Systems and Technologies
Technical University of Sofia
Sofia, Bulgaria
hinov@tu-sofia.bg

Zoran Zlatev
Faculty of computer science
"Goce Delcev" University of Stip
Stip
Republic of North Macedonia
zoran.zlatev@ugd.eud.mk

***Abstract*— This study investigates the sensitivity of the Zeta DC-DC converter to variations in the coupling capacitance, a critical component that directly influences energy transfer, transient behavior, and electromagnetic compatibility (EMC). Through a simulation-based approach in MATLAB/Simulink, the impact of realistic manufacturing deviations in the coupling capacitor is evaluated. A series of frequency-domain analyses are conducted by injecting single current pulses at key nodes of the circuit and observing the resulting voltage responses. The variations in the coupling capacitance, modeled within a commercial tolerance step above and below the nominal value, reveal significant changes in resonant peaks, output ripple, and overall system stability. The findings highlight that even small parameter deviations can induce pronounced shifts in dynamic behavior, necessitating conservative component selection and sensitivity-aware design practices. This work emphasizes the importance of small-signal analysis and node-based spectral evaluation in enhancing the robustness and EMI performance of Zeta converter implementations.**

Keywords*— *Zeta converter, coupling capacitance, parameter sensitivity, frequency simulation, electromagnetic compatibility

I. Introduction

The Zeta converter is one of the key topologies in the DC-DC converter family, characterized by the ability to step down and step up voltages, with polarity inversion. Due to the continuous current in both the output and input, this circuit is widely used in applications requiring low noise, good electromagnetic characteristics and high energy efficiency, such as powering sensitive electronics, photonic systems, sensors and industrial controllers [1-3].

A key element in the Zeta topology is the coupling capacitance (*Cc*), which transfers energy between the input and output parts by commutation of stored charge. Due to its centralized role in the dynamic process, this capacitance has a strong impact on the resonant properties, transients and electromagnetic compatibility (EMC) of the system [4].

In real practice, passive elements are used with tolerances imposed by manufacturing standards, most often ±5% or ±10%. Although considered insignificant, these deviations can lead to serious changes in the behavior of the converter, including unwanted resonant peaks, increased voltage ripple and poor filtering of high-frequency disturbances [5]. Therefore, it is essential to perform a sensitivity analysis to parametric deviations in order to improve reliability and design more robust systems.

This work presents a sensitivity analysis of the Zeta DC-DC converter, focusing on variations in the coupling capacitance. Through simulations in MATLAB/Simulink, the system response to deviations in C_C within one step according to the industry standard is investigated. The analysis includes the introduction of current disturbances into key nodes of the circuit and spectral analysis of the obtained voltage responses, in order to identify frequency regions with an increased risk of instability.

II. Mathematical Model

The Zeta DC-DC converter consists of two inductive elements (input and output chokes), a coupling capacitance *Cc*, a switching element (MOSFET transistor), a diode and filtering capacitors at the input and output. The converter scheme is shown in Figure 1, where the main nodes and elements subjected to analysis are indicated.

The model considers the converter in continuous current mode Continuous Conduction Mode (CCM), in which the currents through L_1 and L_2 do not reach zero within the switching period.

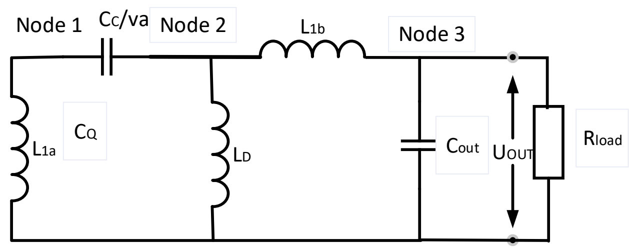

Fig. 1. Equivalent scheme of Zeta DC-DC converter

In the framework of the present study, mathematical modeling and simulation analysis are performed under the condition that the MOSFET transistor is in the off state (Q off). This assumes that no current flows through the switch, and the energy transfer between the input and output is carried out solely by diluting the coupling capacitance *Cc* and the flow of energy through the passive components. The choice of this mode allows to emphasize the role of *Cc* as an intermediate energy buffer and to observe its influence on the resonant behavior of the system without the active influence of commutation. This provides cleaner conditions for small-signal spectral analysis, necessary for deriving sensitivity dependencies between the value of *Cc* and the frequency response of the nodes in the converter.

The capacitance *Cc* is of critical importance for the transfer of energy between the input and output sections. Small deviations in its value lead to a shift of the resonant frequencies, a change in the phase response, an increase in voltage ripple, and a deterioration of EMC parameters. This makes it an ideal object for sensitivity analysis through spectral evaluation of the frequency response.

Using Kirchhoff's laws (KVL and KCL), a system of differential equations is obtained describing the dynamics of the Zeta converter [6]:

For the purposes of the simulation analysis, parameters characteristic of a real implementation of the Zeta converter were used, as presented in Table 1, including values for inductances, capacitances and load, ensuring operation in the continuous current mode and suitable conditions for sensitivity analysis.

$$
\begin{aligned}
L_1 \frac{di_1}{dt} &= V_{in} - v_{C_C} - r_{L_1} \cdot i_1 \\
L_2 \frac{di_2}{dt} &= v_{C_C} - v_{out} - r_{L_2} \cdot i_2
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
C_C \frac{dv_{C_C}}{dt} &= i_1 - i_2 \\
C_{out} \frac{dv_{out}}{dt} &= i_2 - \frac{v_{out}}{R_{load}}
\end{aligned} \tag{2}
$$

Where:

- i_1, i_2 are the currents through the inductors
- v_{Cc} is the voltage across the coupling capacitance
- $_{vout}$ is the output voltage
- r_{L1},r_{L2} are the equivalent parasitic resistances of the inductors

III. SIMULATION RESULTS

After building the MATLAB/Simulink model presented in Figure 2 [7,8], a sensitivity analysis was performed by applying a single current pulse to each node and observing the frequency response of the three main nodes (Bus 1, Bus 2 and Bus 3). The analysis was performed for three different values of the coupling capacitance Cc=14 μF,15.6 μF and 30μF, which correspond to realistic deviations within the standard tolerance of production runs.

TABLE I. PARAMETERS OF ZETA DC-DC CONVERTER

Parameters	Designations	Value
Inductor	L_{1a}	22μH
Inductor	L_{2b}	22μH
Parasitic inductance of the diode	L_D	50nH
Input capacitor	C_{in}	24.7μF
Output capacitor	C_{out}	24.7μF
Capacitor	C_C	14/15.6/30μH
Load	R_{load}	144Ω

Figure 3, Figure 4 and Figure 5 present the frequency characteristics of the Zeta converter at a coupling capacitance Cc=14 μF, measured in BUS 1, BUS 2 and BUS 3 respectively. The graphs show the amplitude-logarithmic response of each node to the input current excitation in a wide frequency range. The spectral features of each node at a fixed value of the capacitance are clearly visualized, which allows for subsequent comparison of the sensitivity of the individual points in the circuit.

Figure 6, Figure 7 and Figure 8 show the frequency responses of the Zeta converter at a coupling capacitance Cc=15.6 μF, in BUS 1, BUS 2 and BUS 3, respectively. Each graph illustrates the spectral behavior of the particular node in response to a single current excitation, keeping all other parameters unchanged. The structure of the response allows direct comparison with other values of Cc and assessment of sensitivity by nodes.

Figure 9, Figure 10 and Figure 11 present the frequency characteristics at an increased value of the coupling capacitance Cc=30 μF, again for BUS 1, BUS 2 and BUS 3 respectively. The graphs track the change in the amplitude-frequency response compared to the previous cases, which creates a basis for a generalized analysis of the influence of the capacitive value on the behavior of the circuit.

The results of the simulation analysis show a clear sensitivity of the Zeta converter to variations in the value of the coupling capacitance Cc, an increased amplitude of the voltage ripple is observed in all studied nodes, as well as a shift of the resonant frequencies to a higher frequency range.

When increasing Cc, the opposite behavior is observed - the spectral peaks are shifted to lower frequencies, and the

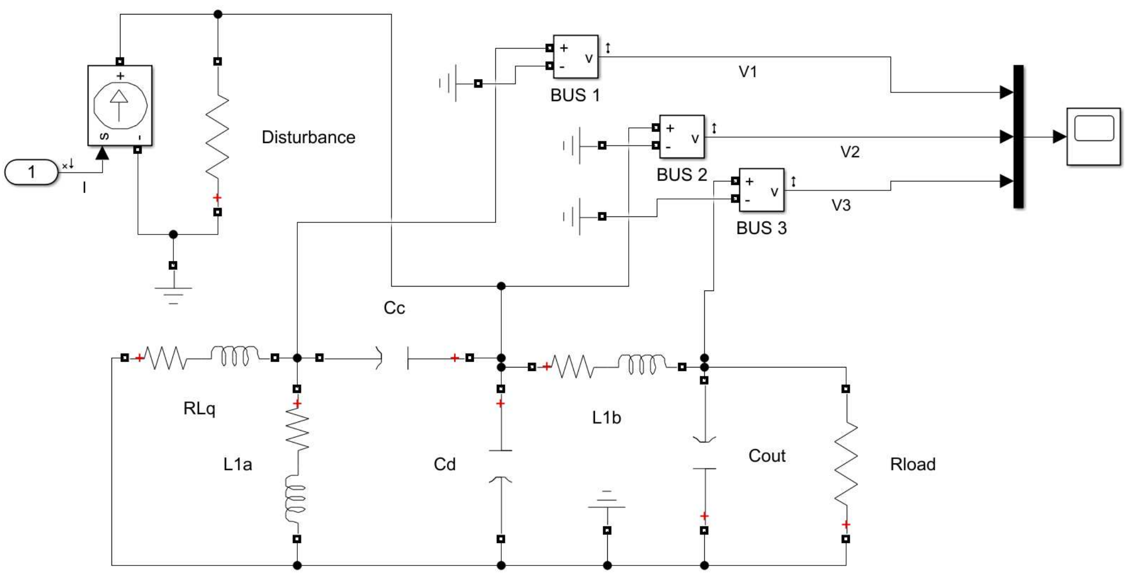

Fig. 2 MATLAB/Simulink simulation diagram of a SEPIC DC-DC converter

ripples are smoother, but with a slower response of the system. The nodes subjected to analysis show different degrees of sensitivity, with the intermediate node demonstrating the highest resonant activity. This confirms the need for careful selection of the value of Cc, consistent with the specific frequency requirements and filtration needs of the application.

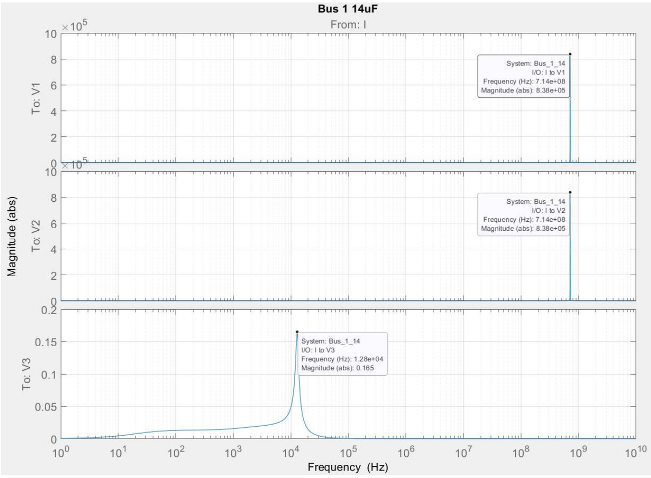

Fig. 3. Magnitude of Bus 1 when Cp=14,0μF

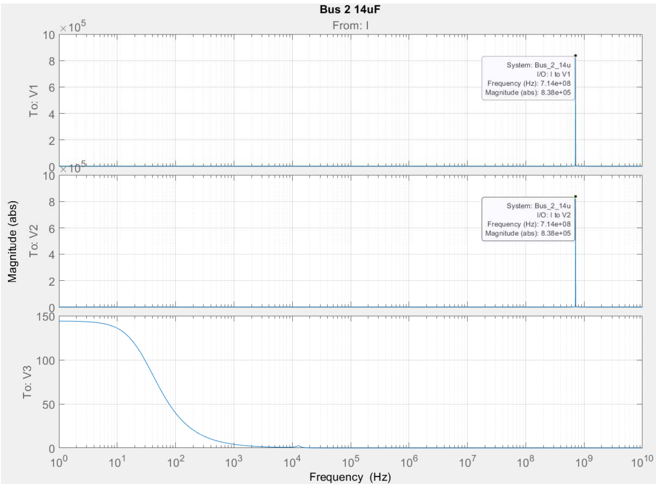

Fig. 4. Magnitude of Bus 2 when Cp=14,0μF

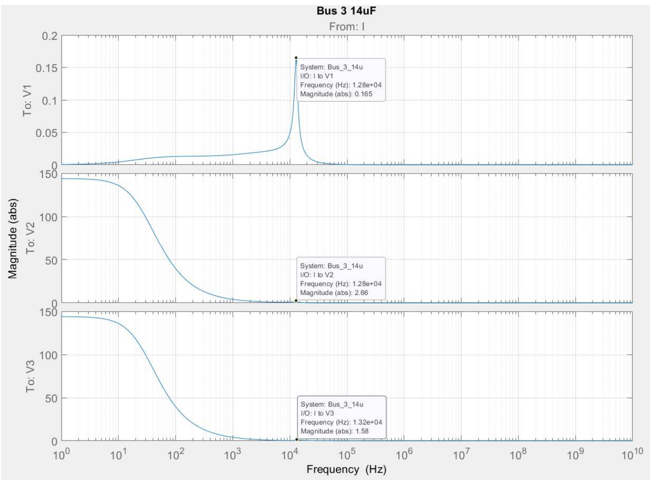

Fig. 5. Magnitude of Bus 3 when Cp=14,0μF

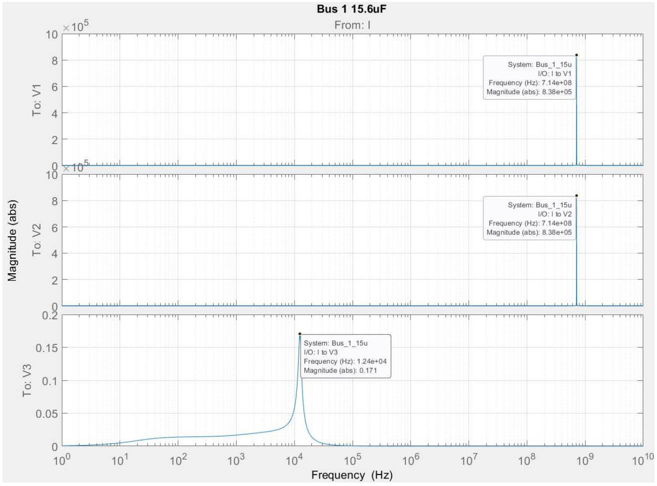

Fig. 6. Magnitude of Bus 1 when Cp=15,6μF

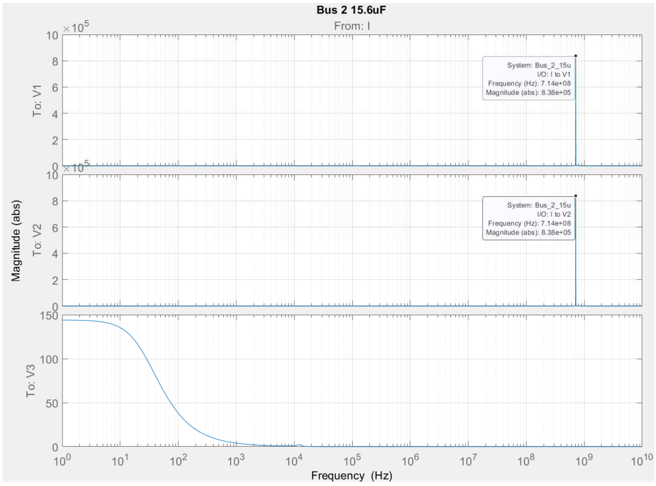

Fig. 7. Magnitude of Bus 2 when Cp=15,6μF

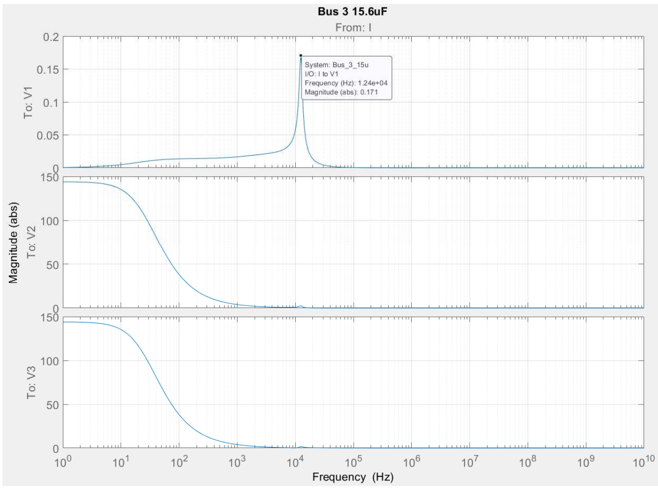

Fig. 8. Magnitude of Bus 3 when Cp=15,6μF

IV. CONCLUSION

This study presents a sensitivity analysis of a Zeta DC-DC converter with respect to variations in the coupling capacitance Cc, using a small-signal spectral approach in a MATLAB/Simulink simulation environment. The obtained results confirm that the value of this capacitance has a significant impact on the resonant behavior, stability and frequency response of the system.

When analyzing the frequency characteristics for three different values of Cc= 14μF, 15.6μF and 30μF, it was found that an increase in capacitance leads to a decrease in the resonant frequency, which is consistent with the theoretical dependence between L and C in LC circuits. The highest amplitude response is observed at the calculated value of 15.6μF, which can be associated with optimal energy transfer efficiency in this configuration. At a value of 30μF, a decrease in the peak amplitude is observed, but an expansion of the frequency range of influence, which can lead to increased vulnerability to low-frequency disturbances. Node BUS 3 was found to be the most sensitive to resonant excitation, regardless of the capacitance value, making it a critical point for monitoring and optimization [9].

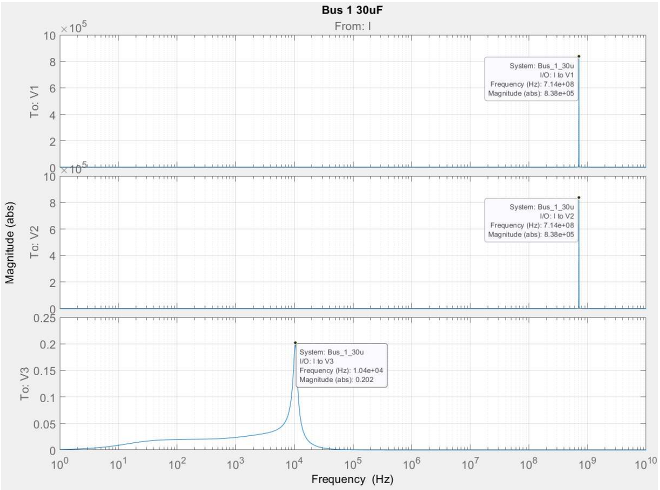

Fig. 9. Magnitude of Bus 1 when Cp=30,0μF

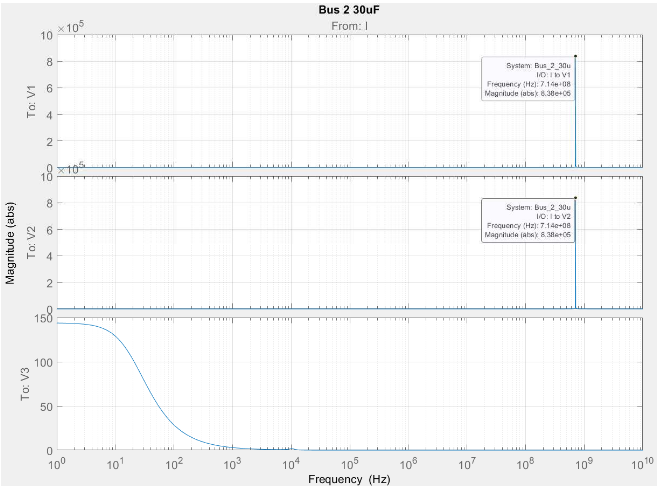

Fig. 10. Magnitude of Bus 2 when Cp=30,0μF

These results highlight the importance of precise selection and tolerance of coupling capacitances in real applications. Even small deviations in Cc within the standard ±10% manufacturing tolerances can lead to significant changes in the dynamic behavior of the converter, affecting the reliability, EMC compatibility and efficiency of the entire system.

Additionally, the used approach based on current excitation and spectral analysis of the voltage at nodes is proven to be an effective tool for sensitivity diagnostics and can be directly applied to other converter topologies, such as SEPIC, Zeta and their variations.

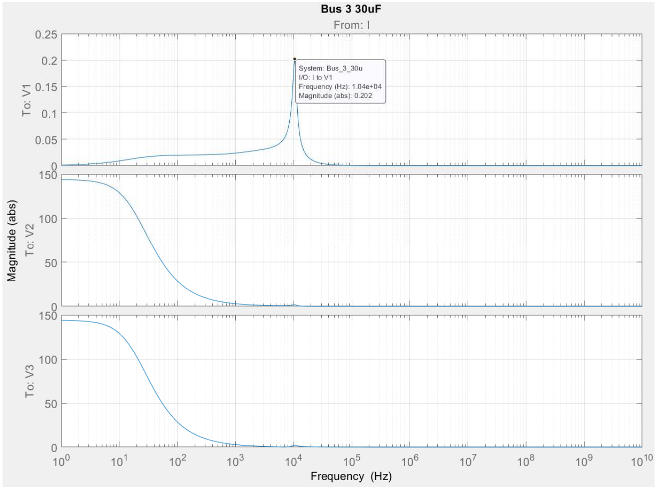

Fig. 11. Magnitude of Bus 3 when Cp=30,0μF

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