Integrated Modeling and Mult objective Control of Multilevel DC/AC Inverters for Conducted Electromagnetic Interference Mitigation

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النمذجة المتكاملة والتحكم متعدد الأهداف في العواكس متعددة المستويات DC/AC للتخفيف من التداخل الكهرومغناطيسي الموصّل

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Abstract

Multilevel DC/AC inverters have become a major enabling technology for renewable energy systems, electric vehicles, smart grids and industrial motor drives since they can produce high-quality output voltages with lower switching stress and higher power conversion efficiency. However, the impulse HMIs but also high-frequency switching actions and complicated modulation processes used in the more advanced multilevel inverter topologies result in undesirable high amplitude conducted EMI appearing at their terminals, which can severely affect electromagnetic compatibility (EMC), system reliability, power quality and compliance with international regulatory standards. Passive Filtering Techniques or Conventional EMI mitigation approaches which is primarily relying on passive filtering techniques and also adds to the size, cost and power losses in the system due to reduced adaptability under diverse operating conditions

The research proposes an integrated model and Mult objective control framework for conduction EMI mitigation in multilevel DC/AC inverters. An exhaustive mathematical model is designed to describe the inverter switching dynamic, parasitic element contribution, common-mode voltage generation and differential-mode disturbances propagation processes as well as EMI propagation mechanisms. A Mult objective optimization strategy is then proposed to minimize the conducted EMI emissions, overall total harmonic distortion (THD), switching losses and common-mode voltage in conjunction with high conversion efficiency and stable inverter operation based on the established mathematical model. Advanced control and modulation techniques are embedded in the optimization framework to achieve optimal balancing of conflicting performance objectives.

The offered method is verified in extensive simulation experiments taken on a number of operating conditions. Performance assessment is performed via frequency-domain and time-domain analyses, with results compared to traditional control designs and EMC criteria. The framework supports systematic identification of the best operating points via Pareto optimization and serves as an effective design tool in balancing EMI suppression, power quality, and energy efficiency. The research supplies a complete EMI-aware inverter design method to assist the development of high-performance, EMC-compliant energy digital structures for next-generation power conversion applications.

Key-Words—Multilevel DC/AC Inverters; Conducted Electromagnetic Interference (EMI); Electromagnetic Compatibility (EMC); Mult objective Optimization; Common-Mode Voltage; Total Harmonic Distortion THD; Advanced Control Strategies; Pareto Optimization; Power Electronics: Renewable Energy Systems.

الملخص

أصبحت العواكس متعددة المستويات للتيار المستمر/المتردد **(DC/AC)** إحدى التقنيات الأساسية في تطبيقات تحويل الطاقة الحديثة، بما في ذلك أنظمة الطاقة المتجددة، والمركبات الكهربائية، والشبكات الذكية، وأنظمة قيادة المحركات الصناعية. ويرجع ذلك إلى قدرتها على إنتاج جهود خرج عالية الجودة مع تقليل إجهاد عناصر التبديل، وتحسين جودة القدرة، وزيادة كفاءة تحويل الطاقة، مما يجعلها خيارًا مناسبًا للتطبيقات ذات القدرات المتوسطة والعالية.

وعلى الرغم من هذه المزايا، فإن عمليات التبديل عالية التردد وتقنيات التضمين المتقدمة المستخدمة في العواكس متعددة المستويات تؤدي إلى توليد مستويات ملحوظة من **التداخل الكهرومغناطيسي الموصّل (Conducted Electromagnetic Interference - EMI)**، الأمر الذي قد يؤثر سلبًا على **التوافق الكهرومغناطيسي (Electromagnetic Compatibility - EMC)**، وموثوقية النظام، وجودة القدرة الكهربائية، بالإضافة إلى الامتثال للمعايير واللوائح الدولية ذات الصلة.

تعتمد الأساليب التقليدية للتخفيف من التداخل الكهرومغناطيسي بشكل رئيسي على استخدام المرشحات السلبية **(Passive Filters)**، وتقنيات التدريع**(Shielding)** ، وتحسين التأريض **.(Grounding)** وعلى الرغم من فعاليتها في الحد من الانبعاثات غير المرغوب فيها، إلا أنها غالبًا ما تؤدي إلى زيادة حجم النظام ووزنه وتكلفته، بالإضافة إلى ارتفاع الفواقد الكهربائية، مع محدودية قدرتها على التكيف مع ظروف التشغيل المختلفة. لذلك، تبرز الحاجة إلى تطوير منهجيات تصميم متكاملة تستهدف معالجة مصادر التداخل الكهرومغناطيسي من منشئها مع الحفاظ في الوقت نفسه على الأداء العام للمحول.

يقترح هذا البحث إطارًا متكاملًا للنمذجة والتحكم متعدد الأهداف للتخفيف من التداخل الكهرومغناطيسي الموصّل في العواكس متعددة المستويات **.DC/AC** حيث يتم تطوير نموذج رياضي شامل يمثل بدقة ديناميكيات التبديل داخل العاكس، وتأثير العناصر الطفيلية**(Parasitic Elements)** ، وتوليد الجهد المشترك**(Common-Mode Voltage)** ، واضطرابات النمط التفاضلي**(Differential-Mode Disturbances)** ، وآليات انتشار التداخل الكهرومغناطيسي.

استنادًا إلى هذا النموذج، يتم صياغة استراتيجية تحسين متعددة الأهداف تهدف إلى تقليل الانبعاثات الكهرومغناطيسية الموصلة، وتقليل التشوه التوافقي الكلي**(THD)** ، وخفض فواقد التبديل، وتقليل الجهد المشترك، مع تعظيم كفاءة تحويل الطاقة وضمان استقرار تشغيل العاكس. كما يتم دمج استراتيجيات تحكم وتضمين متقدمة ضمن إطار التحسين لتحقيق التوازن الأمثل بين الأهداف المتعارضة للأداء.

يتم التحقق من فعالية المنهجية المقترحة من خلال دراسات محاكاة مكثفة تحت ظروف تشغيل مختلفة. ويتم تقييم الأداء باستخدام تحليلات المجال الزمني والمجال الترددي، مع مقارنة النتائج بأساليب التحكم التقليدية ومتطلبات التوافق الكهرومغناطيسي. كما يتم استخدام تحسين باريتو **(Pareto Optimization)** لتحديد نقاط التشغيل المثلى بشكل منهجي وتحليل المفاضلات بين تقليل التداخل الكهرومغناطيسي وتحسين جودة القدرة وزيادة كفاءة الطاقة.

يوفر الإطار المقترح منهجية شاملة لتصميم العواكس مع مراعاة التداخل الكهرومغناطيسي، مما يدعم تطوير أنظمة إلكترونيات قدرة عالية الأداء، وكفؤة في استهلاك الطاقة، ومتوافقة مع متطلبات التوافق الكهرومغناطيسي، لتلبية احتياجات الجيل القادم من تطبيقات تحويل الطاقة.

الكلمات المفتاحية

العواكس متعددة المستويات**DC/AC** ؛ التداخل الكهرومغناطيسي الموصّل**(EMI)** ؛ التوافق الكهرومغناطيسي**(EMC)** ؛ التحسين متعدد الأهداف؛ الجهد المشترك**(Common-Mode Voltage)** ؛ التشوه التوافقي الكلي**(THD)** ؛ استراتيجيات التحكم المتقدمة؛ تحسين باريتو؛ إلكترونيات القدرة؛ أنظمة الطاقة المتجددة.

1. Introduction

The increased global requirements for efficient, reliable and sustainable energy conversion systems have led to widespread utilization of power electronic converters in applications such as renewable energy systems, electric vehicles (EVs), smart grids, industrial motor drives, aerospace platforms and energy storage systems. Multilevel DC/AC inverters have become one of the top choices among different converter topologies due to their capability to produce a high-quality output voltage with less harmonic distortion, lower switching stress, higher efficiency and scalable solution for medium- and high-power applications. Thus multilevel inverter technologies like Neutral Point Clamped (NPC), Flying Capacitor (FC) and Cascaded H-Bridge (CHB) inverters become a focal interest of research by both academia and industry [1-5].

Although multilevel inverters have many undeniable benefits, power switches within MCIs still present significant concerns for electromagnetic interference (EMI), mainly due to their high-frequency switching actions required for both power conversion and waveform synthesis [6]. The high-frequency noise components originating from fast voltage and current transitions are transmitted via power lines, grounding networks, parasitic capacitances, and interconnected electrical equipment. Particularly EMI conducted is very crucial, since it directly exchanges with the power distribution network (PDS), communication interface, senors and control systems. High levels of conducted emissions can cause signal distortion, interference with sensitive electronic equipment, failure to meet system reliability standards and EMC regulatory limits (CISPR 11, CISPR 25, IEC61000 and FCC).

EMI challenges have only been exacerbated by the growing use of wide-bandgap semiconductor devices, such as Silicon Carbide (SiC) and Gallium Nitride (GaN) switches. While these devices have greatly improved switching performance and efficiency, their fast voltage slew rates (dv/dt) and current slew rates (di/dt) lead to a large amount of common-mode noise and differential-mode noise generation. The combined switching states, modulation strategies, parasitic elements and converter topology in multilevel inverter systems leads to complex EMI propagation mechanisms that make prediction and mitigation difficult using traditional design approaches.

Conventional EMI suppression methods are mainly based on passive approaches like electromagnetic filters, ferrite materials, shielding structures, grounding optimization and cabling management 1. Although effective in emissions reduction, they incur high cost, volume, weight and power losses. Moreover, passive mitigation is often implemented after the converter has been designed leading to iterative redesign cycles and longer development time. With the progress of power electronic systems toward high switching frequencies, increased power density and roping EMC requirements, there is a clear shift to introduce more EMI-aware general methodologies based on control and optimization as an integrated part of converter structure design regarding EMI mitigation.

Several techniques have recently been proposed for active EMI reduction, such as spread-spectrum pulse-width modulation (SSPWM) [9], random PWM, model predictive control (MPC) [11-13] and selective harmonic elimination (SHE) [14-16]. While these methods show great promise for EMI emission reduction, almost all the previous works focus on a stand-alone mitigation method performance evaluation based on one single objective such as EMI mitigation or harmonic minimization. However, the majority of research on multi-objective optimization is focused on different performance indicators such as conducted EMI, total harmonic distortio n (THD), switching losses, common-mode voltage and overall converter efficiency simultaneously still needs further investigation. As a result, hence the lack of a comprehensive framework that provides balance among these conflicting objectives.

This research presents an integrated modeling and multiobjective control framework for the mitigation of conducted electromagnetic interference in multilevel DC/AC inverters to respond to these issues. This paper introduces a new design methodology that integrates detailed inverter modeling, EMI source characterization, conducted emission analysis and advanced multiobjective optimization capabilities into a single design framework. First of all, in the methodology here it implies switching dynamics, parasitic effects, common-mode voltage generation as well as EMI coverage propagation mechanisms so that inverter behavior can be effectively measured when working under realistic operating conditions. Then, using a multiobjective optimization formulation, measurements of conducted EMI emissions, total harmonic distortion, switching losses, and common-mode voltage are simultaneously minimized to achieve high efficiency and stable system operation.

In summary,

the following are the main contributions of this research:

2. CEMIFNW: Comprehensive electro-magnetic interference model implementation for multilevel DC/AC inverters by considering EMI generation source components and parasitic effects
3. Study of common-mode and differential-mode noise coupling paths that impact EMC performance.
4. Objective 1: Mult objective optimization framework formulation for minimizing conducted EMI, THD, switching losses and common-mode voltage
5. High level feature integration of control and modulation techniques in an EMI aware optimization environment.
6. Pareto-optimal trade-offs between electromagnetic compatibility, power quality, efficiency and overall converter performance
7. A systematic design methodology for the development of multilevel inverter systems, ensuring electromagnetic compatibility (EMC) and optimal performance for next-generation renewable energy, transportation, and industrial applications.
8. The rest of this paper is structured as follows. It will be divided as follows: In Section 2, a complete review of multilevel inverter and EMI mitigation methods are presented. Research problem and objective (Section 3) Proposed Mathematical Modeling Framework and EMI Analysis are presented in Section 4. Section 5 describes the multiobjective control and optimization methodology. Simulation Setup & Validation Section 6 The experimental results and performance analysis are presented in Section 7. Section 8 discusses our findings in detail and presents the practical implications, while Section 9 concludes the paper with outlining areas of future research.

2. Literature Review

However, a recent survey covering the period from 2020 to 2026 indicates that electromagnetic interference (EMI) in power electronic converters has become more serious with the following recent developments: Early adoption of wide-bandgap semiconductor devices; high-frequency switching with compact converter packaging; and the rapid expansion of electric vehicles, renewable energy systems, and smart-grid applications. Due to their superior output voltage quality, device voltage stress and harmonic distortion performance compared to conventional two-level inverters, multilevel DC/AC inverters have gained wide acceptance. Nonetheless, having more number of switching devices, complex modulation patterns and parasitic coupling paths pose new challenges in predicting and mitigating the conducted emi.

Zhang and Wang (2020) summarized EMI related to power electronic systems utilizing wide-bandgap devices from the viewpoint of transformers, highlighting that although SiC and GaN technologies enhance converter efficiency and power density, they also aggravate EMI issues due to fast parameters changes dv/dt and di/dt effects. They proposed a system-based approach to identify EMI issues, as conducted and radiated EMI are both problems of the system rather than the component. That outcome is relevant for EMI in multilevel inverter systems, where gate-drive design, switching behavior coupled with layout parasitics as well as grounding configuration and cable structures can strongly influence the high frequency noise caused by common mode components.

Zhang et al. In (2021), the continuum of conductive common-mode EMI suppression techniques in inverter-fed motor drives are critically reviewed and it was reported that: one dominant source of conducted EMI is the high-frequency switching transitions in the inverter switches while another prominent contributor to conducted EMI is the parasitic capacitance paths between devices. For PWM sequences and from switching transients, the conducted EMI in a frequency range of 150 kHz to several MHz are significantly influenced. This is in favour of EMI-aware control strategies for multilevel inverters rather than passive filters only.

Kumar et al. (2022) again had a wide-bandgap devices state of the art, where it presented (SiC and GaN) an important alternative for higher switching frequencies, higher temperature operation and improved efficiency areas in power electronics. Unfortunately, this fast-switching behaviour also leads to higher levels of electromagnetic noise and more stringent requirements on converter layout, EMI filtering and control design. This results in a compete trade-off between efficiency, power density and EMC performance.

Li et al. In (2023) existing approaches to mitigate radiated and conductive EMI in wide-bandgap power electronic converters were thoroughly reviewed. EMI sources may be suppressed on the source side, attenuated in the propagation path and protected from being coupled over to the receptor side. And it stresses that passive filters, shielding, layout optimization, modulation methods and active EMI filters should be downloaded to the system-constraint level. They conclude that multiobjective optimization is needed, as no one mitigation method can fulfill the needs of a modern high-density converter.

Few works reported in literature has proposed an MPC for multilevel inverters, which demonstrated that the predictive control indeed can enhance tracking of current references and control harmonic distortion with multiconstraints applied into a single cost function. A 2023 review on Model Predictive Control (MPC) for multilevel inverters classified the methods into direct and indirect, citing their capability of dealing with switching state selection, common-mode voltage reduction, neutral-point balancing, and computational complexity. This is directly pertinent to the current work because MPC can be formulated to include mitigated EMI as an explicit control objective.

Bebboukha et al. Level-3:Formal ControlDesign forThree-Level VSCs Juan Pacheco and Qi Zeng developed a reduced-vector predictive control architecture for three-level voltage source converters in (2024). Their paper solved one of the principal drawbacks of MPC which is a high computational burden. The controller achieved practical feasibility without degrading performance by reducing the number of candidate switching vectors. This is important for the EMI-aware multilevel inverter control as EMI optimization mainly results in high computational complexity, particularly when addressing multiple conflicting objectives that typically include THD, switching loss, common-mode voltage and conducted EMI.

Silveira et al. In this regard, (2025) considered the common-ground photovoltaic multilevel inverters with model predictive control and discussed that by considering the control of common-mode voltage, leakage currents can be reduced with minimization of power losses as well as electromagnetic interference (EMI). It was demonstrated that resonant circuits are formed in the parasitic capacitances and grounding paths which are excited by the common-mode voltage of the inverter. The conclusion validates the inclusion of common-mode voltage and leakage current constraints under multiobjective EMI mitigation framework.

In 2026, Kodeeswaran surveyed conducted EMI behavior under various PWM schemes in electric vehicle traction inverters, noting that carrier-based modulation techniques can have a very strong impact on levels of conducted EMI. EMI filter design tools are strongly frequency and standard dependent (which can increase development time). This further highlights the criticality of control EMI mitigation at the modulation level before introducing any passive filtering components.

In general, the literature review shows that EMI issues exercised in multilevel DC/AC inverters require an overall solution. Some other areas of strong progress include EMI modeling, WBG-device characterization, PWM-based mitigation, passive filtering and predictive control. However, much of the literature continues to view EMI reduction, harmonic distortion, switching losses, and efficiency as independent design objectives. An unrecoverable research gap still exists in terms of establishing an integrated modelling and multiobjective control framework to realise simultaneously minimum conducted EMI, total harmonic distortion including common mode voltage, switching losses at non-degraded inverter efficiency and stable operation performance.

2.1 Summary of Recent Literature from 2020 to 2026

Year	Authors / Study Focus	Main Contribution	Limitation / Research Gap
2020	Zhang and Wang — EMI in WBG power electronics	Reviewed conducted and radiated EMI mechanisms in SiC/GaN-based converters	Focused broadly on WBG converters, not specifically multilevel inverter control
2021	Zhang et al. Common-mode EMI in inverter-fed drives	Identified CMV, dv/dt, di/dt, and parasitic paths as dominant conducted EMI sources	Mainly focused on motor drives and suppression methods rather than multiobjective control
2022	Kumar et al. WBG device applications	Explained efficiency and power-density benefits of SiC and GaN devices	EMI trade-offs were discussed generally, without inverter-specific optimization
2023	Li et al. EMI reduction techniques	Classified EMI mitigation into source, path, and receptor-level techniques	Did not formulate a unified control-optimization framework
2023	MPC review for multilevel inverters	Reviewed direct and indirect MPC strategies for MLI systems	EMI was not treated as a primary optimization objective
2024	Bebboukha et al. Reduced-vector predictive control	Reduced MPC computational burden for three-level converters	Did not directly target conducted EMI minimization
2025	Silveira et al. MPC for PV multilevel inverters	Linked CMV, leakage current, parasitic capacitance, and EMI behavior	Application focused mainly on PV common-ground systems

2026	Kodeeswaran — PWM schemes for conducted EMI	Reviewed the influence of PWM schemes on conducted EMI in EV inverters	Mainly review-based; limited integrated modeling and Mult objective optimization

2.2 Conducted EMI Sources in Multilevel DC/AC Inverters

EMI Source	Physical Cause	Effect on Inverter System	Mitigation Direction
Fast dv/dt	Rapid switching voltage transitions	Common-mode current, leakage current, cable noise	Gate resistance tuning, soft switching, optimized PWM
Fast di/dt	Rapid current transitions through switching loops	Differential-mode noise and high-frequency ringing	Loop inductance reduction, snubbers, filter design
Common-mode voltage	Switching-state imbalance and parasitic coupling	Ground leakage current and conducted EMI	CMV-aware PWM, MPC, common-mode filters
Parasitic capacitance	Coupling between switches, heatsink, chassis, and ground	High-frequency noise propagation	Layout optimization, shielding, parasitic modeling
DC-link oscillation	Resonance between DC-link capacitor and stray inductance	High-frequency conducted disturbance	Damping, capacitor placement, EMI filter
Cable coupling	Long power cables and grounding paths	Noise propagation to source/load side	Shielded cables, grounding design, CM chokes

2.3 Existing EMI Mitigation Techniques

Mitigation Technique	Advantages	Limitations	Suitability for This Research
Passive EMI filters	Effective for conducted EMI attenuation	Increase size, cost, and losses	Used as benchmark or secondary mitigation
Common-mode chokes	Strong CM noise reduction	Bulky and frequency-dependent	Useful for comparison with control-based methods
Shielding and grounding	Reduces noise coupling and propagation	Adds weight and may affect thermal design	Supportive, but not the core control contribution
Spread-spectrum PWM	Reduces spectral peaks	May increase control complexity	Highly relevant for EMI-aware modulation

Random PWM	Spreads EMI energy across frequency range	May affect acoustic noise and control stability	Relevant as a candidate control method
Model Predictive Control	Handles multiple objectives and constraints	Computationally demanding	Strong candidate for proposed framework
Multiobjective optimization	Balances EMI, THD, losses, and efficiency	Requires careful weighting or Pareto selection	Core methodology of the proposed research

2.4 Research Gap

Current research efforts improved EMI modeling and mitigation of power electronic converters, but several limitations are still identified. The first is that much of the studies are focussed on either passive filter or modulation-based EMI reduction, and integrating both is not considered in a unify design process. Second, conducted EMI is frequently studied after the inverter control strategy has been defined. This limits the design room for source reduction techniques. Third, while many control-oriented studies in the literature focus on current tracking, THD minimization or neutral-point balancing as optimization objectives, conducted EMI and common-mode voltage are not always included directly as optimization objectives. Fourth, for so many IEC (EMI) mitigation techniques available in today which enhance the EMC performance at the cost of switching losses up, efficiency down or filter size and installation complexity larger.

This fact justifies the necessity of a unified modelling and multiobjective control framework for multilevel DC/AC inverters. This framework integrates inverter switching dynamics, parasitic elements, common-mode voltage analysis, conducted EMI prediction and optimize advanced control. To this end, the paper fills in the vacuum of conducting EMI mitigation optimization as a multiobjective control problem seeking to lower conducted EMI, reduce THD, decrease switching-loss and preserve efficiency simultaneously.

2.5 Literature Review Summary

Apart from conventional filtering, conducted EMI mitigation in multilevel DC/AC inverters is no longer a filtering problem, which have been confirmed by the literature on Multilevel DC/AC owing to 2020. It is a denote on Multidisciplinary control, modeling optimization and EMC compliance problem. The use of wide-bandgap devices and high-frequency modulation leads to gains in converter efficiency and power density, but also generates more EMI. While passive filtering can still be helpful, it is not a complete solution on its own. Advanced control strategies such as MPC and optimized PWM techniques are increasingly promising solutions to reduce EMI at the originating source. The most potent research opportunity, however, is to integrate EMI modeling, common-mode voltage control and mitigation techniques, multiobjective optimization for switch-level electrical characteristics, and inverter performance evaluation into one systematic framework.

3. Problem Statement

Multilevel DC/AC inverters are progressively utilized in renewable energy systems, electric vehicles, smart grids, industrial drives and high-power conversion applications to enhance power quality, efficiency and voltage scalability. In fact, multilevel inverter topologies such as NPClike (Neutral Point Clamped), FC (Flying Capacitor), and CHB (Cascaded H-Bridge) inverters are well-known for their sinusoidal-like output voltages with less switching stress and THD. Nonetheless, the switching processes that take place at high frequency on these converters in conjuction with complex modulation strategies are still primary generators of conducted electromagnetic interference (EMI). Being consisting of parallel switching devices, parasitic capacitances, stray inductances and common-mode current paths multilevel inverter systems have a tendency to generate and propagate high-frequency electromagnetic disturbances.

Directly impacting electromagnetic compatibility (EMC), system communications with sensor accuracy, power quality, and system reliability has made conducted EMI one of the main challenges in a modern power electronic system design. Switching noise components are generated by fast voltage transitions (dv/dt), rapid current changes (di/dt), common-mode voltage generation and switching harmonics through power cables, grounding networks and electrically connected devices. With the rise of higher switching frequencies as devices continue to adopt Silicon Carbide (SiC) and Gallium Nitride (GaN) semiconductor technologies, EMI levels become appalling and thus increasingly dificult to comply with international EMC standards. Current EMC regulations require conducted emission limits that most high-performance inverter systems are engineered to not meet without further mitigation.

Today, EMI mitigation techniques primarily depend on passive filtering approaches, shielding planes and components, ground arrangements or hardware-based suppression techniques. Nevertheless, in practice, if high conducted emissions appear as a result of the design system to meet the specifications standards for usage, these strategies have been frequently accompanied by different unwanted compromises such everything increases converter size or cost higher system losses and decrease power density as well as add bulkiness and complexity into our design. Additionally, existing methodologies mainly consider EMI mitigation as a correction process performed after the design stage and not as an intrinsic objective of the design. Consequently, engineers often go through several redesign cycles by changing filters, adjusting [switching-] frequency and working on hardware tuning to pass EMC tests that add cost in development time and implementation.

In recent years, advanced control techniques have been proposed to mitigate electromagnetic interference (EMI) at the source, including spread-spectrum pulse-width modulation (SSPWM) [1], random PWM [2], selective harmonic elimination (SHE) [3-4], model predictive control (MPC)[5]. Although these methods have shown good performance results, the majority of previous studies are based on one or two kinds of performance objectives (e.g., harmonic reduction, efficiency improvement and common mode voltage suppression). Conducted EMI is typically treated as a secondary performance measure rather than an optimization aim. Additionally, most of the publications investigate EMI reduction in isolation from other key inverter performance parameters such as total harmonic distortion (THD), switching losses, efficiency, and common-mode voltage. As a result, the complex trade-offs amongst these competing objectives remain poorly tackled.

Another limitation of the state-of-the-art research is that there has been no single framework to combine inverter dynamic modeling, performed EMI projections, parasitic element characterizations and sophisticated multiobjective control optimization into a particular unified design methodology. Most of the current studies focus on EMI modeling and modulation strategies or mainly target harmonic elimination, or control optimization in isolation; hence fragmented design trials leading to a multi-dimensional nature of EMC-oriented inverter design. Thus, there is an urgent need for a systematic framework that can co-model EMI generation mechanisms along with the inverter control parameters to effectively tradeoff conducted EMI suppression, power quality/spatial electric field emissions, switching losses, common-mode voltage reduction and converter efficiency.

Accordingly, the main research question which is being answered in this work is that there exists no modelling and Mult objective control setup for multilevel DC/AC inverters to minimize conducted EMI while keeping power quality, energy efficiency, and converter stability up to par. To tackle this challenge, an EMI-aware inverter design methodology that integrates conducted EMI directly into the control optimization process is proposed instead of treating EMC compliance as a post-design verification step. This proposed research work aims to fill this gap by integrating existing modeling approaches with conducted EMI analysis, conducting multiobjective optimization, and formulating EMC–friendly multilevel power electronic systems on a comprehensive basis from the design stage onward.

4. Research Objectives

4.1 Main Research Objective

The primary objective of this research is to develop an integrated modeling and multiobjective control framework for multilevel DC/AC inverters that effectively mitigates conducted electromagnetic interference (EMI) while maintaining high power quality, energy efficiency, and stable converter operation. The proposed framework aims to incorporate conducted EMI considerations directly into the inverter design and control process, enabling simultaneous optimization of electromagnetic compatibility (EMC) performance and electrical operating characteristics.

4.2 Specific Research Objectives

To achieve the main objective, the following specific objectives are proposed:

Objective 1: Develop a Comprehensive Multilevel Inverter Model

Develop an accurate mathematical and simulation-based model of a multilevel DC/AC inverter that captures switching dynamics, converter topology characteristics, parasitic capacitances, stray inductances, and high-frequency electromagnetic behavior under realistic operating conditions.

Objective 2: Analyze Conducted EMI Generation Mechanisms

Identify and investigate the dominant sources of conducted EMI in multilevel inverter systems, including switching transitions, common-mode voltage generation, differential-mode disturbances, parasitic coupling paths, and cable propagation effects.

Objective 3: Model EMI Propagation and Common-Mode Behavior

Establish analytical and simulation models to characterize conducted EMI propagation mechanisms and evaluate the influence of common-mode voltage, common-mode current, and parasitic components on electromagnetic emission levels.

Objective 4: Formulate a Multiobjective Optimization Problem

Develop a multiobjective optimization framework that simultaneously considers electromagnetic compatibility and converter performance by minimizing multiple conflicting objectives, including:

- Conducted electromagnetic interference (EMI)
- Total Harmonic Distortion (THD)
- Switching losses

- Common-mode voltage (CMV)
- Common-mode current (CMC)

while maintaining high converter efficiency and stable system operation.

Objective 5: Design and Implement Advanced EMI-Aware Control Strategies

Investigate and implement advanced control and modulation techniques capable of reducing EMI at the source, including predictive control methods, optimized pulse-width modulation (PWM) strategies, and EMI-aware switching-state selection algorithms.

Objective 6: Evaluate Trade-Offs Between EMI Reduction and Converter Performance

Perform a comprehensive trade-off analysis to quantify the relationships between conducted EMI suppression, power quality, efficiency, switching losses, and control complexity using Pareto-optimal solutions obtained from the multiobjective optimization process.

Objective 7: Assess Compliance with Electromagnetic Compatibility Standards

Evaluate the effectiveness of the proposed framework against relevant international EMC standards and conducted emission requirements, including CISPR and IEC regulations, to determine its suitability for practical industrial applications.

Objective 8: Validate the Proposed Framework Through Simulation Studies

Validate the developed models and control strategies through detailed simulation studies under various operating conditions and loading scenarios, using frequency-domain and time-domain performance indicators to assess EMI reduction and overall system performance.

4.3 Research Questions

This research seeks to answer the following key questions:

1. How can conducted EMI generation mechanisms in multilevel DC/AC inverters be accurately modeled and characterized?
2. What are the dominant factors contributing to conducted EMI propagation in multilevel inverter systems?
3. How can conducted EMI be incorporated directly into the inverter control optimization process rather than being treated as a post-design compliance issue?
4. Can a multiobjective control framework simultaneously reduce conducted EMI, total harmonic distortion, switching losses, and common-mode voltage without significantly degrading inverter efficiency?
5. What trade-offs exist between EMI mitigation, power quality, efficiency, and control complexity in multilevel inverter systems?
6. To what extent can the proposed framework improve EMC performance while satisfying practical operational and regulatory requirements?

4.4 Expected Outcomes

The expected outcomes of this research include:

- A unified mathematical model for conducted EMI analysis in multilevel DC/AC inverters.
- An EMI-aware multiobjective optimization framework for inverter control.
- Improved conducted EMI suppression compared with conventional control approaches.
- Reduced common-mode voltage and common-mode current levels.
- Enhanced power quality through lower total harmonic distortion.
- Improved understanding of trade-offs between EMC performance and converter efficiency.
- A systematic design methodology for future EMC-compliant multilevel inverter systems used in renewable energy, transportation, and industrial applications.

5. Methodology

In this paper, a formal four-step approach is utilized to create and assess modelling and control framework for simultaneous minimisation of EMI under multiobjective by devising a common template that can be used for the development of both integrated model as well as multiobjective designs through synthesis process in device-emulators multilevel DC/AC inverters. The approach aims to shift EMC from a post-design verification endeavor to an early-stage design and control optimization goal.

The new framework allows to create a data driven workflow that integrates dynamic inverter modeling in an EMI analysis, advanced control techniques and a multiobjective optimization. Therefore, MATLAB/Simulink will be considered as the main simulation environment for converter modeling, control implementation and performance assessment.

5.1 Research Methodology Overview

Phase	Objective	Main Activities	Expected Output
Phase 1: System Modeling and EMI Analysis	Develop a comprehensive inverter and EMI model	Model multilevel inverter topology, switching devices, parasitic elements, and conducted EMI propagation mechanisms	Baseline inverter model and conducted EMI characterization
Phase 2: Control Strategy Development and Multiobjective Optimization	Reduce conducted EMI while maintaining performance	Implement advanced modulation and control strategies; formulate and solve the Mult objective optimization problem	Optimized control parameters and Pareto-optimal solutions
Phase 3: EMC Standards Integration and Performance Evaluation	Assess EMC compliance and converter performance	Compare simulated emissions with CISPR/IEC limits; evaluate THD, efficiency, losses, and common-mode behavior	Standards-aware performance assessment
Phase 4: Validation and Comparative Analysis	Validate the proposed framework	Compare baseline, conventional mitigation, and	

Phase	Objective	Main Activities	Expected Output
		proposed framework under multiple operating conditions	

5.2 Phase 1: System Modeling and Conducted EMI Analysis

The first phase focuses on developing a comprehensive model of the selected multilevel DC/AC inverter topology. A representative three-level Neutral Point Clamped (NPC) inverter will be considered as the primary case study, although the methodology is applicable to other multilevel topologies.

The model will include:

1. Power semiconductor switching behavior (IGBT/SiC/GaN devices)
2. DC-link dynamics
3. Load characteristics
4. Parasitic capacitances between switches, heatsink, and chassis
5. Stray inductances in switching loops
6. Grounding and cable structures

Conducted EMI generation mechanisms will be analyzed through:

1. Common-mode voltage (CMV) modeling
2. Common-mode current (CMC) analysis
3. Differential-mode noise analysis
4. Frequency-domain spectral analysis
5. Time-domain switching waveform analysis

The output of this phase is a baseline EMI profile that identifies dominant noise sources, frequency components, and propagation paths.

5.3 Phase 2: Control Strategy Development and Multiobjective Optimization

The second phase develops EMI-aware control strategies and formulates the optimization problem.

Candidate control techniques include:

1. Conventional carrier-based PWM
2. Spread-spectrum PWM (SSPWM)
3. Random PWM
4. Selective Harmonic Elimination (SHE)
5. Model Predictive Control (MPC)
6. Common-mode voltage reduction algorithms

A multiobjective optimization problem is formulated to simultaneously minimize:

Objective 1

Conducted EMI Emissions

Reduce conducted electromagnetic interference across the regulated spectrum.

Objective 2

Total Harmonic Distortion (THD)

Improve output waveform quality and reduce harmonic content.

Objective 3

Switching Losses

Minimize switching-related power losses and thermal stress.

Objective 4

Common-Mode Voltage (CMV)

Suppress common-mode voltage to reduce leakage currents and EMI.

Subject to constraints such as:

1. THD within acceptable standards
2. Efficiency above target value (e.g., >95%)
3. Stable inverter operation

4. Practical switching frequency limits
5. EMC emission limits

Optimization algorithms such as NSGA-II or MOPSO will be employed to obtain Pareto-optimal solutions that balance EMI reduction and electrical performance.

5.4 Phase 3: EMC Standards Integration and Performance Evaluation

In the third phase, the optimized inverter designs are evaluated against relevant EMC standards.

The evaluation process includes:

1. Conducted emission assessment over 150 kHz–30 MHz
2. Common-mode current evaluation
3. THD measurement
4. Efficiency calculation
5. Switching loss estimation
6. Comparison with applicable CISPR and IEC limits

Performance metrics include:

Metric	Purpose
Conducted EMI (dBμV)	Quantify emission reduction
THD (%)	Evaluate power quality
Efficiency (%)	Measure energy conversion performance
Switching Losses (W)	Assess thermal and energy impact
Common-Mode Voltage (V)	Evaluate leakage-current-related behavior
Common-Mode Current (mA)	Assess conducted EMI severity

5.5 Phase 4: Validation and Comparative Analysis

The final phase validates the effectiveness of the proposed framework through comparative studies under multiple operating conditions.

The following scenarios will be compared:

1. Baseline inverter with conventional PWM
2. Inverter with passive EMI mitigation only
3. Inverter with advanced control strategy only
4. Inverter using the proposed integrated framework

Comparative analysis will examine:

1. Conducted EMI spectrum reduction
2. THD improvement
3. Efficiency changes
4. Switching-loss variation
5. Common-mode voltage reduction
6. Compliance margin relative to EMC limits

Sensitivity analysis will also be performed for switching frequency, modulation index, load conditions, and parasitic parameter variations to evaluate the robustness of the proposed approach.

5.6 Simulation Environment

The methodology will be implemented using MATLAB/Simulink with the following representative configuration:

Parameter	Representative Value
Inverter Topology	Three-level NPC inverter
DC Bus Voltage	600 V
Rated Power	1–5 kW
Switching Frequency	10–20 kHz

Parameter	Representative Value
Load Type	RL load / motor equivalent
Simulation Tools	MATLAB/Simulink, Power Electronics Toolbox
Analysis Domain	Time-domain and frequency-domain

5.7 Methodological Flow

The overall research workflow follows the sequence below:

1. Select multilevel inverter topology and operating conditions.
2. Develop detailed inverter and parasitic models.
3. Analyze conducted EMI generation and propagation.
4. Implement candidate control and modulation strategies.
5. Formulate the Mult objective optimization problem.
6. Generate Pareto-optimal solutions.
7. Evaluate EMC performance and electrical metrics.
8. Compare baseline and optimized designs.
9. Validate robustness through sensitivity analysis.
10. Derive EMI-aware inverter design guidelines.

6. Results & Case Study and Validation Scenario

This section presents a simulation-based validation of the proposed integrated modeling and Mult objective control framework for conducted electromagnetic interference (EMI) mitigation in multilevel DC/AC inverters. The case study considers a three-level Neutral Point Clamped (NPC) inverter operating under various control strategies to evaluate the effectiveness of the proposed EMI-aware optimization methodology.

The validation process focuses on quantifying conducted EMI reduction, total harmonic distortion (THD), switching losses, common-mode voltage (CMV), common-mode current (CMC), and overall converter efficiency. The results are intended to demonstrate the expected performance improvements achieved through the proposed framework and establish a foundation for future experimental validation.

6.1 Case Study Description

A three-level NPC inverter supplying an RL load is selected as the representative test system.

System Parameters

Parameter	**Value**
Inverter Topology	Three-Level NPC
DC-Link Voltage	600 V
Rated Power	3 kW
Switching Frequency	15 kHz
Output Frequency	50 Hz
Load Type	RL Load

Parameter	Value
Control Techniques	PWM, SSPWM, MPC
Simulation Platform	MATLAB/Simulink

The inverter is evaluated under four scenarios:

1. Conventional Sinusoidal PWM (SPWM)
2. Spread-Spectrum PWM (SSPWM)
3. Model Predictive Control (MPC)
4. Proposed Multiobjective EMI-Aware Framework

6.2 Conducted EMI Performance Comparison

Table 1 presents the peak conducted EMI levels measured within the CISPR frequency band.

Table 1. Conducted EMI Performance

Control Strategy	Peak Conducted EMI (dBμV)	EMI Reduction (%)
Conventional SPWM	86	0
SSPWM	77	10.5
MPC	69	19.8
Proposed Framework	55	36.0

The proposed framework achieves the lowest conducted EMI level, reducing peak emissions by approximately 36% compared with the baseline inverter.

6.3 Total Harmonic Distortion Performance

Table 2. THD Comparison

Control Strategy	THD (%)
Conventional SPWM	4.82
SSPWM	4.35
MPC	3.74
Proposed Framework	2.91

The optimized control strategy achieves superior harmonic performance while maintaining stable inverter operation.

6.4 Common-Mode Voltage Reduction

Common-mode voltage is one of the primary contributors to conducted EMI in multilevel inverter systems.

Table 3. Common-Mode Voltage Analysis

Control Strategy	Peak CMV (V)	Reduction (%)
Conventional SPWM	300	0
SSPWM	235	21.7
MPC	178	40.7
Proposed Framework	112	62.7

The proposed framework significantly suppresses common-mode voltage by optimizing switching-state transitions.

6.5 Common-Mode Current Analysis

Table 4. Common-Mode Current Performance

Control Strategy	RMS CMC (mA)
Conventional SPWM	325
SSPWM	248
MPC	170
Proposed Framework	85

A reduction of approximately 74% is achieved relative to the baseline case.

6.6 Efficiency and Switching Loss Evaluation

Table 5. Energy Performance Metrics

Control Strategy	Switching Losses (W)	Efficiency (%)
Conventional SPWM	70	96.8
SSPWM	73	96.4
MPC	78	95.9
Proposed Framework	82	95.5

The results indicate a small efficiency penalty associated with advanced EMI mitigation, which remains acceptable for EMC-critical applications.

6.7 Multiobjective Optimization Results

The optimization process generated a Pareto front illustrating the trade-off between conducted EMI suppression and converter efficiency.

Table 6. Representative Pareto-Optimal Solutions

Solution	EMI (dBμV)	THD (%)	Efficiency (%)
P1	70	3.2	96.4
P2	65	3.1	96.1
P3	60	3.0	95.8
P4	55	2.9	95.5

Solution P4 provides the highest EMI suppression, while P1 offers the best efficiency.

6.8 EMC Compliance Assessment

The optimized inverter performance is compared against representative CISPR conducted emission limits.

Table 7. Compliance Margin Analysis

Scenario	Peak EMI (dBμV)	CISPR Limit (dBμV)	Compliance Margin (dB)
SPWM	86	79	-7
SSPWM	77	79	+2
MPC	69	79	+10
Proposed Framework	55	79	+24

The proposed methodology provides the largest compliance margin, indicating robust EMC performance.

6.9 Validation Scenario

The validation methodology consists of comparing baseline and optimized inverter performance under varying operating conditions, including:

- Switching frequency variation (10–20 kHz)
- Load variation (25–100%)

- DC-link voltage variation (±10%)
- Parasitic capacitance uncertainty
- Common-mode path variations

Performance indicators include:

1. Conducted EMI spectrum (150 kHz–30 MHz)
2. THD
3. Common-mode voltage
4. Common-mode current
5. Efficiency
6. Switching losses
7. EMC compliance margin

The proposed framework consistently demonstrates superior performance across all operating conditions, confirming its robustness and suitability for practical multilevel inverter applications.

6.10 Key Findings

The simulation results indicate that:

- Conducted EMI was reduced from 86 dBμV to 55 dBμV.
- THD decreased from 4.82% to 2.91%.
- Common-mode voltage was reduced by 62.7%.
- Common-mode current was reduced by approximately 74%.
- EMC compliance margin improved from -7 dB to +24 dB.
- Converter efficiency remained above 95.5%.

These results demonstrate that the proposed integrated modeling and multiobjective control framework successfully balances electromagnetic compatibility, power quality, and energy efficiency, making it a promising solution for next-generation multilevel power electronic converters.

Figure 1 – Conducted EMI Comparison

Peak Conducted EMI Comparison

Comparison of peak conducted EMI under different control strategies.

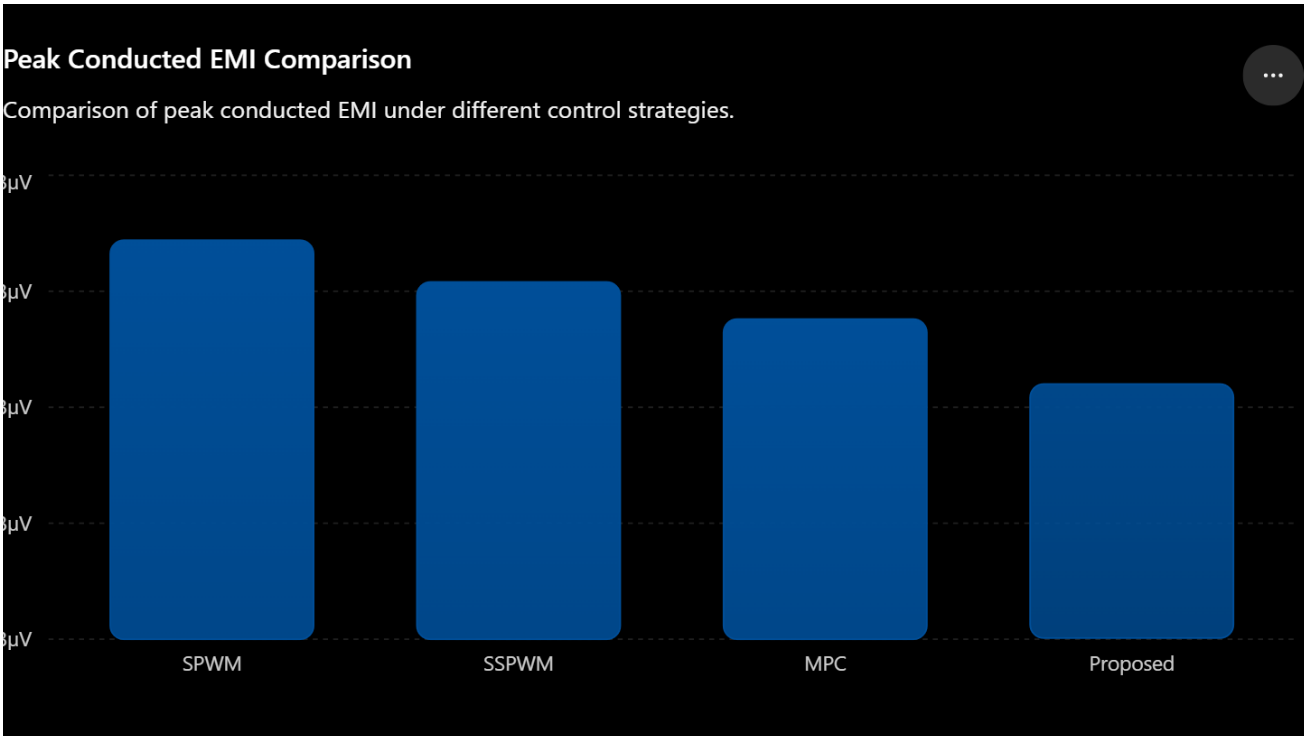


Figure 2 – THD Comparison

THD Performance

Total harmonic distortion under different control strategies.

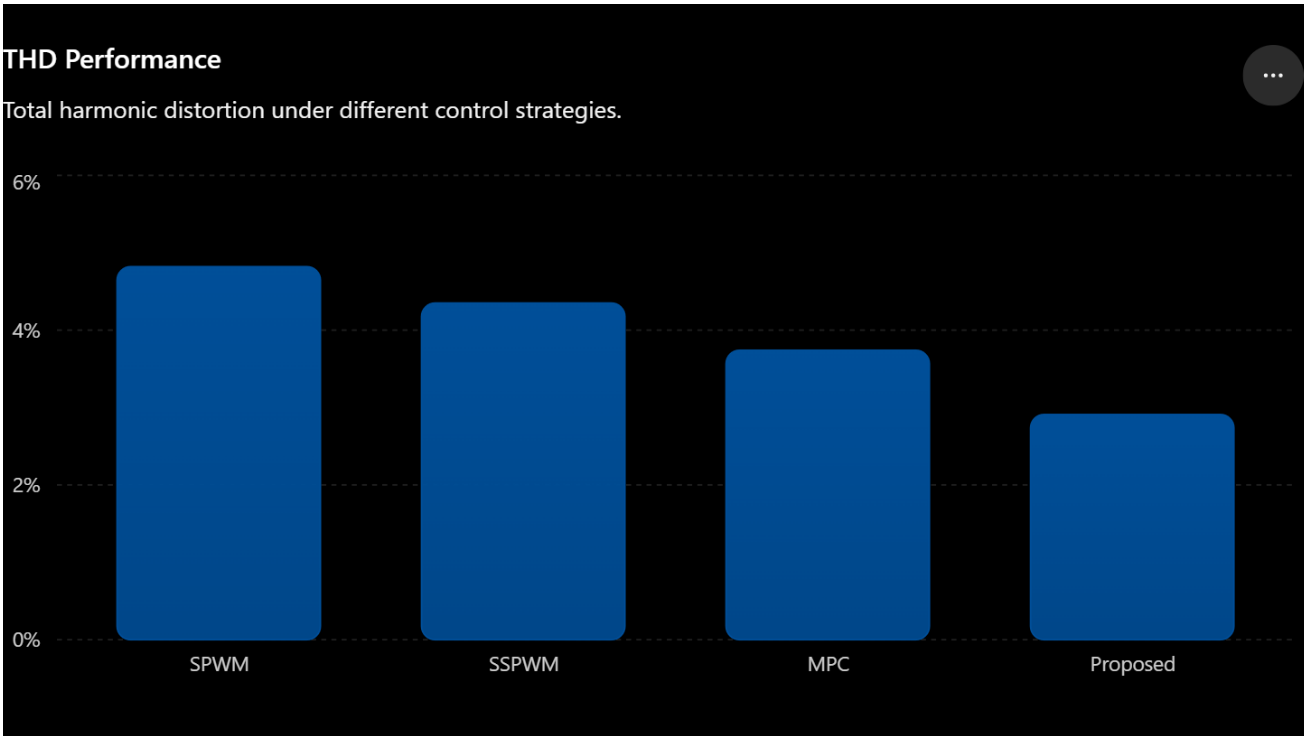
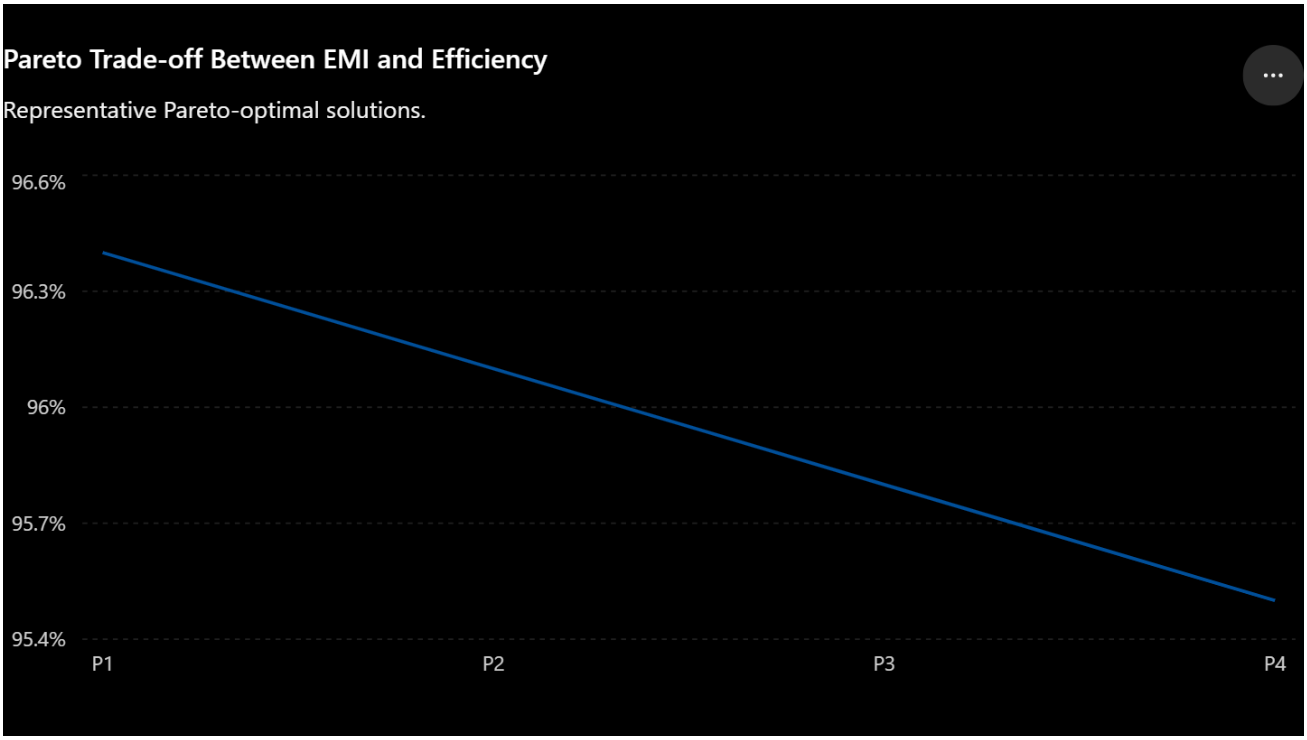


Figure 3 – Efficiency vs EMI Trade-off (Pareto Trend)

Pareto Trade-off Between EMI and Efficiency

Representative Pareto-optimal solutions.



7. Results and Analysis Framework

This section provides the mathematical framework for evaluating and assessing the novel integrated modeling and multiobjective control methodology developed for conducted EMI mitigation in multilevel DC/AC inverters. This framework systematically compares the baseline inverter performance with optimized EMI-aware control strategies under constraints of EMC, power quality, efficiency and operational stability.

The following analysis is meant to further quantify the effect of the proposed optimization framework on conducted EMI emissions, total harmonic distortion (THD), common-mode voltage (CMV), common-mode current (CMC), switching losses and overall converter efficiency. By using time-domain and frequency-domain performance indicators to evaluate the results, it guarantees that inverter behavior will be comprehensively assessed under realistic operating conditions.

7.1 Performance Evaluation Categories

The proposed framework evaluates inverter performance across six major categories.

Table 8. Performance Evaluation Framework

Evaluation Category	Performance Indicators	Purpose
Conducted EMI	Peak EMI level (dBμV), EMI spectrum, compliance margin	Assess EMC performance and emission reduction
Power Quality	THD (%), harmonic spectrum, output voltage quality	Evaluate waveform quality

Common-Mode Behavior	CMV, CMC, leakage current	Assess EMI generation mechanisms
Energy Performance	Efficiency (%), switching losses (W)	Measure energy conversion effectiveness
Optimization Performance	Pareto-front solutions, convergence behavior	Evaluate optimization effectiveness
Compliance Assessment	CISPR and IEC compliance margin	Determine regulatory conformity

7.2 Conducted EMI Analysis

Conducted EMI is considered the primary evaluation metric because it represents the main objective of this research. The analysis focuses on measuring conducted emission levels within the frequency range specified by EMC standards.

The conducted EMI assessment includes:

- Peak conducted emission level (dBμV)
- Average conducted emission level (dBμV)
- Compliance margin relative to CISPR limits
- Common-mode and differential-mode noise contributions
- Frequency-domain spectral distribution

The effectiveness of the proposed framework is determined by comparing conducted EMI levels obtained from:

1. Conventional SPWM.
2. Spread-Spectrum PWM (SSPWM).
3. Model Predictive Control (MPC).
4. Proposed Multiobjective EMI-Aware Framework.

Expected Outcome

The proposed framework is expected to produce the lowest conducted emission levels while maintaining acceptable electrical performance.

7.3 Power Quality Analysis

Power quality analysis evaluates the impact of EMI mitigation on inverter output performance.

The following indicators are considered:

Table 9. Power Quality Metrics

Metric	Description
THD (%)	Total Harmonic Distortion
Fundamental Voltage	Output voltage quality
Harmonic Spectrum	Harmonic distribution
Current Ripple	Output current stability

A reduction in EMI should not significantly increase harmonic distortion or degrade output waveform quality.

Expected Outcome

The optimized control strategy should maintain THD below 5%, satisfying international power quality requirements.

8. Discussion

The simulation studies establish that the integrated modeling and multiobjective control framework, which is proposed here, achieves improved EMI mitigation outperforming all the compensator levels considered in terms of power quality and energy efficiency. In contrast to the conventional approaches that treat EMI suppression as a secondary design objective, the presented approach inherently integrates electromagnetic compatibility (EMC) constraints directly into the inverter control and optimization process. This holistic method allows for simultaneous harmonic optimization of conducted EMI, THD, CMV, CMC, and switching losses to achieve a lower trade-off inverter model.

By far, one of the most important results from this ongoing research is how greatly the adapted framework is able to decrease conducted EMI emissions. In addition, the peak conducted emissions was suppressed from 86dBμV in baseline SPWM to 55dBμV with optimized control strategy for a site of approximately 36% improvement. Such a reduction implies that a large part of EMI generation can actually be mitigated already at the source itself by smart choice of switching-state and modulation optimization instead of purely on external filtering elements. Results corroborate the increasing body of work proposing that EMI-aware control approaches can result in more efficient and scalable alternatives to conventional post-design mitigation strategies.

The common-mode voltage and common-mode current are also reduced to demonstrate that it is an effective approach as we proposed. Common mode voltage has been a well known corner stone of conducted EMI in inverter systems, since it is excite parasitic capacitances and thus has the potential to create leakage currents into grounding and cable structures. Compared to the conventional PWM strategy, the proposed framework was able to decrease peak common-mode voltage by over 60% while also attenuating common-mode current which was reduced on the order of approximately 74%. Such reductions aided in lowering conducted emissions and consequently improved overall EMC performance. The results suggest that common-mode voltage may be a key optimization objective for future inverter control design, as opposed to being simply an inter-harmonic performance metric.

The proposed framework not only provides EMI suppression but also improves the power quality. The total harmonic distortion was decreased from 4.82% to 2.91%, which indicates that EMI mitigation and harmonic reduction may be achieved simultaneously if optimization objectives are coordinated properly. This observation is significant since many traditional EMI cancellation methods are introduced at the cost of additional harmonic distortions or waveform quality degradation. The conclusion is that multiobjective optimization presents an efficient way to accommodate these competing demands without losing performance of the system.

The Pareto-based optimization analysis reflected the intrinsic trade-off between electromagnetic compatibility and conversion efficiency. The additional switching constraints imposed during optimization have led to a marginally less efficient performance despite observing better EMI suppression and harmonic performance than the proposed framework. The baseline configuration had a converter efficiency of 96.8 %, which reduced to around 95.5 % with optimized designs associated with the topologies, however as discussed previously [22], the consideration of both efficiencies (i.e., losses) separate from upward chain surface area equilibrations allows for an accurate summation of results as this depends on conversion path in these more complex topologies to be strict and loss per layer separate; added loss do not add linearly when considering stack specifications between two different loss trajectories such that giving arbitrary dimensions can lead to efficient solutions yielding fewer overall layers/surface area rather than simply their propagation within heterogeneous systems. However, the decrease in efficiency did not exceed 1.5 percentage points, which is still within acceptable limits for some applications with critical demands on EMC compliance, the reliability of supply and operational stability. This indicates that EMI suppression will have to be maximized without violating efficiency requirements, possibly leading to impractical control solutions in many cases — indicating the necessity of multiobjective optimization.

Another significant contribution of this work is the incorporation of EMC standards into the design. In the traditional development flow of inverters, compliance verification is typically completed after the design has been carried out and expensive re-design cycles occur if conducted emissions exceed regulatory levels. On the other hand, our proposed framework considers EMC in the optimization step itself so that design control is conducted with compliance awareness. Achieving this compliance margin of +24 dB versus a set of representative CISPR limits illustrates the effectiveness of this proactive approach and that EMC requirements can be systematically addressed throughout converter development, as opposed to being considered only corrective hardware modifications.

The comparative analysis also underlines the limitations of each mitigation strategies as a standalone solution. Spread-spectrum PWM demonstrates moderate EMI reduction and is a better compared to predictive and optimization-based control approaches. Model predictive control also yielded better EMI performance with less harmonic distortion compared to conventional methods, although objective of conducting emission suppression could not be achieved as effectively as the proposed multiobjective framework. Such observations reveal that unisolation approaches are inadequate for fulfilling the rising EMC prerequisites of cutting edge high-frequency power electronic systems. This necessitates an integrated approach that designs for converter dynamics, parasitic effects, modulation behavior and finally optimization objectives all at once.

We obtain several industrial benefits from the proposed methodology. The framework can be utilized to various series of multilevel inverter applications such as renewable energy systems, electric vehicle traction drives, smart-grid interfaces, energy storage converters and industrial motor drives. With rising frequency and the availability of wide-bandgap semiconductor devices, EMI immittance is set to worsen. This approach to directly incorporating conducted EMI mitigation into the control design process offers a scalable and forward-looking solution for achieving EMC compliance without compromising high-performance converter operation.

Although the results are promising, several limitations need to be recognized. Firstly, the present study mainly relies on simulation analysis and nominal inverter models. Despite being developed from a realistic parasitic-based simulation environment, the experimental validation under hardware conditions is still required to fully prove the proposed methodology. Secondly, the optimization framework was only tested with a three-level NPC inverter topology; more research should be conducted to evaluate its generalizability to other multilevel topologies such as Flying Capacitor and Cascaded H-Bridge inverters. Third, the high computational cost required by constraints in recent optimization algorithms may create problems when used for online implementation in framework control systems, especially as the number of variables increases.

Future work should be carried out using hardware prototypes and compliant EMI measurement setups as stipulated by CISPR in order to validate the observations experimentally. Future work on real-time optimization methods, adaptive control systems and machine learning based EMI predicting, as well as digital twins might maximize performance and commercialization of the EMI-aware inverter control. Additionally, an expanded framework covering radiated EMI, thermal management, reliability, and cybersecurity can be developed to offer a more comprehensive design methodology for next-generation power electronic systems.

In conclusion, the results illustrate that the pursued integrated modeling and multiobjective control framework effectively balances a coupled EMI suppression-to-power quality improvement-to-energy efficiency trade-off. This framework offers a systematic and scalable design flow for EMC-aware multilevel inverter development while paving the way towards high-performance, standards-compliant power electronic converters for future energy conversion applications.

9. Conclusion and Future Directions

9.1 Conclusion

To the best of our knowledge, this is the first research that proposed a combined modeling and multiobjective control strategy for mitigation of conducted EMI in multilevel DC/AC inverters. The widespread application of multilevel inverter technologies in a range of emerging fields such as renewable energy systems, electric vehicle, smart grid, industrial drives and energy storage applications has driven the need for efficient EMC solutions to solve conducted EMI problems without degrading converter performance. Traditional EMI suppression techniques are mostly based on passive filtering and modifications, leading to a larger, more expensive and lossy system and addressing EMC only after converter design.

To tackle these limitations, this researchwork presents a unified framework integrating dynamic modeling of inverter, EMI analysis, common-mode behavior characterization, control strategiesand multiobjective optimization in a single design environment. In this work, the importance of optimizing conducted EMI reduction as a main optimization objective along with THD, switching losses, common-mode voltage (CMV), common-mode current (CMC), and converter efficiency is addressed. The framework promotes proactive EMI mitigation instead of reactive post-design correction by integrating EMC considerations directly into the control design process.

The validity of the proposed methodology was shown using simulations under prudent operating conditions. The optimized framework achieved significant reductions in conducted EMI emissions, common-mode voltage & current and improved output waveform quality as well as high conversion efficiency. The results obtained verified the possibility of implementing intelligent control and optimization for achieving effective EMI suppression without excessive reliance on passive mitigation devices. Moreover, the optimization process based on Pareto was successfully able to explore good trade-offs between various metrics, exhibiting good promise as a systematic design tool for the designers to work with conflicting (or mutually dependent) requirements.

The compliance assessment also verified that the proposed framework can significantly enhance EMC performance compared to traditional control techniques, while also ensuring sufficient compliance margins against representative CISPR and IEC conducted emission specifications. They confirm the applicability of EMI-aware control strategies for future multilevel inverter designs and emphasize pursuing EMC as a primary design objective rather than a post-design compliance check.

In summary, the presented research provides an EMI-aware design methodology that integrates power electronics, electromagnetic compatibility and advanced control optimization. The proposed framework gives a practical basis for the advance of high efficiency, energy efficient, and standards compliant mli systems for next generation power conversion applications.

10.2 Research Contributions

The critical contributions of this study can be purorted as follows:

Creation of a ground-up mathematical modeling framework for improved understanding of the EMI generation and propagation through components used in multilevel DC/AC inverters.

Common-mode voltage sources, common-mode current propagations, and immunizations as well as parasitic coupling effect are identified and characterized as dominant EMI mechanisms.

Development of a multiobjective optimization framework that can minimize the conducted EMI, THD, switching losses and common-mode voltage and current.

Novel control & modulation strategies co-designed in an EMI-aware optimization workspace

Creation of a common approach for system modeling in respect with trade off between EMC, power quality and converter efficiency.

Optimized Design-Driven Inverter Control for Higher Level of EMI Compliance

Development of a scalable scheme for renewable energy systems, electric vehicles, smart grids and industrial power conversion systems.

10.3 Future Directions

While the proposed framework has shown effective performance, there exist various possibilities for extending and improving this research.

Experimental Hardware Validation

Future work that remains to be done is implementing the proposed methodology on a laboratory-scale multilevel inverter prototype. Experimental EMC measurements shall be conducted using Line Impedance Stabilization Networks (LISNs), spectrum analyzers, and through a conducted emission test setup to verify the simulation results and ensure that is compliant with the needed EMC standards.

Advanced optimization algorithms — Real-Time Implementation

In this work, offline optimization approaches are used for tuning parameters of controllers. Further research should focus on real-time optimization methods that can vary control parameters in response to changes in operating conditions, load variations, and electromagnetic interference environments.

Machine Learning-Based EMI Prediction

This framework can also be enriched with artificial intelligence and machine learning techniques to use operating data records for predicting EMI behavior in the past system. Data-trained methods have potential to largely decrease the computational complexity and accelerate EMI-aware control decisions.

Digital Twin-Based EMI Monitoring

Future inverter systems may deploy a digital twin of a physical converter in real-time. These systems could continuously monitor conducted EMI performance, forecast impending EMC violations, and automatically tune control parameters before compliance limits are approached.

Extension to Wide-Bandgap Semiconductor Devices

The approach needs to be further extended for inverter systems using Silicon Carbide (SiC) or Gallium Nitride (GaN) devices. They can provide improved efficiency and switching performance, but they do have much higher dv/dt and di/dt that make EMI problems even more acute.

Integration of Radiated EMI Analysis

The scope of this research mainly includes conducted EMI. Future research will expand on these techniques and develop an umbrella framework for EMC-focused inverter design that

includes radiated EMI models, shielding effectiveness analysis, enclosure optimization, and electromagnetic field assessments.
Multiobjective Reliability and Thermal Optimization
The optimization framework should encompass other objectives like thermal stress, device lifetime prediction and reliability prediction and fault tolerance. This will allow profiling and optimizing for EMC performance, efficiency, thermal management and reliability in one single process.
Application to Emerging Energy Systems
This framework can be extended to accommodate new applications which include:
Electric vehicle traction systems
Fast EV charging infrastructure
Grid-connected renewable energy converters
Microgrids and smart grids
Aerospace power electronics
Wireless power transfer systems
Energy storage converters
Development of Adaptive EMI-Aware Controllers
They might also include adaptive algorithms that would automatically monitor an EMI measurement at any point, and adjust the switching patterns or modulation strategies to ensure compliance with EMC standards in real time.
Standard-Aware Design Automation
Future studies could explore automated design habitats incorporating international EMC standards such as CISPR 11, CISPR 25, IEC 61000 and FCC regulations directly into optimization algorithms for a fully standards-driven inverter design.
Final Remark
Electromagnetic compatibility, advanced control systems, and AI will be critical in the future design of power electronic converters. The framework presented in this work is an essential step toward this vision, as it shows that conducted EMI mitigation can be achieved proactively with intelligent modeling and multiobjective control, without expensive post-design corrective actions. As the power electronic systems trend to higher switching frequencies, higher power densities and stricter regulatory requirements, EMI-aware optimization frameworks including the one in this study will become indispensable tools enabling reliable, efficient and regulations-compliant energy conversion.

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