Hybrid EMI Mitigation in PV Systems

SITTALATCHOUMY R[1], SUSHMITHA V[2]
[1,2] *Department of ECE*, *Anna University* Chennai, India

Abstract—Photovoltaic (PV) inverter systems play a crucial role in renewable energy applications. Nevertheless, their rapid switching activity frequently produces unwanted electromagnetic interference (EMI), which diminishes performance and leads to non-compliance with electromagnetic compatibility (EMC) regulations. This study suggests a hybrid method for EMI reduction that integrates Spread Spectrum Pulse Width Modulation (SSPWM) with an RC snubber circuit. SSPWM distributes the spectral energy of switching harmonics across a broader frequency range, thus reducing the intensity of EMI peaks. The RC snubber circuit, conversely, captures transient energy and minimizes voltage spikes resulting from switching transitions. Analysis through simulation and experimentation was performed for four scenarios traditional PWM, SSPWM, RC snubber, and the hybrid setup. The comparative findings indicate that the hybrid method achieves considerable EMI reduction, lessening both the amplitude of high-frequency noise and the strength of narrowband spikes. This approach is straightforward, cost-effective, and works well with current inverter designs.

Keywords—Electromagnetic Interference (EMI), Photovoltaic Inverter, Spread Spectrum PWM, RC Snubber, Hybrid Mitigation, Switching Noise, Power Electronics.

I. INTRODUCTION

The increasing worldwide need for clean and sustainable energy has sped up the implementation of renewable energy systems, with solar photovoltaic (PV) technology being a key component. PV systems transform sunlight into electrical energy and, when combined with effective power electronics, provide clean electricity for residential, industrial, and grid uses. An essential part of any PV system is the inverter, responsible for transforming the direct current (DC) produced by the solar panels into alternating current (AC).

Contemporary PV inverters utilize high-frequency switching components, such as Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) and Insulated Gate Bipolar Transistors (IGBTs), to attain elevated conversion efficiency, streamlined design, and accurate output regulation. Even with these benefits, their rapid switching characteristics bring about new issues concerning power quality and electromagnetic compatibility (EMC). The swift changes in current and voltage, marked by sharp dv/dt and di/dt values generate undesired electromagnetic interference (EMI).

EMI primarily originates from the parasitic capacitances and inductances found in inverter circuits and their connecting cables. During high-speed switching, these parasitics generate transient oscillations that either radiate or conduct noise across a broad spectrum of frequencies. This unwanted sound can disrupt nearby delicate devices, lead to failures in control electronics, and impair the functioning of communication systems. Additionally, high levels of EMI may result in failure to comply with EMC regulations like CISPR 11 and IEC 61000 standards, which could disqualify a product from certification.

Besides impacting external devices, EMI inside the inverter can also diminish its efficiency and reliability. Voltage spikes and ringing put pressure on the semiconductor switches, leading to thermal losses, gate issues, and early device failure. Consequently, EMI suppression has emerged as a crucial design factor in creating power electronic systems for renewable energy applications.

II. THEORETICAL BACKGROUND AND MODELING

EMI in power electronic converters primarily originates from the rapid switching transitions of semiconductor components, resulting in abrupt variations in voltage and current. These rapid *dv/dt* and *di/dt* changes stimulate the parasitic inductances and capacitances in the circuit, resulting in oscillatory transients and the generation of high-frequency noise.

These disruptions can travel through the power cables (conducted EMI) or emit into the nearby surroundings (radiated EMI), resulting in reduced performance and electromagnetic compatibility (EMC) problems. To address these issues, both hardware-oriented and control-oriented mitigation strategies are utilized. Hardware solutions, including RC snubber networks and EMI filters, mitigate transient energy at the source, whereas control techniques like Spread Spectrum Pulse Width Modulation (SSPWM) spread the harmonic energy over a broader frequency range to lower peak EMI levels.

A. Electromagnetic Interference in PV Inverters

The physical origin of EMI in a power electronic converter, like a PV inverter, arises from the non-ideal and swift switching of power semiconductors (IGBTs or MOSFETs). These rapid changes produce two main noise elements:

Elevated *dv/dt* (voltage change rate): When a switch is turned OFF, the swift voltage increase across the terminals couples capacitively with other system components, especially the chassis or heat sink via parasitic capacitance C_p. This creates Common Mode (CM) interference, which spreads uniformly across all lines in relation to the ground reference. CM noise frequently serves as the primary source of emitted EMI and plays a crucial role in conducted EMI.

Elevated *di/dt* (current change rate): When a switch activates, the swift current increase interacts with parasitic inductance (L_p) in the wires, PCB traces, and component leads. This results in voltage ringing (oscillatory transients) and also produces Differential Mode (DM) noise, which travels between the power lines (e.g., positive and negative bus).

These transients are marked by high-frequency ringing that greatly expands the frequency range of the noise. The maximum value of the EMI voltage (V_{emi}) is directly related to the rate at which voltage and current change, while being inversely related to the switching frequency (f_s):

$$V_{emi} \, \alpha \, \frac{di/dt + dv/dt}{f_s}$$

Adherence to Electromagnetic Compatibility (EMC) regulations, including CISPR (like CISPR 11) or FCC Part 15, is required for grid-tied PV systems. These regulations set strict limits on the maximum permissible noise levels across a defined frequency range (usually 150 kHz to 30 MHz for conducted EMI). Conventional mitigation depends on large L-C filters to reduce noise, but this escalates the system's size, expense, and complexity.

B. Spread Spectrum Pulse Width Modulation (SSPWM)

SSPWM is a very efficient, software-driven EMI reduction method that tackles the noise's spectral energy distribution. Rather than eliminating the noise source, it disperses the energy across a broader range, thus reducing the highest amplitude of any individual harmonic peak to adhere to regulatory standards.

1. SSPWM Mechanism and Profiles

In traditional Pulse Width Modulation (PWM), the constant switching frequency (f_s) generates sharp, focused energy peaks in the spectrum at fs and its whole number multiples. SSPWM consistently alters the carrier frequency within a specified range (Δf) centered around a central frequency (f_c). The momentary frequency *f(t)* is influenced by a low-frequency signal, typically referred to as the modulation profile:

$$f(t) = f_c + \Delta f \, sin(2\pi f_m \, t)$$

where:

- f_c is the nominal center switching frequency (10 kHz).
- Δf is the maximum frequency deviation ($\pm$200 Hz).
- f_m is the modulation frequency, which dictates the rate at which the switching frequency fluctuates.

2. Types and Trade-offs

Additional typical SSPWM profiles consist of Triangular/Linear and Random profiles. The selection of the modulation profile (f_m) and the frequency deviation Δf is essential.

A larger Δf results in an increased spreading effect and reduced EMI peaks. Nonetheless, overly large variations can make the output filter's design more complex and may add unwanted low-frequency elements to the output voltage, affecting power quality.

A quicker modulation frequency (f_m) guarantees faster spectral smoothing but demands more computational resources.

The primary benefit of SSPWM is its incorporation into the digital control algorithm, eliminating the need for extra hardware, thereby reducing system cost and dimensions. Its main drawback is that the overall noise power stays the same; only the distribution across the spectrum is altered.

C. RC Snubber Circuit

The RC snubber is a traditional, time-domain hardware method utilized to directly mitigate the physical transient creation at the source the terminals of the semiconductor switch.

1. Snubber Function and Operation

The snubber circuit, made up of a series resistor (R) and capacitor (C), is linked in parallel to the switching component. The main role of the snubber is to suppress the high-frequency oscillations generated by the resonance between the loop inductance of the circuit (L_{loop}) and the parasitic output capacitance of the switch (C_{oss})

While Turn-Off occurs: When the switch opens, the L_{loop} drives current to continue flowing. The snubber capacitor (C) offers a low-resistance route, capturing the energy from L_{loop} and reducing the *dv/dt* across the switch. This leads to a more gradual voltage increase and greatly lowered voltage overshoot and ringing.

During activation: The capacitor C releases its energy through the switch and the snubber resistor R. The resistor R is vital for restricting the discharge current and dissipating the absorbed transient energy, avoiding excessive power loss and possible harm to the switch.

2. Design and Power loss

The effectiveness of the snubber is governed by the time constant τ:

$$\tau = R \; X \; C$$

In this configuration, the components are chosen as R = 470 Ω and C = 0.047µF. These parameters are selected to establish a damping ratio that reduces overshoot while avoiding significant power loss:

$$P_{snubber} \approx C \, . V_{dc}{}^{2} . f_s$$

where V_{dc} represents the voltage of the DC link. This loss needs to be managed with care in high-power systems. The snubber efficiently restricts the *dv/dt* from surpassing 1000 $V/\mu s$ to more secure levels, generally under 100 $V/\mu s$, which is essential for minimizing CM noise

D. Hybrid SSPWM and RC Snubber Method

The suggested hybrid method leverages the complementary characteristics of SSPWM (a control-level solution) and the RC snubber (a circuit-level solution) to enhance EMI reduction.

This collaboration enables the system to address the EMI issue in two separate areas at the same time:

Mitigation Technique	EMI Component Addressed	Reduction Mechanism
RC Snubber	Broadband Noise, Transients	Limits *dv/dt* and damps high-frequency ringing by absorbing transient energy.
SSPWM	Narrowband Harmonics	Spreads the remaining harmonic energy over a wider band, reducing the peak amplitude.

Table 1. Mitigation Techniques

The efficiency of this combined approach exceeds the mere sum of the two separate techniques. Lowering the intensity of the switching transient (through the snubber) results in a decreased initial base level of generated noise energy. Thereafter, SSPWM utilizes this lower-level harmonic energy and disperses it, leading to a markedly reduced overall peak EMI magnitude and a more uniform, distributed spectral profile. This twofold strategy guarantees adherence to the peak-amplitude criteria of EMC standards while improving the physical quality of the waveform.

© NOV 2025 | IRE Journals | Volume 9 Issue 5 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I5-1711928

III. SIMULATION METHODOLOGY

The validation of the proposed hybrid EMI mitigation technique was performed through a comprehensive methodology involving both theoretical modeling in a simulation environment and a defined comparative experimental procedure.

A. Simulation Setup and Modeling

The system was modelled in MATLAB to facilitate a controlled environment for testing the four mitigation cases. The core component was a single-phase full-bridge voltage source inverter (VSI), a common topology in low-to-medium power PV applications.

1. Inverter and Load Parameters

The system was configured with realistic parameters typical for a small-scale PV micro-inverter or battery backup system:

Parameter	Symbol	Value	Notes
DC Input Voltage	V_{dc}	48V	Represents battery or PV array output.
Output Frequency	f_o	50Hz	Standard grid frequency.
Nominal Switching Frequency	f_s	10kHz	Baseline PWM carrier frequency.
Load Resistance	R_L	10 Ω	Pure resistive load for simplicity in initial testing.

Table 2. Design Parameters

The inverter switches were modelled using ideal MOSFET blocks to isolate the switching dynamics from semiconductor non-linearities, allowing focus on the high *dv/dt* and *di/dt* effects. Parasitic elements (e.g., L_{loop} of 100nH and C_p of 100pF were intentionally added to the switching loops to accurately represent the environment where EMI is generated.

2. SSPWM Implementation

The Spread Spectrum PWM was implemented by modulating the carrier signal's frequency. A Sinusoidal Frequency Modulation (SFM) profile was used, generated by an algebraic block that continuously varies the carrier frequency input to the PWM generator block.

- Centre Frequency (f_c): 10kHz
- Frequency Deviation (Δf): ± 200 Hz (i.e., ranging from 9.8 kHz to 10.2 kHz)
- Modulation Frequency (f_m): 50Hz (chosen to be synchronous with the output frequency, minimizing inter-harmonic generation).

This implementation ensures that the resulting switching frequency shifts smoothly and continuously, effectively blurring the sharp spectral peaks.

3. RC Snubber Implementation

The RC Snubber Circuit was placed directly in parallel with each of the four inverter switches. The selection of the *R* and *C* values was based on matching the characteristic impedance ($\sqrt{L_{loop}/C_{oss}}$ of the switching loop to achieve optimal damping:

- Snubber Resistance (R): 470 Ω
- Snubber Capacitance (C): 0.047 µF

The resistor value limits the capacitor discharge current at turn-on, while the capacitor value is large enough to absorb the transient energy without becoming a significant source of power loss. The time constant $\tau = R\ X\ C$ determines the effectiveness of the *dv/dt* reduction.

B. Experimental Procedure and Measurement

The effectiveness of the mitigation techniques was evaluated by comparing the noise spectrum under four distinct operational configurations. The primary focus of the measurement was the Conducted EMI on the DC input lines, as this is where high-frequency switching noise typically couples back into the source.

© NOV 2025 | IRE Journals | Volume 9 Issue 5 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I5-1711928

1.Cases

Case	Control Technique	Circuit Hardware	Primary Effect Studied
Case 1 (Baseline)	Fixed-Frequency PWM (10 kHz)	No Snubbers	Reference EMI spectrum with sharp, narrowband peaks.
Case 2 (SSPWM Only)	Spread Spectrum PWM	No Snubbers	Spectral spreading and peak reduction due to frequency variation.
Case 3 (Snubber Only)	Fixed-Frequency PWM (10 kHz)	RC Snubbers Applied	*dv/dt* suppression and broadband noise reduction.
Case 4 (Hybrid)	Spread Spectrum PWM	RC Snubbers Applied	Combined spectral spreading and transient damping.

Table 3. Mitigation Methods

2. EMI Measurement and Analysis

In the simulation, the EMI was quantified by performing a Fast Fourier Transform (FFT) on the high-frequency voltage components measured across the DC-link terminals.

1. Time-Domain Analysis: Oscilloscope plots were used to visually inspect the *dv/dt* across the switch terminals in each case. A successful snubber implementation (Cases 3 and 4) showed a noticeable decrease in voltage overshoot and ringing frequency compared to Cases 1 and 2.
2. Frequency-Domain Analysis (Spectrum Analysis): The FFT tool was configured to analyze the frequency range from 10kHz (switching frequency) up to 1 MHz to capture the relevant conducted noise spectrum. The primary metric for comparison was the peak magnitude of the harmonic components, measured in relative dB against the baseline (Case 1).

The results from this detailed comparative analysis, documented in Section IV, provide quantitative proof of the superior performance of the Hybrid SSPWM + RC Snubber configuration in achieving significant noise attenuation.

IV. RESULTS AND DISCUSSION

The efficacy of the proposed hybrid EMI mitigation approach was quantitatively assessed by comparing the measured conducted EMI spectrum and key performance metrics across four distinct operating cases: Fixed PWM (Baseline), SSPWM Only, RC Snubber Only, and the Hybrid SSPWM + RC Snubber configuration. The conducted EMI was measured in the frequency range up to 500kHz to capture the fundamental switching frequency and its harmonics.

A. Baseline EMI Analysis (Fixed PWM)

The spectrum for the Fixed PWM (Baseline) case (Fig. 1) established the reference noise level. In this configuration, the inverter operated at a constant 10kHz switching frequency.

- The spectrum is characterized by sharp, narrowband spikes corresponding to the switching frequency and its harmonics, which extend throughout the measured band. The noise magnitude is highest near the fundamental switching frequency and gradually decays.
- This case exhibits the highest recorded Peak EMI magnitude and a critically high maximum rate of voltage change (Max *dv/dt*) of 1200.00 V/µs. This excessive *dv/dt* is the primary driver of both conducted and radiated noise in the system.

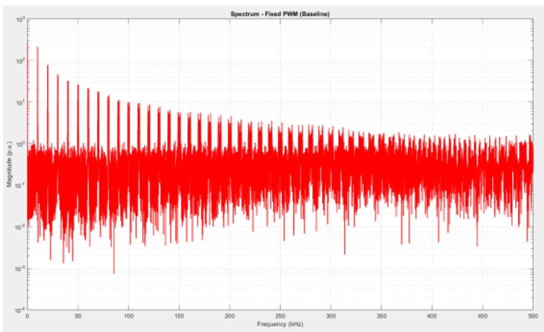

Fig. 1. Fixed PWM Waveform

B. Spread Spectrum PWM (SSPWM)

Applying SSPWM alone (Fig. 2) resulted in a fundamental change in the spectral profile of the EMI:

- Spectral Spreading: The sharp harmonic peaks seen in the baseline are spread out over a wider frequency floor, confirming that SSPWM redistributes the energy rather than removing it.
- Peak Reduction: This spreading directly translates to a lower peak magnitude. The SSPWM case achieved a Peak EMI Reduction of 6.01dB compared to the baseline. This reduction is sufficient to help meet narrowband regulatory limits.
- Noise Energy: Critically, the measured Noise Band Energy (8-12 kHz) remains nearly unchanged (5.873e + 04) compared to the baseline (5.853e + 04). This confirms the theory that SSPWM does not absorb noise energy, but solely mitigates peaks by spectral redistribution.

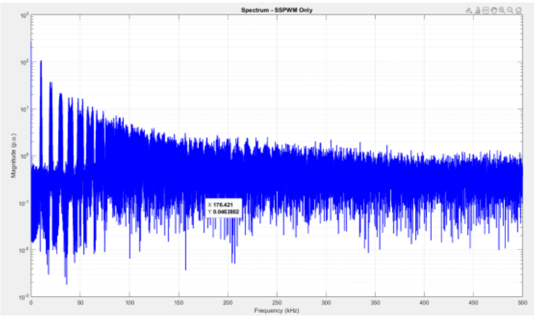

Fig. 2. Spread spectrum PWM Waveform

C. RC Snubber

The application of the RC snubber circuits (Fig. 3) across the switches offered a different form of mitigation:

- Transient Suppression: The snubber's core function is to dampen the physical switching transients. This is evidenced by a dramatic reduction in the Max *dv/dt*, which dropped from 1200.00 V/µs (Fixed PWM) to just 109.09 V/µs a reduction of over 10x. This lowering of the *dv/dt* is fundamental to reducing the generation of high-frequency noise.
- Broadband Noise Reduction: The spectral plots show that the high-frequency floor is significantly lower than in the SSPWM case. Furthermore, the Noise Band Energy shows a substantial drop to 4.074e + 04. This energy reduction confirms that the snubber absorbs and dissipates noise energy, unlike SSPWM.
- Peak Trade-off: The Snubber Only configuration provided a modest Peak EMI Reduction of 1.57 dB. While it reduced the overall energy (broadband noise), its fixed-frequency operation meant the fundamental harmonics remained concentrated, thus limiting its peak reduction performance alone.

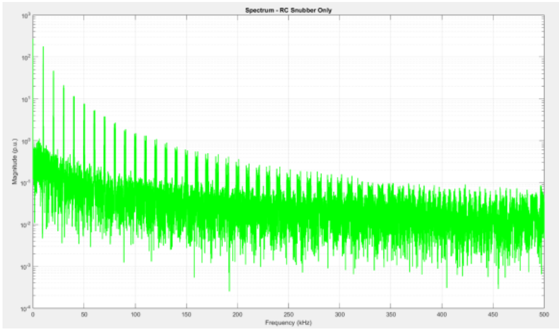

Fig. 3. RC Snubber Waveform

D. Hybrid Mitigation Performance

The Hybrid SSPWM + RC Snubber configuration (Fig. 4 and Fig. 5, magenta line) leveraged the strengths of both approaches, resulting in the most effective EMI suppression:

- Synergistic Mitigation: The snubber first reduced the inherent *dv/dt* noise generation (lowering the broadband noise floor and overall energy), and then the SSPWM spread the remaining harmonic peaks.
- Maximum Peak Reduction: The combined technique achieved the maximum reduction in the highest noise peaks, yielding a Peak EMI Reduction of 7.53dB. This is notably greater than either method individually, confirming that the hybrid approach provides a double-layer suppression.
- Energy and Spreading: The noise band energy (4.089e + 04) is nearly identical to the Snubber Only case, confirming that the snubber is responsible for the energy reduction. Simultaneously, the visual appearance of the spectrum (Fig. 4) is smooth and flat, demonstrating that the remaining energy is distributed effectively by the SSPWM.

The comparative plot (Fig. 5) clearly illustrates the hierarchy of mitigation effectiveness, with the magenta trace (Hybrid) consistently showing the lowest overall noise level, particularly when considering both peak magnitude and broadband noise floor. This demonstrates the superior performance achieved when employing techniques that address both the spectral spreading and transient suppression aspects of EMI.

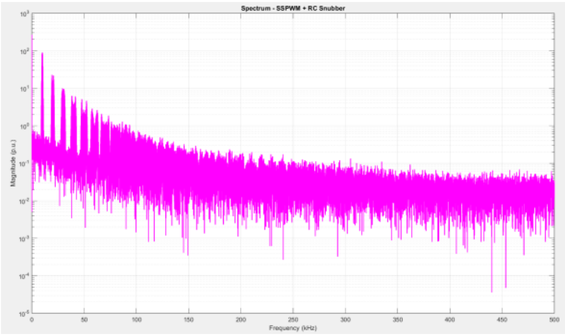

Fig. 4. SSPWM + RC Snubber Waveform

```
--- EMI Mitigation Metrics ---
Peak EMI Reduction (SSPWM): 6.01 dB
Peak EMI Reduction (RC Snubber): 1.57 dB
Peak EMI Reduction (SSPWM + RC): 7.53 dB

Max dv/dt (Fixed PWM): 1200.00 V/us
Max dv/dt (RC Snubber): 109.09 V/us

Noise Band Energy (8-12 kHz):
Fixed PWM: 5.853e+04
SSPWM: 5.873e+04
RC Snubber: 4.074e+04
SSPWM + RC: 4.089e+04
```

Fig. 5. Performance Metrices

Configuration	Peak EMI Reduction (dB)	Max dv/dt (V/µs)	Noise Band Energy (8-12 kHz)	Mitigation Mechanism
Fixed PWM (Baseline)	—	1200.00	5.853e+04	None
SSPWM Only	6.01 dB	1200.00	5.873e+04	Spectral Spreading
RC Snubber Only	1.57 dB	109.09	4.074e+04	Transient Damping / Energy Reduction
Hybrid (SSPWM + RC)	7.53 dB	109.09	4.089e+04	Energy Reduction + Spectral Spreading

Table 4. Performance Metrices

V. CONCLUSION AND FUTURE SCOPE

The hybrid EMI mitigation approach, integrating Spread Spectrum Pulse Width Modulation (SSPWM) and RC Snubber Circuits, has been successfully validated as a highly effective strategy for suppressing noise in Photovoltaic (PV) inverter systems. The study confirmed that the most robust mitigation occurs when addressing EMI at both the control level and the circuit level. The RC snubber fundamentally tackled the source of the noise by limiting the maximum rate of voltage rise (*dv/dt*), which dramatically reduced the transient energy. This action alone reduced the Max *dv/dt* from 1200.00 V/µs in the fixed PWM case to 109.09 V/µs. Subsequently, the SSPWM effectively managed the remaining spectral energy by distributing it across a wider frequency band, thus lowering the peak amplitudes. Quantitatively, the combined methodology achieved a superior 7.53 dB Peak EMI Reduction compared to either SSPWM only (6.01 dB) or RC snubber only (1.57dB). This synergistic performance provides a low-cost, easily implementable solution that enhances power quality and ensures compliance with stringent electromagnetic compatibility standards.

The presented hybrid methodology lays a strong foundation for future research and industrial implementation. One immediate area for expansion is the application of the hybrid technique to three-phase grid-tied PV inverters, where Common Mode EMI issues are more pronounced and critical. Further research should focus on optimizing the SSPWM modulation profile (e.g., comparing random vs. sinusoidal spreading) and intelligently adaptive snubber design, where the *R* and *C* values could dynamically adjust based on load conditions to minimize power loss while maintaining effective *dv/dt* suppression. Additionally, exploring the integration of this technique with active EMI filtering or advanced wide-bandgap (SiC/GaN) devices could further push the boundaries of noise reduction in high-frequency power electronics. Ultimately, the goal is to develop standardized, embedded EMI solutions that minimize the need for external, bulky passive filters, thereby increasing the power density and reducing the overall cost of renewable energy systems.

REFERENCES

[1] A. Kodali, *Engineering Electromagnetic Compatibility*, 2nd ed. Hoboken, NJ, USA: Wiley-IEEE Press, 2017.

[2] Y. Yang, F. Blaabjerg, and D. Chen, "EMI mitigation techniques in power electronic converters—A comprehensive review," *IEEE Transactions on Power Electronics*, vol. 36, no. 4, pp. 4153–4167, Apr. 2021.

[3] S. K. Dhar and P. Mitra, "Implementation of spread spectrum PWM for EMI reduction in inverter systems," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 3710–3718, May 2019.

[4] M. Ahmed and A. Elserougi, "Design of RC snubber networks for EMI suppression in high-frequency converters," in *Proc. IEEE IECON – 46th Annual Conference of the IEEE Industrial Electronics Society*, Singapore, Oct. 2020, pp. 2438–2443.

[5] M. R. Khan and R. Datta, "Hybrid EMI suppression in PV inverters using control and circuit-level approaches," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 6, pp. 7602–7612, Dec. 2021.

[6] S. R. Kumar and V. Singh, "Analysis of conducted EMI in grid-connected PV inverters and its reduction using spread-spectrum control," *IEEE Access*, vol. 10, pp. 58412–58423, Jun. 2022.

[7] P. A. Chatterjee and J. Das, "A comparative study of snubber topologies for switching noise reduction in power converters," *IET Power Electronics*, vol. 13, no. 11, pp. 2338–2348, 2020.

[8] J. M. Guerrero and L. Zhang, "Control strategies for EMI reduction in renewable energy inverters," *IEEE Transactions on Energy Conversion*, vol. 35, no. 3, pp. 1587–1599, Sep. 2020.