

The paper introduces a range of Electromagnetic Interference (EMI) suppression methods to address this challenge, as shown in Figure 2. The advantages and limitations of each approach are summarised through an exhaustive analysis of past scholars' research. Furthermore, future development directions are proposed, building upon existing technical research.

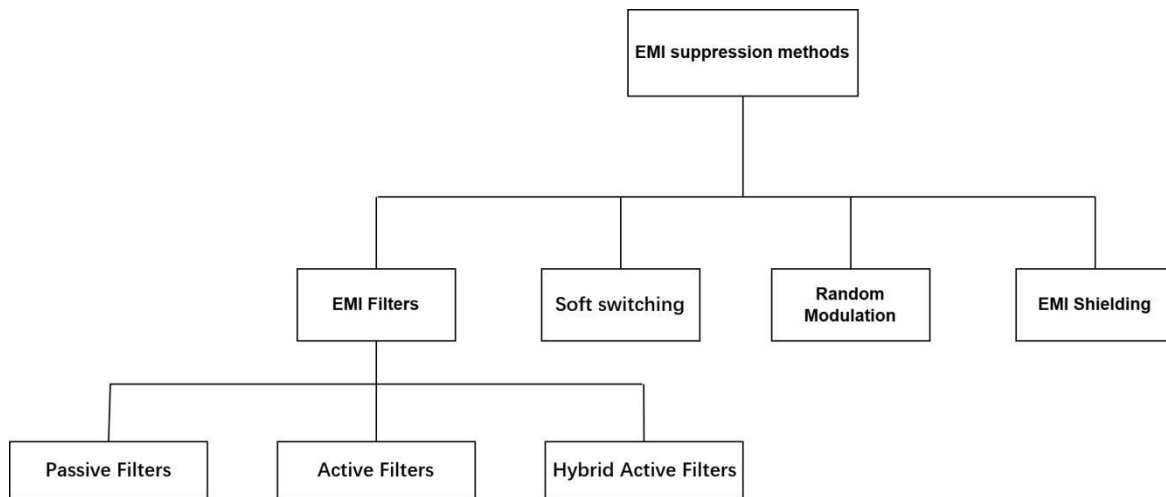


Fig.2 Classification of EMI suppression methods (Photo/Picture credit : Original)

2. Techniques to reduce EMI

2.1. EMI Filter

2.1.1 Passive filter

The most widely employed method for effective electromagnetic interference (EMI) suppression in practical applications is passive EMI filters. The most widely employed method for effective electromagnetic interference suppression in practical applications is passive EMI filters. Figure 3 shows the structure of this type of filter. EMI filters are often created separately to suppress EMI effectively [6]. The expense of the output filter is crucial and may even be more in high-power applications than the price of the converter power unit. Additionally, passive filters have intrinsic disadvantages such as significant extra losses, lower dynamics, diminished voltage, inadequate power density, frequency dependence, and oscillation susceptibility [7]. These disadvantages of passive filters can be further amplified when more stringent harmonic limits are imposed [8].

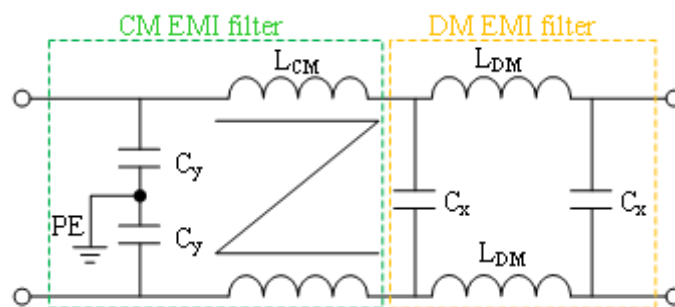


Fig.3 Basic structure of passive electromagnetic interference [6]

2.1.2 Active filter

The most commonly used active filter in practical applications is the shunt active filter, as shown in the figure 4. It is designed to function through harmonic current control, enabling the attenuation of individual harmonics by injecting opposing phases. Consequently, this technique enhances the power quality of passive loads [9], [10]. The active components impose limitations on the dynamic range of an active filter. Consequently, active filters may be required in certain applications to

accommodate extremely high input amplitudes or frequency ranges, thereby diminishing the filter's performance.

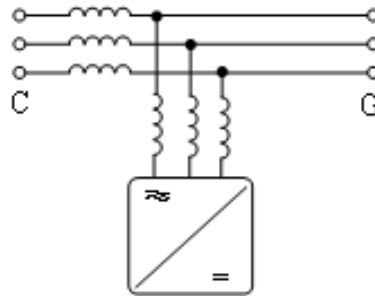


Fig.4 Shunt-active filter [10]

2.1.3 Hybrid active filter

Hybrid filters typically comprise a passive filter stage and an active amplifier or operational amplifier. They leverage the frequency selectivity of the passive filter along with the amplification and compensation functions of the active filter to enhance the performance and adaptability of the filter. Additionally, they enable more effective compensation of non-linear loads at a reduced cost [11].

2.2. Soft Switching

Large output dv/dt contributes to interference due to capacitive coupling, while larger di/dt values result in EMI. The presence of higher dv/dt and di/dt levels generates a significant source of electromagnetic interference. Soft switching strategies have been created to reduce the dv/dt and di/dt levels produced by power devices in the system in order to reduce EMI [12]. In [13] gives a theoretical overview and analysis of the SiC MOSFET switching circuit shown in Figure 5. The effect of MOSFET switching losses is analyzed and evaluated experimentally. Soft switching reduces switching losses by 97% while reducing dv/dt during switching transients by 86%, significantly mitigating electromagnetic interference characteristics. These results demonstrate that the soft-switching approach can significantly improve the performance of high-speed SiC MOSFET converters.

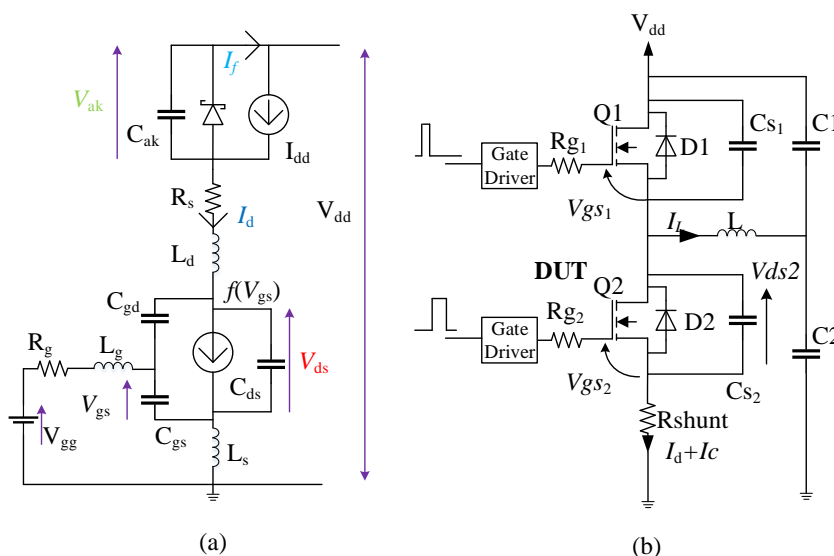


Fig.5 SiC MOSFET test circuit. (a) Test for hard switching. (b) Test for soft switching. [13]

Study was conducted to optimize the efficiency of soft switching converters through the balanced design of PCB winding coupling inductors. The number of turns, coupling coefficients between the

primary inductors, and winding structure were design criteria. Experimental results showed that the PCB winding coupling inductor for the balancing approach significantly increased efficiency [14].

Soft switches, however, exhibit certain limitations. Particularly in environments characterized by high frequencies, high voltages, or high currents, where soft switches are more prone to electromagnetic interference. Additionally, incorporating supplementary components in the soft switch design amplifies power loss and introduces increased complexity to the switch mode converter design, posing additional challenges.

2.3. Random Modulation

Random Pulse Width Modulation (RPWM) is utilized to regulate the switching signals of a power converter, aiming to mitigate harmonic peaks by expanding the noise spectrum. Numerous power converter manufacturers have adopted this modulation technique to adhere to electromagnetic compatibility (EMC) test standards [15].

[16] explores the optimization of the output signal for CSPWM modulation with a low switching frequency. Through the circuit simulation experiment as shown in Figure 6, employing stochastic modulation with a high degree of randomness at low switching frequencies can significantly elevate the level of low-frequency harmonics in the output signal but lead to considerable distortion. To address this issue, adjusting the system's feedback loop parameters is imperative, allowing for the effective application of stochastic modulation at low frequencies. Additionally, determining the specific optimal parameters of the circuit should be done in conjunction with the switching frequency.

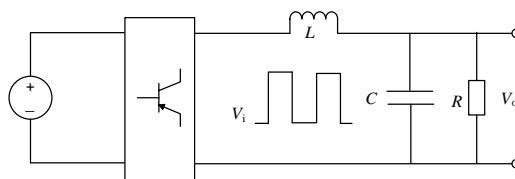


Fig.6 Topology of low switching frequency random modulation [16]

There exist two limitations associated with this form of regulation. Firstly, the real-time generation of random signals poses a significant challenge. Secondly, the parameter design becomes complicated due to the incorporation of random frequencies [17].

2.4. EMI Shielding

Three general scenarios occur when an electromagnetic wave passes through a shielding material. i) Due to the material's weak electromagnetic attenuation capability, a majority of the electromagnetic waves will be transmitted. ii) A significant portion of the electromagnetic wave can be reflected, resulting in excellent shielding efficiency but leading to secondary electromagnetic pollution. iii) If the material possesses proper impedance matching and exhibits good electromagnetic wave attenuation capability, it can effectively absorb the majority of the electromagnetic wave through multiple attenuation mechanisms [18,19].

A novel and eco-friendly form of electromagnetic interference (EMI) shielding has recently emerged, known as green EMI shielding. This advanced shielding technique not only safeguards internal components but also significantly reduces or eliminates potential hazards posed to the external environment. Compared to conventional shielding methods, green EMI shielding exhibits superior performance by efficiently mitigating the adverse effects of electromagnetic waves. Its strong ability to absorb and suppress secondary reflections ensures optimal shielding effectiveness, making it an ideal choice for applications where reliable EMI protection is of utmost importance [20].

However, the results of the present study cannot be widely applied. The link between the reaction principle, regulatory approach, and effectiveness still has to be thoroughly understood, and the mechanism of structure assembly needs to be made more explicit. Therefore, there is a constant need to research new mechanisms, materials, architectures, and methods. This will improve the existing

research framework and provide the development of multifunctional green EMI shielding materials and technologies with enormous potential [20].

Table 1. Advantages and disadvantages of each method

Method	Advantages	Disadvantages
Filters	Effective suppression of electromagnetic interference Simple and easy to use Reduces switching losses	Limited frequency range Higher cost
Soft Switching	Effective reduction of common mode (CM) noise	Complicated design
Random Modulation	Mitigate harmonic peaks	Not easy to generate real-time signals Parametric signal design is complex
EMI Shielding	Environment friendly Effective absorption of electromagnetic wave	In the research stage Not yet widely used

3. Comparison between Different EMI Suppression Methods

After exploring four distinct approaches to mitigate electromagnetic interference, the findings are consolidated and presented in the Table 1.

Each method's principles, advantages, and limitations are thoroughly discussed to provide insights for future research. Furthermore, this article outlines potential directions for further research, offering guidance and inspiration for the ongoing development of EMI suppression technology.

Filters: The study focuses on researching and designing specialized filter structures suitable for high-frequency applications. Additionally, efforts are made to optimize filter layout and connections to minimize conduction and radiation losses, ensuring consistent suppression effects even at high frequencies.

Soft Switching: Soft switching circuits, while effective, pose challenges due to their complex design, leading to increased costs. To overcome this, researchers are encouraged to explore new topologies and control strategies that reduce circuit complexity and optimize hardware design for cost reduction.

Stochastic Modulation: The article advocates for upgrading intelligent algorithms and control techniques for implementing stochastic modulation. Advanced algorithms and control mechanisms can adaptively adjust stochastic modulation parameters based on real-time EMI interference situations, thus enhancing suppression efficiency and stability.

Electromagnetic Shielding: Research in this area focuses on exploring innovative shielding materials and structures to improve shielding effectiveness while minimizing impacts on equipment performance.

For optimal EMI suppression, a combination of methods may be required. A comprehensive evaluation of the pros and cons of various suppression technologies is critical during the design phase. The decision on the appropriate way and their combination should be based on specific needs to ensure effective EMI suppression, system stability and reliability.

4. Conclusion

This thesis presents a comprehensive synthesis of existing research on electromagnetic interference suppression and introduces four novel methods for achieving effective EMI mitigation. The discussed methods include filters, soft switching, shielding, and stochastic modulation. By pursuing the research directions outlined in this study, EMI suppression technology will be better

equipped to adapt to the ever-evolving demands of electronic equipment and system requirements. This, in turn, will elevate the system's anti-interference capabilities and overall reliability.

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