



Comparative Analysis of Hard Switching and Soft Switching for EMI Reduction in DC-DC Converters

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Abstract:

DC-DC converters are widely used in power electronic applications, including electric vehicles, renewable energy systems, battery chargers, and industrial power supplies. However, switching operations in these converters generate electromagnetic interference (EMI), which can affect the performance and reliability of nearby electronic devices. This paper presents a comparative analysis of hard switching and soft switching techniques for reducing EMI in DC-DC converters. In hard switching, semiconductor devices turn ON and OFF while voltage and current overlap, resulting in higher switching losses, voltage and current spikes, and increased electromagnetic noise. In contrast, soft switching techniques, such as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS), reduce switching losses by minimizing voltage or current during switching transitions. The study evaluates both techniques based on EMI levels, switching losses, efficiency, voltage and current stress, circuit complexity, and overall performance. Simulation-based analysis can be performed using MATLAB Simulink or suitable power electronics simulation tools under identical operating conditions to ensure a fair comparison. The results are expected to demonstrate that soft switching offers improved EMI performance and reduced switching losses compared with conventional hard switching, although it may introduce additional circuit components and control complexity. This comparative study aims to identify a suitable switching technique for developing efficient, reliable, and low-EMI DC-DC converters for modern power electronic applications.

Keywords: DC converters

1. Introduction

DC-DC converters are essential power electronic circuits used to convert a direct current (DC) voltage level into another DC voltage level. They are widely used in electric vehicles, renewable energy systems, battery charging, telecommunications, and industrial power supplies. These converters provide efficient power management and voltage regulation for electronic devices. Their performance depends on switching frequency, semiconductor devices, circuit topology, and switching techniques. Hard switching and soft switching are two important techniques used to control semiconductor switching operations in DC-DC converters.

HARD SWITCHING TECHNIQUE:

Hard switching is a conventional switching technique in which semiconductor devices turn ON and OFF while voltage and current may overlap during the switching transitions. This overlap produces switching losses and generates high-frequency electromagnetic interference (EMI). Rapid changes in voltage and current can also cause voltage spikes, current surges, and additional stress on switching devices. Although hard-switching converters have relatively simple circuit designs and control methods, their switching losses and EMI become significant at higher switching frequencies. Therefore, reducing these effects is important for improving converter efficiency and electromagnetic compatibility.

SOFT SWITCHING TECHNIQUE:

Soft switching is an advanced technique designed to reduce switching losses and electromagnetic interference. It mainly includes Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS). In ZVS, the switching device turns ON or OFF when the voltage across it is approximately zero during the relevant transition. In ZCS, switching occurs when the current through the device is approximately zero. These techniques reduce the overlap between voltage and current during switching transitions, thereby minimizing switching losses and reducing high-frequency noise. However, soft-switching converters may require additional resonant components and more complex control circuits.

ELECTROMAGNETIC INTERFERENCE IN DC-DC CONVERTERS:

Electromagnetic interference is an unwanted electrical disturbance generated by switching operations. It can propagate through conducted and radiated paths, affecting nearby electronic circuits and communication systems. The main sources of EMI include high switching frequencies, rapid voltage and current changes, parasitic inductance, and parasitic capacitance. Effective EMI reduction is necessary to improve system reliability, satisfy electromagnetic compatibility requirements, and prevent interference with sensitive electronic equipment.

OBJECTIVE OF THE STUDY:

The main objective of this project is to design and simulate a DC-DC converter using the hard-switching technique in LTspice and analyze its switching characteristics, power losses, and electromagnetic interference (EMI). A soft-switching technique, particularly Zero Voltage Switching (ZVS), will be implemented to reduce switching losses by enabling semiconductor devices to switch when the voltage across them is approximately zero. The switching voltage and current waveforms of both techniques will be analyzed to evaluate their switching behavior, energy dissipation, and overall efficiency.

Furthermore, Fast Fourier Transform (FFT) analysis will be performed in LTspice to examine the frequency spectrum, identify dominant switching-frequency components, and compare high-frequency harmonics associated with EMI. Both techniques will be evaluated under identical operating conditions to ensure a fair comparison of their performance. The study will focus on EMI characteristics, switching losses, conversion efficiency, voltage and current stress, and circuit complexity. Finally, the simulation results will be used to determine the effectiveness of soft switching in reducing high-frequency noise and improving the performance and reliability of DC-DC converters for modern power electronic applications.

2. LITERATURE SURVEY

The paper [1] by Cheng et al. presents a comprehensive review of soft-switching technologies for non-isolated DC-DC converters. It discusses various converter topologies, including buck, boost, and buck-boost converters, and explains the principles of Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS). These techniques aim to reduce switching losses, semiconductor stress, and electromagnetic interference (EMI). The review highlights the advantages of soft-switching techniques in improving converter efficiency and performance. However, further comparative analysis is required to evaluate the EMI reduction achieved by hard-switching and soft-switching techniques under identical operating conditions.

The paper [2] by Mohammed and Jung provides a state-of-the-art review of soft-switching techniques used in DC-DC, DC-AC, AC-DC, and AC-AC power converters. It examines different switching methods, including ZVS and ZCS, and discusses their effects on switching losses, efficiency, and converter performance. The study explains how auxiliary circuits and resonant components can facilitate soft switching. Although the review provides a broad understanding of soft-switching technologies, further simulation-based studies are required to compare their EMI performance with conventional hard-switching converters.

The paper [3] by Saygun et al. presents a comparative study of different soft-switching methods used in DC-DC converters. It investigates the operating principles and performance characteristics of various switching techniques and highlights their potential to reduce switching losses and improve power-conversion efficiency. The study provides a useful foundation for selecting suitable soft-switching methods for power-electronic applications. However, a detailed comparison of conducted EMI using frequency-spectrum analysis under the same input voltage, load, and switching frequency can provide further insight into the effectiveness of these methods.

The paper [4] by Hua et al. introduces novel Zero-Voltage-Transition Pulse-Width-Modulated (ZVT-PWM) converters. The proposed technique enables the main power switch to turn on under approximately zero-voltage conditions, reducing the overlap between voltage and current during switching transitions. This approach helps decrease switching losses and improve converter efficiency while retaining the benefits of PWM control. However, additional investigation is required to quantify the EMI reduction achieved by ZVT-based converters compared with conventional hard-switching converters.

The paper [5] by Hua et al. presents novel Zero-Current-Transition Pulse-Width-Modulated (ZCT-PWM) converters. The technique enables switching transitions to occur under approximately zero-current conditions, helping reduce switching losses and semiconductor stress. The study demonstrates the potential of ZCT techniques to improve the performance of PWM power converters. However, a direct comparison of switching waveforms, power losses, and EMI spectra between hard-switching and ZCT-based DC-DC converters would help establish the practical effectiveness of the proposed approach.

The paper [6] by Bodur and Bakan proposes an improved ZCT-PWM DC-DC converter intended for high-power and high-frequency applications. The design uses an auxiliary resonant switching arrangement to achieve zero-current-transition operation and reduce switching stress. This technique can improve converter performance under suitable operating conditions. Nevertheless, further analysis of conducted EMI, switching-frequency harmonics, and the additional complexity introduced by auxiliary components would be useful when comparing the proposed converter with a conventional hard-switching design.

The paper [7] by Pareschi et al. investigates spread-spectrum techniques for reducing electromagnetic interference in DC-DC converters. The study reviews methods that distribute switching noise across a wider frequency range instead of concentrating energy at particular switching-frequency harmonics. It also discusses the trade-offs associated with EMI reduction, control complexity, and converter performance. Although spread-spectrum modulation is a useful EMI mitigation technique, a comparative study involving soft-switching methods can help determine whether reducing switching-transition losses provides additional benefits.

The paper [8] by Kharanaq et al. reviews modeling techniques for analyzing conducted emissions in power converters. It discusses the importance of converter parasitic elements, common-mode and differential-mode noise, and electrical circuit behavior in EMI prediction. The study highlights the role of accurate modeling in understanding and reducing conducted electromagnetic emissions. However, further comparative simulation work is required to evaluate the conducted EMI generated by hard-switching and soft-switching DC-DC converters using consistent circuit parameters and operating conditions.

The paper [9] discusses modulation, control, and tuning approaches for high-performance DC-DC converters using small-signal and large-signal analysis. It provides a foundation for understanding converter control behavior, stability, and dynamic performance. These concepts are important when designing and evaluating DC-DC converters operating under different load and input conditions. However, the study does not directly establish the EMI reduction achieved by replacing hard switching with soft switching. Therefore, frequency-domain analysis and switching-loss calculations can be incorporated to provide a more focused comparison.

The paper [10] by Bellar et al. reviews soft-switched DC-AC converters and explains techniques used to improve switching performance and reduce power losses. It discusses the benefits of soft switching in power-electronic conversion systems and provides useful background on resonant switching techniques. Although the study primarily focuses on DC-AC converters, its concepts are relevant to understanding soft-switching principles. Further investigation specifically focused on DC-DC converters is needed to compare hard-switching and soft-switching operation in terms of switching losses, EMI, efficiency, and circuit complexity.

Research Gap: From the above literature, it is evident that several studies investigate soft-switching techniques, converter efficiency, and EMI reduction separately. However, a focused comparison of hard-switching and soft-switching operation in the same DC-DC converter, under identical input voltage, load, and switching-frequency conditions, can provide a clearer understanding of their relative performance. Therefore, the proposed work aims to simulate both switching techniques using LTspice, compare voltage and current waveforms, calculate switching losses and efficiency, and analyze frequency spectra to evaluate the potential for EMI reduction. The results will help identify the advantages and limitations of soft switching compared with conventional hard switching.

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3. EXPERIMENTAL AND SIMULATIONS

A. THEORY FOR LTSPICE IMPLEMENTATION

The proposed work compares hard-switching and soft-switching techniques in a DC-DC converter to evaluate switching losses and electromagnetic interference (EMI). LTspice is used to develop circuit models, simulate switching behavior, and analyze the frequency spectrum.

In the hard-switching converter, a PWM signal controls the MOSFET, which switches between ON and OFF states under non-zero voltage and current conditions during transitions. This can produce significant switching losses and rapid voltage and current changes, contributing to EMI.

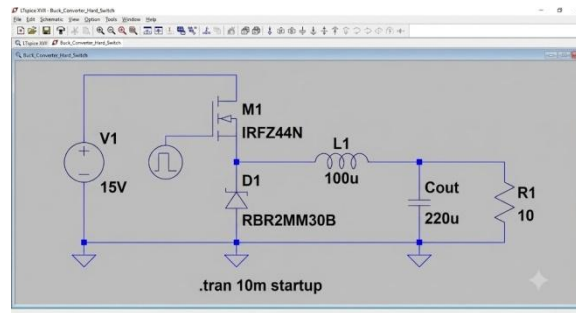


Fig 1. Hard Switching Circuit

In the soft-switching converter, a resonant inductor-capacitor (LC) network is introduced to enable Zero Voltage Switching (ZVS). The resonant circuit helps bring the MOSFET voltage close to zero before turn-on, reducing switching energy dissipation and potentially lowering high-frequency EMI.

The switching power loss can be estimated using:

$$P_{SW} = f_s(E_{On} + E_{Off})$$

where f_s is the switching frequency, and E_{On} and E_{Off} are the energy dissipated during turn-on and turn-off, respectively.

The converter efficiency is calculated as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

Fast Fourier Transform (FFT) analysis is used to compare the frequency components of switching waveforms. The resulting spectra help identify dominant harmonics and evaluate relative changes in EMI-related noise.

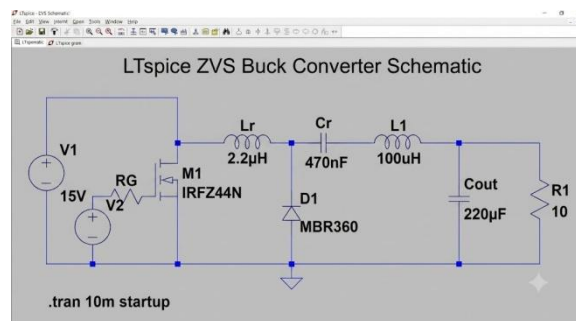


Fig 2 Soft Switching Circuit

B. Simulation Setup

The two converter circuits are implemented in LTspice using the same input voltage, output load, and switching frequency to ensure a fair comparison.

C. Calculation of Performance Metrics

1. Switching losses: Determine the energy dissipated during turn-on and turn-off by integrating the instantaneous MOSFET power over each switching transition.

$$E_{sw} = \int_{\text{transition}} v_{DS}(t) i_D(t) dt$$

2. Average switching power loss: Calculate the average switching energy per cycle multiplied by the switching frequency.

$$P_{sw} = f_s (E_{on} + E_{off})$$

3. Conversion efficiency: Calculate the ratio of output power to input power.

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

4. EMI frequency spectrum: Apply FFT analysis to the drain-source voltage, MOSFET current, or another consistently selected waveform. Compare the fundamental switching component and significant harmonics between both circuits.

5. Relative harmonic reduction: For a particular harmonic, calculate the reduction in amplitude using:

$$R_{dB} = 20 \log_{10} \left(\frac{A_{hard}}{A_{soft}} \right)$$

where (A_{hard}) and (A_{soft}) are the harmonic amplitudes measured using the same FFT settings. A positive value indicates a reduction in that harmonic's amplitude with soft switching.

4. RESULTS AND DISCUSSION

A. RESULT

Metric	Hard Switching	Soft Switching (ZVS)
Switching Frequency	50 – 200	50 – 200
Output Voltage (Vout)	~18	~18
Switching Loss (Psw)	Higher	Lower
Conduction Loss (Pcond)	Moderate	Slightly higher
Total Power Loss (Ptotal)	Higher	Lower
Voltage Spike (Vspike)	High (~120–200 V)	Low (~10–40 V)
Current Spike (Ispike)	High (~8–12 A)	Low (~1–3 A)
EMI Peak Magnitude	Higher (≈ 0 to -20 dB)	Lower (≈ -20 to -60 dB)
Efficiency (η)	88 – 92	94 – 97
Switching Stress (dv/dt, di/dt)	High	Low
Thermal Stress / Temperature	Higher	Lower
Harmonic Distortion (THD)	Higher	Lower
Load Regulation	Moderate	Better
Transient Response	Slower	Faster
Reliability / Lifespan	Lower	Higher

Table 1 Performance Metrics

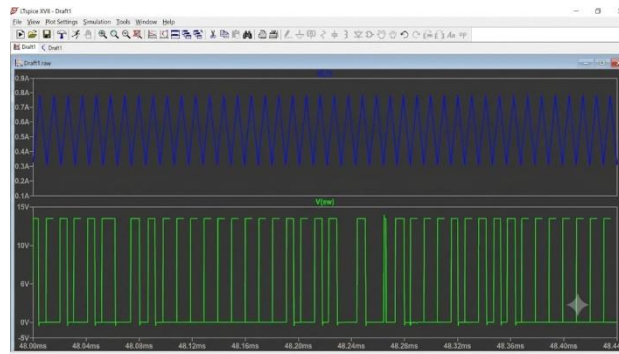


Fig 3 Output Characteristics of Hard Switching

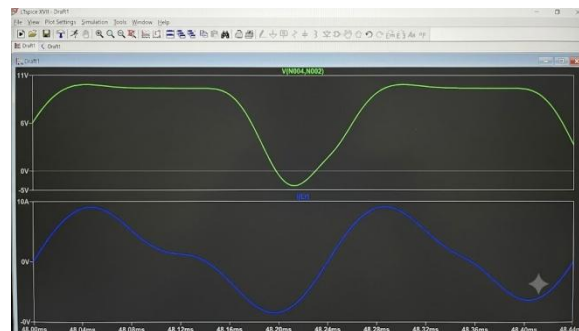


Fig 4 Output Characteristics of Soft Switching

B. SWITCHING WAVEFORM ANALYSIS

1. Hard-switching DC-DC converter

In the hard-switching converter, the MOSFET switches while voltage and current overlap during turn-on and turn-off transitions. The voltage and current waveforms can show rapid changes, and parasitic inductance and capacitance may produce ringing and spikes. These effects contribute to switching losses and high-frequency EMI. The switching waveforms obtained from LTspice will be used to calculate turn-on and turn-off energy.

2. Soft-switching DC-DC converter using ZVS

In the ZVS converter, the resonant LC network is designed to reduce the MOSFET drain-source voltage close to zero before turn-on. The voltage and current waveforms should be examined to confirm that zero-voltage turn-on actually occurs. If ZVS is achieved, turn-on losses can be reduced. The extent of turn-off loss reduction depends on the circuit topology and switching conditions.

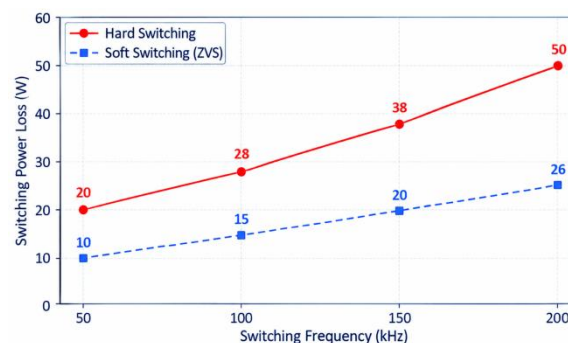


Fig 5 Performance Analysis 1

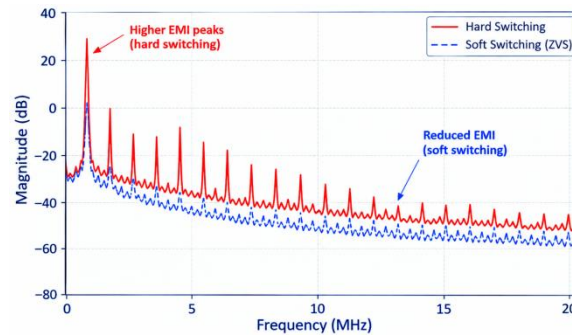


Fig 6 Performance Analysis 2

C. FFT-BASED EMI ANALYSIS

The FFT spectra of both converter circuits are compared using identical simulation durations, sampling settings, and waveform windows. The hard-switching circuit may exhibit stronger high-frequency harmonic components due to rapid switching transitions. The ZVS circuit may reduce selected harmonic amplitudes by smoothing the switching transition.

However, the magnitude of the reduction must be established from the actual simulation. FFT analysis of switching waveforms is useful for comparing relative spectral content, but it does not alone establish compliance with conducted or radiated EMI standards.

D. DISCUSSION

1. **Switching losses:** Hard switching typically has higher turn-on losses because voltage and current overlap during the transition. ZVS can reduce turn-on energy when the circuit achieves zero-voltage switching. Actual losses should be calculated from the simulated voltage and current waveforms.
2. **EMI characteristics:** Fast voltage and current transitions can excite parasitic circuit elements and generate high-frequency spectral components. ZVS may reduce some of these components, although resonant ringing can introduce additional frequency peaks.
3. **Efficiency:** Reduced switching losses can improve overall converter efficiency, particularly at higher switching frequencies. The improvement depends on additional resonant losses, conduction losses, and the operating load.
4. **Circuit complexity:** Hard-switching converters generally require fewer components and simpler control. ZVS converters require careful selection of resonant inductance, capacitance, timing, and operating conditions.
5. **Overall performance:** The preferred technique should be selected by comparing measured switching losses, efficiency, and FFT amplitudes under identical conditions. A lower harmonic amplitude in selected frequency bands does not automatically mean lower EMI across the entire spectrum.

5. CONCLUSION

This project presents a comparative analysis of hard-switching and soft-switching techniques for reducing electromagnetic interference (EMI) in DC-DC converters. The study focuses on evaluating switching behavior, power losses, conversion efficiency, and EMI characteristics using LTspice simulation. In conventional hard-switching converters, semiconductor devices turn ON and OFF while voltage and current overlap during switching transitions. This results in switching losses, voltage and current spikes, and high-frequency harmonic components that contribute to electromagnetic interference. Although hard-switching converters offer simple circuit design, low implementation complexity, and ease of control, their performance may be limited by increased switching losses and EMI at higher switching frequencies. In comparison, soft-switching techniques, particularly Zero Voltage Switching (ZVS), aim to reduce switching losses by enabling semiconductor devices to switch when the voltage across them is approximately zero. This approach can reduce switching-related energy dissipation and limit high-frequency noise generated during switching transitions. However, the effectiveness of soft switching depends on circuit topology, operating conditions, load variations, and the selection of resonant components. Additional components and control requirements may also increase circuit complexity and implementation cost. The proposed simulation evaluates both techniques under identical input voltage, switching frequency, and load conditions. Switching voltage and current waveforms are

analyzed to identify differences in switching transitions and power losses. Fast Fourier Transform (FFT) analysis is used to examine the frequency spectrum and compare the harmonic components associated with each technique. The results can help determine whether ZVS provides measurable improvements in EMI-related frequency components and converter efficiency compared with hard switching. Overall, soft switching is a promising approach for developing efficient, low-noise DC-DC converters for applications such as electric vehicles, renewable energy systems, battery chargers, and industrial power supplies. The final selection of a switching technique should consider EMI performance, efficiency, circuit complexity, and operating requirements. Future work may include experimental validation, conducted and radiated EMI measurements, load-dependent performance analysis, and optimization of resonant components to achieve improved EMI reduction and reliable converter operation.

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