Multiport Smart Transformers: A Review of Architectures, Applications, and Future Trends

Abstract

Multiport Smart Transformers (MSTs) are transforming modern power systems by offering enhanced flexibility, efficiency, and control. This advanced functionality makes MSTs essential components of next-generation grids, where adaptability is crucial. By enabling the seamless integration of renewable energy sources (RESs), MSTs help balance variable generation and load demands. Moreover, their ability to support bidirectional power flow plays a vital role in emerging applications such as electric vehicle (EV) charging, microgrids, and other decentralized energy systems. This paper provides a comprehensive review of MST architectures, focusing on design principles, topologies, and control strategies essential for managing power flow, voltage regulation, and fault protection. It highlights real-world applications, demonstrating how MSTs enable RES integration, grid reliability, and support advanced technologies like vehicle-to-grid (V2G) systems. The paper also explores recent advancements in MST technology, such as efficiency improvements and thermal management, while addressing current challenges related to standardization and control complexity. Finally, it discusses emerging trends, including the use of artificial intelligence for real-time control, and outlines future research opportunities aimed at enhancing MST capabilities.

Index Terms

Multiport smart transformers, smart grid, energy flexibility, power electronics.

I. Introduction

Multiport Smart Transformers (MSTs) are emerging as a transformative solution in modern power systems, offering enhanced flexibility, control, and reliability in energy distribution. By integrating power electronic converters with advanced control algorithms, MSTs enable seamless bidirectional power flow, which is essential for accommodating distributed energy resources such as renewable energy sources (RESs), electric vehicle (EV) charging stations, and microgrids [1]. This functionality not only supports dynamic power exchange but also facilitates grid stability in the face of fluctuating generation and demand. Unlike traditional transformers, MSTs can regulate voltage and frequency with high precision, while simultaneously improving energy conversion efficiency and providing robust fault protection. As a result, MSTs play a critical role in addressing the complex challenges of decentralized and digitalized power systems [2].

MST architectures are tailored to meet varying operational demands, with several power electronic topologies employed to optimize performance. Among these, the Triple Active Bridge (TAB) has gained significant attention due to its high efficiency, modularity, and scalability in managing bidirectional power flows [3]. Other widely explored configurations include the Dual Active Bridge (DAB), known for its compact structure and simplified control, and the Multilevel Modular Converters (MMC), which offer improved voltage quality and reduced electromagnetic interference—particularly beneficial in medium- to high-voltage applications. The choice of topology often influences the design of control strategies, which are vital for maintaining system stability, coordinating multiport power flows, and enabling real-time energy optimization through AI-based algorithms [4]. With their architectural versatility and intelligent control, MSTs play a key role in enhancing grid resilience, supporting flexible EV charging, and enabling autonomous microgrid operation [5]. Despite these advantages, MSTs face challenges such as thermal management, material constraints, electromagnetic interference, and control complexity [6]. Standardization and interoperability remain key hurdles.

This paper reviews MST architecture, topologies, control strategies, applications, and the challenges shaping their future in power systems. It also explores opportunities for advancing MST technology and overcoming the current limitations to fully realize their potential in modern energy systems.

II. Architectural Overview of Multiport Smart Transformers

A. Design principle

The MST system integrates multiple sources and loads through a magnetic core that eliminates the need for direct electrical connections, using high-frequency signals. The design involves separate development of critical components such as the magnetic core, power converters, and control system, each essential for the system's functionality and efficiency. The core design includes multiple steps, as illustrated in Fig.1, starting with the selection of the appropriate

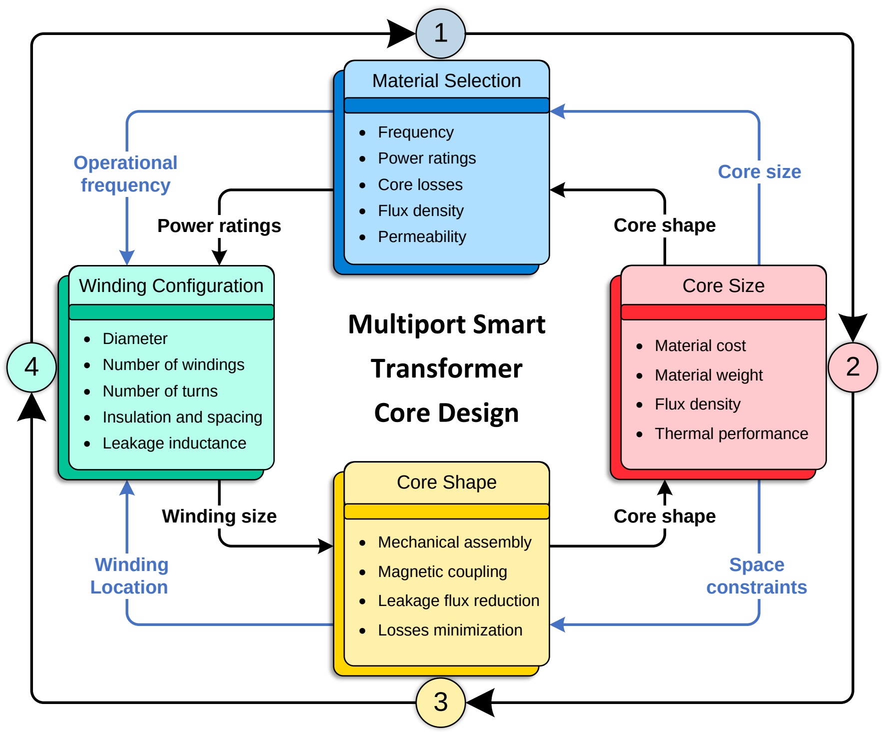

Fig. 1. Magnetic core design steps and key considerations

magnetic material, considering factors such as saturation flux density, permeability, and core losses, which are influenced by the operational frequency and temperature stability. Common materials include Si-Steel, nanocrystalline, amorphous, and ferrite, each chosen based on a trade-off between efficiency, cost, and availability [7]. Designers often use empirical models or Finite Element Analysis (FEA) to simulate and optimize the core geometry and performance [8]. While empirical models offer a time-efficient preliminary selection, FEA provides a detailed approach that incorporates the exact material specifications and simulates various operational conditions, enhancing the design precision. A significant design challenge is estimating core losses, especially under non-sinusoidal conditions where traditional Steinmetz Equation (SE) may lead to inaccuracies. Adjustments to SE or the use of FEA for a more accurate frequency spectrum analysis are critical for precise loss calculations [9]. Winding design also plays a vital role, with choices around wire types like Litz wires to minimize losses due to skin and proximity effects at high frequencies [10]. Advanced cooling strategies and insulation materials are required, especially in high-density settings, to effectively manage thermal loads. Finally, configuring windings to optimize coupling coefficients and minimize leakage inductance, while managing increased parasitic capacitance, exemplifies the complex interplay of factors in MST design [8]. As the number of ports increases, system integration and maintenance become increasingly complex, underscoring the need for innovative approaches in both design and operational strategy.

B. Topologies

Many power converter topologies have been proposed for MSTs. Depending on the application of the MST, it may contain an AC/DC or DC/AC stage to allow the grid integration with the Medium Voltage (MV) or Low-Voltage (LV) grid or operate as a grid-forming converter to supply local AC loads. Nonetheless, the core of the MST corresponds to the internal DC/DC converter stages, which enable magnetic isolation, voltage scaling, and modularity, which are crucial for multiport operation. This stage is common to all MSTs, regardless of the power converter topology or architecture.

The diagram presented in Fig.2 summarizes the stages that form an MST, including only voltage-source converters. Nonetheless, MSTs based on current source power converters can be classified in a similar fashion [11].

Regarding the isolated internal DC/DC stage, Medium or High-frequency Transformers (MFT or HFT) in different configurations are typically employed in conjunction with a power converter stage on each winding. In this regard, one of the most recurrent power converter topologies used in solid-state transformers (SSTs) and MSTs is the Dual-Active Bridge (DAB), corresponding to two active bridges connected through an HFT as shown in Fig.2.(a). The active bridges allow the bidirectional power flow between the two ports. Thanks to its simplicity and high efficiency, several DABs can be interconnected to form an MST.

The DAB can be extended by adding a winding to the HFT, forming a TAB, as shown in Fig.2.(b). The TAB by itself is already an MST, allowing the integration of multiple energy sources or loads into their ports [12]. The additional degree of freedom increases reliability and adaptability. Nonetheless, its control is not as simple as in the DAB.

DABs and TABs can be generalized by the Multiactive Bridge (MAB), which supports more than three magnetically isolated ports, as Fig.2.(c) shows. Its modular nature makes it scalable, especially for the continuously growing energy demands and applications in smarts grid, RES systems, and electrombility. Nonetheless, there is a high coupling between the ports, and complex control algorithms are required to decouple and avoid circulating power flows between the ports.

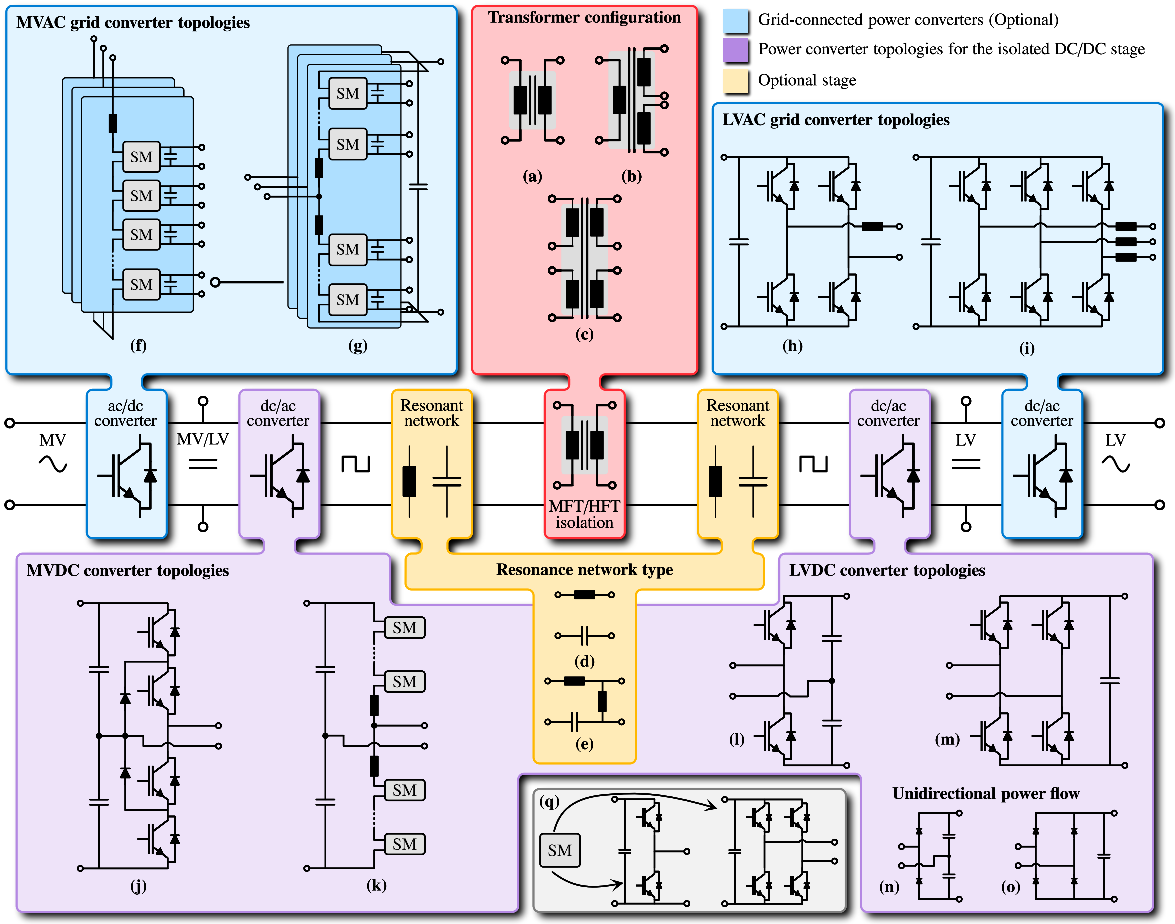

Fig. 2. MST power converter topologies. **(a)-(c)** Winding configuration of active bridge power converters. **(a)** Dual-Active Bridge. **(b)** TAB. **(c)** Multi-Active Bridge. **(d)-(e)** Resonance networks. **(d)** *LC* type. **(e)** *LLC* type. **(f)-(g)** Multilevel topologies for MV grid connection. **(f)** Cascaded H-Bridge. **(g)** Modular Multi-Level Converter. **(h)-(i)** Power converter topologies for LV grid connection. **(h)**H-Bridge converter. **(i)** Three-Phase Two Level Converter. **(j)-(k)** Power converter topologies for MV DC/DC stage. **(j)** NPC. **(k)** Single-Phase MMC. **(l)-(m)** Power converter topologies for LV DC/DC stage. **(l)** Split-Cpacitor Half-Bridge converter. **(m)** H-Bridge Converter. **(n)-(o)** Unidirectional power converters. **(n)** Unidirectional Split-Capactior Half-Bridge converter. **(o)** Unidirectional H-Bridge converter. **(q)** MMC submodule topologies.

Several power converter topologies have been proposed for the DABs, TABs, and MABs, which vary depending on the operating voltages. The following power converters are the most common in MV and LV applications.

- **Low-Voltage Topologies - Fig.2.(l)-(m)**: The most recurrent topology corresponds to the Full-Bridge cell. It generates a three-level output voltage on its output terminals when properly modulated. The split-capacitor Half-Bridge cell is an alternative among the reduced switch topologies. Only a bipolar output voltage can be synthesized, which is useful for medium-power applications.

- **Medium-Voltage Topologies - Fig.2.(j)-(k)**: A common MV topology corresponds to the Neutral Point Clamped (NPC) half-bridge converter [13]. This topology allows for the generation of three-level voltages in its output. Another alternative is the Modular-Multilevel Converter (MMC), synthesizing output voltages with a high number of levels and low harmonic content. Its scalability is suitable for MST applications at the MV level.
- **Unidirectional Power Converters - Fig.2.(n)-(o)**: These power converters, typically based on diode networks, are employed in applications in which bidirectional power flow is not needed, such as EV chargers without vehicle-to-grid (V2G) operation [14]. They are typically utilized in high-power applications due to the simple control.

Besides the power converter topologies mentioned previously, they can be modified by including resonant networks to achieve Zero-Voltage or Zero-Current Switching (ZVS or ZCS), boosting the conversion efficiency. Typical resonant networks includes the *LC* and *LLC* resonant tanks shown in Fig.2.(d)-(e) [15].

The power converter topology has a significant impact due to the relation between the number of voltage levels, the instant in which they are applied, and resonance, which will impact variables such as the active power transfer characteristic, rms current levels through the HFTs, and DC currents on the HFT. An example of this corresponds to modulation techniques, such as single phase-shift and triple phase-shift in DABs.

Regarding the grid-connection stage, in LV voltage applications (Fig.2.(h)-(i)), typically Full-Bridge topologies are employed in single-phase networks, whereas conventional two-level converters are used in three-phase networks. Variations for distribution grids with neutral connection include the active 4th leg or split capacitor topology [16]. Regarding the MV integration (Fig.2.(f)-(g)), typically it is achieved by employing multilevel converters, such as the cascaded H-Bridge converter, or the MMC. The floating cells are typically based, but not restricted, on half- or full-bridge converters, which are later connected to the internally isolated DC/DC stages [17].

C. Comparison of Architectures

Although the DAB is not a multiport topology, due to the magnetic isolation provided by the HFTs, it is possible to combine it with other DABs to form MSTs. On the other side, while TABs and MABs are intrinsically multiport power converter topologies, they can also be reconfigured

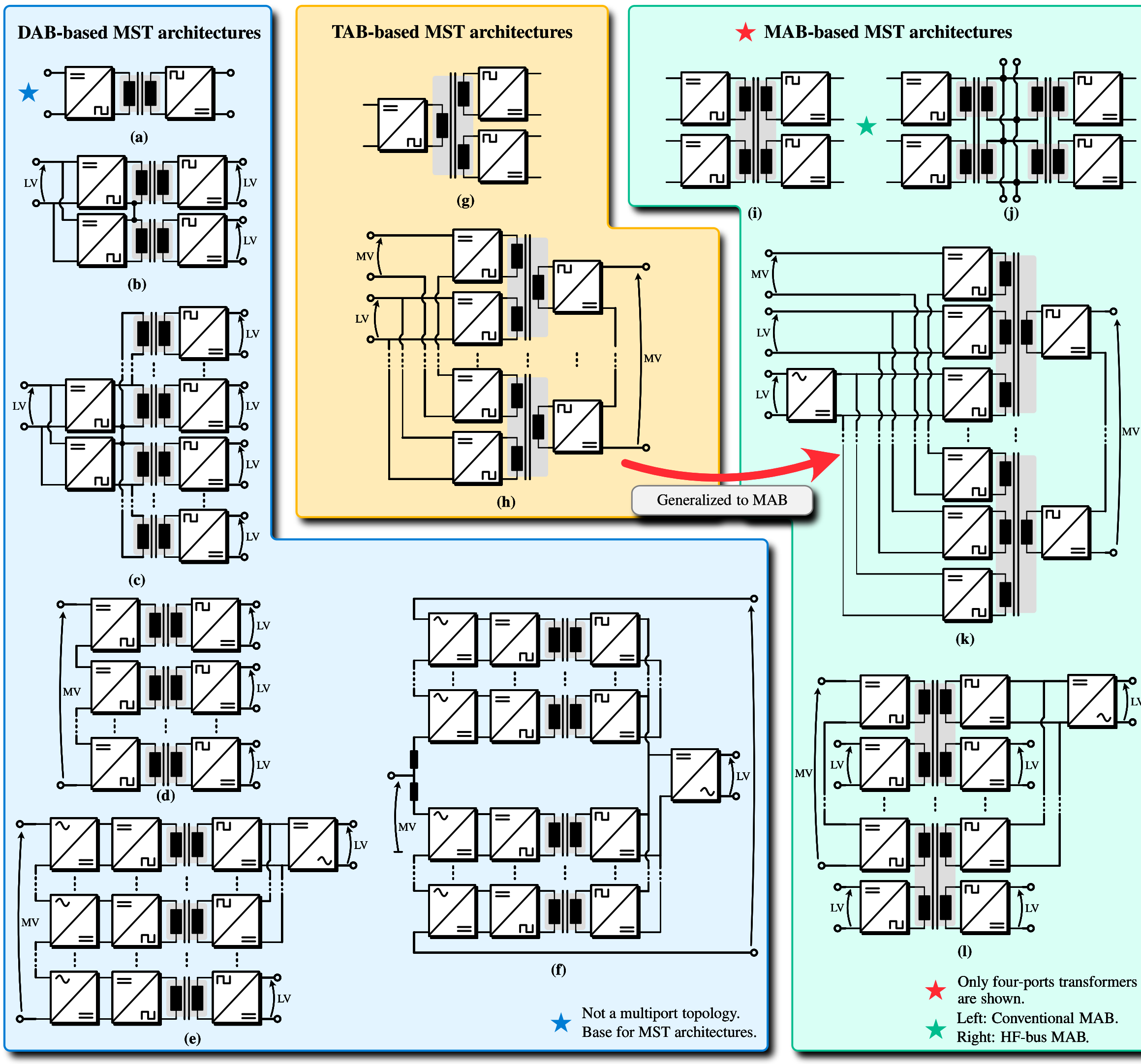

Fig. 3. MST architectures. **(a)-(f)** DAB-based MST architectures. **(a)** DAB converter. **(b)** 1 parallel LVDC - 2 LVDC ports. **(c)**. 1 parallel LVDC port - Multiple LVDC ports. **(d)** 1 MVDC port - Multiple LVDC ports. **(e)** 1 MVAC port - 1 parallel LVDC port and multiple LVDC ports. **(f)** MMC-based - 1 MVAC port - 1 LVDC and MVDC ports. **(g)-(h)** TAB-based MST architectures. **(g)** TAB converter. **(h)** 2 MVDC port - 1 parallel LVDC port. **(i)-(l)** MAB-based MST architectures. **(i)** MAB converter. **(j)** MAB with HF bus. **(k)** 2 MVDC ports - 1 LVDC port - 1 LVAC port. **(l)** 1 MVDC port - 2 LVDC ports - 1 parallel LVDC port.

to create new MSTs and more complex architectures. The diagram presented in Fig.3 shows some MST architectures based on combining basic DAB, TAB, and MAB modules.

DAB-based MST architectures are presented in Fig.3.(b)-(f). A three-port MST can be obtained by the parallel connection of the primary side of two DABs, sharing the neutral connection, as Fig.3.(b) shows. Each secondary side generates an isolated LVDC port. The previous architectures can be extended by increasing the number of HFT, therefore augmenting the number of output ports, as shown in Fig.3.(c) [13]. Another DAB-based DC MST is presented in Fig.3.(d). The series connection of DABs allows integration into an MVDC grid while each secondary generates an isolated LVDC port. This architecture has been employed to integrate multiple renewable sources and energy storage systems [18]. In some scenarios, some of the LVDC ports can be connected in parallel to increase the current capability of the system. The previous architecture can be extended to achieve the MVAC integration, which is typically done with cascaded H-bridge converters. Each submodule is then connected to a DAB, which on the secondary side can be parallelized to form a high-current LVDC port. Additional ports can be generated for supplying small loads or integrating local generation. Multiple variants of this architecture are found in railways applications [19]. Another MST architecture is achieved based on the MMC. Due to the high number of cells, the MMC enables the MVAC integration, generating an MVDC port simultaneously. Similarly, as in the previous architecture, each cell can be connected to DABs to form a high-current LVDC port [20].

Regarding the TAB, its multiport capability allows for integrating Photovoltaic systems and maximizing the power extraction by independent control of each port. By the parallel connection of multiple ports of TABs, it is possible to generate a high-current LVDC port for EV fast charging applications. An extension of the architecture presented in Fig.3.(d) has been proposed by replacing each DAB with TABs. This action enables doubling the amount of LVDC ports. [21]. Thanks to its flexibility, the TAB has been proposed as a transformer for supplying subsea loads by offshore wind energy and energy storage, which requires high efficiency and low electromagnetic emissions. The series connection of the TAB ports allows the MV connection to offshore wind energy sources, while the parallel ports enable the integration of energy storage systems. Both energy sources can be routed to the loads, which operate at MV thanks to the series connection of the TAB ports.

The MAB is presented in Fig.3.(i). A variation of this converter is known as the Modular Multiactive Bridge, in which the HFT windings are connected to a common HF bus, increasing the modularity and scalability of the converter. The characteristics of the MAB enable the integration of multiple energy sources, such as fuel cells, energy storage systems such as batteries and supercapacitors, and loads, in applications such as more electric aircrafts. When its ports are connected to the grid, it can be employed in EV charger applications.

By the modular connection of MABs, several architectures can be achieved. The architecture shown in Fig.3.(k) corresponds to the extension of that shown in Fig.3.(h), in which an additional port of the MAB is connected in parallel to later form a high-current LVDC port [22]. Similarly to the previous architecture, Fig.3.(l) enables the integration into the MVAC grid, the generation of a high-current LVAC port, and multiple LVDC ports for the integration of battery energy storage systems and EV chargers [23]. A similar structure has been proposed for green airports, in which several different kinds of load with varied characteristics, such as voltage, frequency, and power, are supplied [24].

III. Control Strategies for MSTs

A. *Power Flow Management*

Effective power flow management is crucial in power systems, ensuring the balance between generation and demand to improve stability, efficiency, and reliability. MSTs offer enhanced control by enabling bidirectional power transfer and seamless integration of both AC and DC energy sources. They play a transformative role in modernizing power systems, but managing these systems presents challenges such as fluctuating consumption patterns, intermittent renewables, bidirectional power distribution, and varying user preferences.

To address these challenges, a power flow management system for MSTs must meet several key operational objectives. First and foremost, it must maintain a stable generation-demand balance while ensuring system components operate within their power ratings to prevent overloads and inefficiencies. The system must also prioritize the power demand of critical loads to guarantee reliability, especially during supply shortages. Maximizing the utilization of RESs is essential for sustainability, reducing reliance on conventional generation. Additionally, managing EV batteries according to user preferences enhances demand response and facilitates V2G applications, improving user satisfaction and system flexibility. Lastly, incorporating time-of-use pricing allows for advanced energy management, optimizing power distribution based on fluctuating prices and demand patterns over time.

Various techniques have been developed to meet these objectives by regulating power distribution and coordinating multiple sources and loads, as summarized in Table I. Each approach offers distinct benefits and trade-offs, with simpler methods being favored for their ease of implementation, while more advanced techniques provide superior adaptability and optimization at the cost of increased complexity.

TABLE I
DIFFERENT POWER MANAGEMENT STRATEGIES FOR MSTS

Power Management Strategies	**Advantages**	**Disadvantages**
Rule Based Methods [25]	Simple implementation	Suboptimal performance in complex systems
Droop Based Methods [26]	Decentralized control	Requires extensive tuning of controller gains
Look-up Table Based Methods [27]	Fast decision-making capability	Require extensive recalibration
Model Predictive Based Methods [28]	Handles multivariable systems	Demands significant computational resources
AI Based Methods [29]	Highly adaptive in non-linear scenarios	Requires extensive training datasets

B. Voltage and Frequency Regulation

Voltage and frequency regulation are crucial in MSTs, especially if they operate as decentralized power systems. Unlike conventional transformers, MSTs utilize advanced power electronic interfaces that provide precise control over voltage and frequency across multiple ports, ensuring system stability under varying conditions. MSTs implement hierarchical control frameworks, typically including primary, secondary, and tertiary layers. The primary control layer, which operates on the fastest timescale, uses droop control algorithms to autonomously share power among MST ports. This approach enhances robustness against communication failures. For medium-voltage applications, cascaded MMC topologies improve voltage regulation and fault tolerance.

Advanced control methodologies, such as Model Predictive Control (MPC), are also gaining traction, particularly in applications with strict power quality requirements [30]. In addition, MPC helps to eliminate steady-state errors and harmonic distortion by achieving high gain at specific frequencies. Similarly, MSTs are critical for supporting frequency regulation in interconnected

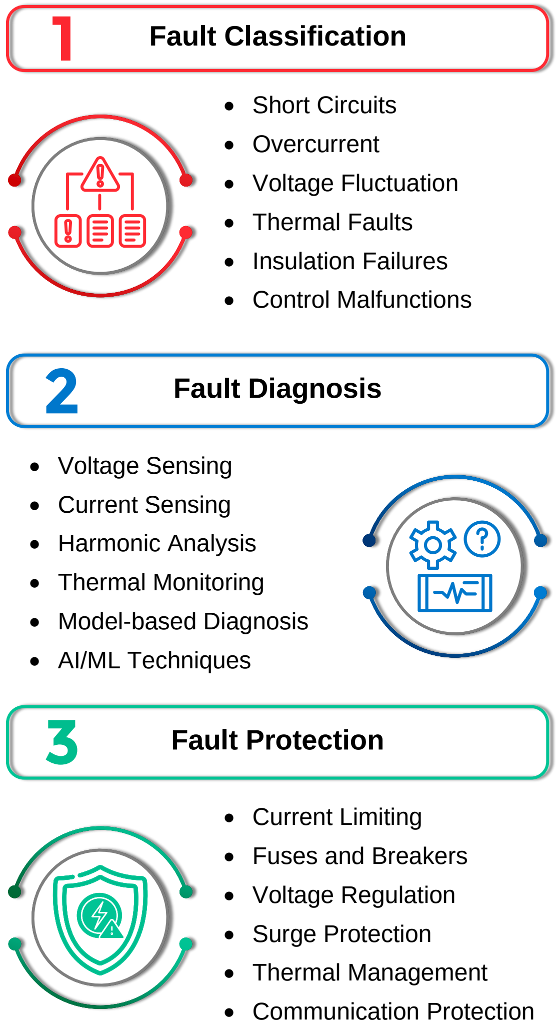

Fig. 4. Fault classification, diagnosis, and protection hierarchy

networks through mechanisms like synthetic inertia, primary frequency restoration, and fast frequency response.

Furthermore, MSTs are increasingly adopting grid-forming control strategies, allowing them to set voltage and frequency references rather than simply following grid conditions. This is beneficial in weak grid scenarios or during islanded operation. However, smooth transitions between grid-following and grid-forming modes are essential and require sophisticated algorithms to avoid voltage spikes or circulation currents. MSTs also mitigate voltage unbalance by compensating for phase imbalances, maintaining compliance with the EN 50160 standard [31].

C. Protection Mechanisms

MSTs face various fault types due to their integration with RES, EVs, and microgrids (as shown in Table II). These faults include short circuits, overcurrents resulting from load changes, voltage fluctuations, thermal issues arising from high power densities, insulation failures, and control malfunctions [32]. To ensure reliable operation, effective protection strategies must swiftly detect and address these challenges, minimizing disruptions and enhancing system stability.

TABLE II
FAULT DETECTION AND PROTECTION STRATEGIES FOR MSTS

Fault Type	**Detection Methods**	**Protection Strategies**
Input/Output Short Circuits	Voltage and current sensing, harmonic analysis	Active current limiting, fuses and circuit breakers
Overcurrent Faults	Voltage and current sensing	Active current limiting, fuses and circuit breakers
Overvoltage/Undervoltage Conditions	Voltage sensing, harmonic analysis	Dynamic voltage control, surge arresters
Thermal Faults	Thermal monitoring, model-based predictive fault diagnosis	Adaptive thermal protection, cooling systems
Insulation Failures	Voltage sensing, harmonic analysis	Surge arresters, active current limiting
Control System Malfunctions	Voltage and current sensing, AI/ML analysis, and states forecasting analysis	Intelligent controllers, real-time data exchange, cybersecurity measures
Power electronic faults	Real-time monitoring and AI/ML analysis	Redundant power paths, dual-mode operation, adaptive control techniques

The protection hierarchy against these faults follows a structured three-step approach as shown in Fig.4. First, faults are classified based on their nature. Next, diagnostic methods are employed to identify the most effective detection techniques. Finally, protection mechanisms are implemented to mitigate and resolve faults.

Voltage and current sensing play the key role in identifying overcurrents and voltage deviations [33]. Additionally, harmonic analysis detects faults stemming from non-linear loads or inverter-related issues, while temperature sensors provide early warnings for overheating [34]. To further enhance reliability, model-based predictive diagnosis leverages algorithms to anticipate potential failures, while AI/ML techniques analyze historical data and fault patterns, enabling preemptive responses [35].

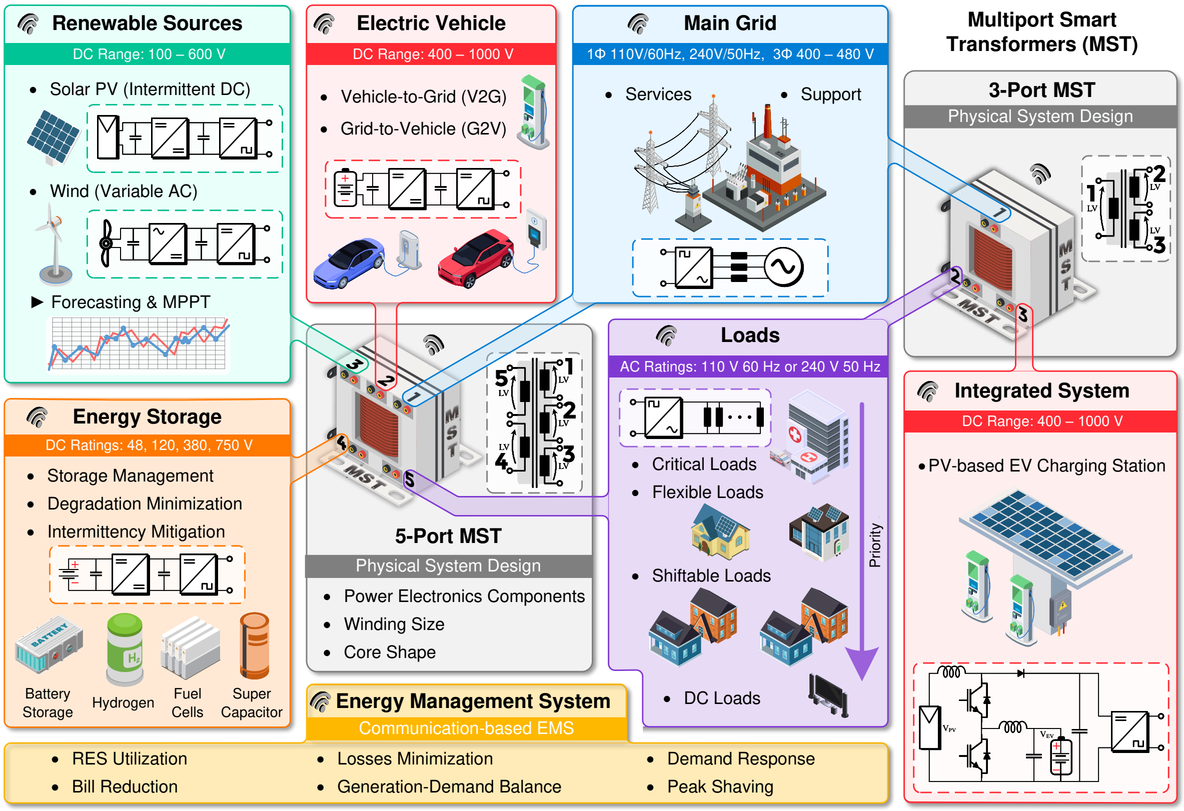

Fig. 5. MST applications with various distributed energy resources considering a 3-port and a 5-port MSTs with a communication-based energy management system.

A range of protection strategies is employed to safeguard MSTs. Active current limiting, achieved through semiconductor switching, prevents excessive currents, while fuses and circuit breakers ensure rapid fault isolation. Dynamic voltage regulation mitigates fluctuations, and surge arresters protect against voltage spikes. Thermal protection relies on adaptive cooling and real-time monitoring to prevent overheating. Additionally, redundancy mechanisms—such as backup power paths and dual-mode operation—enhance system reliability. Finally, communication-based protection integrates real-time data exchange and cybersecurity measures, ensuring a coordinated response to emerging threats.

IV. Applications of Multiport Smart Transformers

MSTs become widely common in multiple applications (as illustrated in fig.5) such as EV fast charging stations, where they facilitate the integration of RESs and energy storage systems.

MSTs also play a key role in smart grids and microgrids, enabling efficient power management, bidirectional power flow, and voltage regulation. In railway electrification, MSTs ensure smooth power conversion between AC and DC systems. Additionally, they are vital in RES integration, supporting the coupling of solar PV, wind, and storage systems, thereby enhancing grid stability and efficiency.

A. RES Integration

MSTs enable the seamless integration of RESs like solar, wind, and other sustainable sources into the grid, addressing challenges posed by their intermittency and variability. They provide a flexible, efficient, and scalable solution for managing diverse renewable inputs while enhancing overall system efficiency.

A key advantage of MSTs is their ability to interface with multiple RESs simultaneously, regardless of voltage or frequency. By directly coupling DC sources like PV-systems and battery storage with AC sources like wind turbines, MSTs eliminate unnecessary conversion stages, reducing energy losses and improving performance. Beyond integration, MSTs enhance power quality by mitigating voltage fluctuations, harmonics, and reactive power imbalances. Active filtering minimizes harmonic distortion, while voltage regulation stabilizes grid voltage, preventing equipment damage and grid instability. MSTs also regulate reactive power, compensating for renewable generation fluctuations to ensure grid stability [36].

Additionally, MSTs manage RES intermittency by integrating energy storage systems and using predictive balancing. Their multiport design allows direct storage connections, enabling rapid buffering during fluctuations. This intelligent management maximizes RES utilization while reducing reliance on fossil fuels.

B. Electric Vehicle Infrastructure

The integration of EVs into power grids presents challenges due to high power demands and unpredictable charging patterns. MSTs offer flexible, efficient, and bidirectional power management for EV charging infrastructure [37].

MSTs enhance charging stations by supporting multiple standards and power levels. Their isolated multiport topologies provide galvanic isolation, ensuring safety and protecting vehicle electronics. These topologies efficiently convert power between the AC grid and DC fast-charging needs. For instance, the TAB configuration connects to MV grids, LVAC loads, and multiple DC ports, supporting 50 kW to 350 kW charging without separate converters [38]. This reduces infrastructure footprint and conversion losses.

MSTs enable V2G functionalities, allowing EVs to return energy to the grid during contingencies or when economically beneficial. They support ancillary services like frequency regulation and voltage control [39] and coordinate EVs as virtual power plants to support peak demand and renewable fluctuations.

Additionally, MSTs mitigate EV charging impacts on local infrastructure through dynamic power balancing, preventing grid overloads. Active filtering improves power quality, while peak shaving reduces excessive grid draw. MSTs also enable smart charging strategies, optimizing time-of-use, renewable integration, and user preferences, reducing costs and enhancing sustainability. Their scalability minimizes grid reinforcements while maximizing RES use.

C. Microgrids and Distributed Generation

MSTs are becoming essential components in microgrid applications, offering the flexibility and control required to manage diverse energy resources while ensuring reliability and autonomy. Their capability to interface multiple energy sources and loads with precise power flow control makes them particularly well-suited for the complex energy management demands of modern microgrids [40].

As a foundational technology for advanced microgrid architectures, MSTs enable seamless integration of distributed generation resources with varying electrical characteristics. They are particularly advantageous in RES-based DC microgrids, providing galvanic isolation between critical subsystems while maintaining high operational flexibility [41]. In remote communities, MSTs facilitate the integration of RESs with battery energy storage and local distribution networks. Similarly, MSTs play a significant role in testbeds showcasing their potential for broader deployment.

MSTs support multiple operational modes, each crucial for microgrid functionality, with seamless transitions between them representing a key control challenge. In grid-connected mode, they enable bidirectional power exchange with the main utility grid while maintaining power quality and adhering to interconnection standards such as IEEE 1547-2022 [42]. During utility outages or in off-grid scenarios, MSTs shift to islanded mode, establishing reference voltage and frequency while ensuring internal power balance. Additionally, their advanced control strategies support black start capability, leveraging energy storage to restore system operation after a complete shutdown, sequentially energizing microgrid components to bring the network back online.

Furthermore, MSTs contribute significantly to microgrid reliability through advanced fault management capabilities. Isolated MST topologies offer inherent fault isolation between ports, preventing fault propagation across subsystems with different voltage and protection characteristics. This capability is particularly valuable in microgrid applications with critical loads requiring high reliability.

D. Case Studies

1) Delta Electronics 400 kW SST for Mobility and Grid Applications: Delta Electronics has demonstrated a 400 kW SST designed for mobility applications, RES integration, and grid modernization [43]. The system, showcased at the U.S. Department of Energy's Center for Mobility, aims to enhance energy efficiency, power conversion flexibility, and bidirectional power flow capabilities.

The SST technology integrates high-power AC and DC conversion, enabling seamless operation across EV charging infrastructure, microgrids, and industrial applications. By replacing traditional transformer systems, Delta's solution offers higher efficiency, reduced size, and improved dynamic response to fluctuating loads. The demonstration highlighted its potential to support high-power EV fast charging, stabilize grid fluctuations, and facilitate RES adoption. Delta continues to advance power electronics-based transformer technology, positioning SSTs as a key enabler of next-generation energy infrastructure.

2) ABB and DG Matrix Power Router for AI Data Centers: In 2025, ABB announced a strategic investment in DG Matrix, a North Carolina-based company specializing in SSTs [44]. This collaboration aims to advance SST technology for AI-driven data centers, renewable microgrids, and industrial electrification. The Power Router platform integrates multiple AC and DC sources and loads, replacing up to 20 conventional electrical devices with a single, high-efficiency system. Capable of achieving 98% energy efficiency, the system enhances grid flexibility while reducing operational costs.

ABB's investment supports the commercialization and deployment of this SST-based platform, addressing the growing power demands of AI-driven industries and the energy transition. By enabling real-time power optimization and advanced load management, this initiative aligns with ABB's long-term strategy to develop intelligent, efficient, and sustainable power solutions.

3) QEERI 6-Port MST for Integrated Energy Systems: The Qatar Environment and Energy Research Institute (QEERI) has developed an innovative 6-port MST that addresses the challenges of integrating diverse energy sources and loads within a single unified system. The MST features dedicated ports for grid connection with local loads, PV array, battery energy storage system, EV charging connection, and fuel cell-equipped electrolyzer, as presented in Fig. 6. This comprehensive architecture enables seamless power routing between multiple energy domains, establishing a flexible platform for renewable integration, energy storage, and transportation electrification.

The QEERI MST achieves system-wide conversion efficiency exceeding 95% while facilitating multi-directional power flow based on real-time conditions and economic signals. By consolidating multiple power conversion functions into a single unit, the system reduces component count, minimizes conversion losses, and reduces physical footprint compared to conventional approaches requiring separate converters. The bidirectional AC port provides grid support services including voltage regulation and frequency response, while the electrolyzer-fuel cell combination establishes a hydrogen energy pathway for long-term storage capabilities. This innovative system represents a significant advancement in integrated energy management, supporting the convergence of renewable generation, energy storage, and transportation electrification within a unified high-efficiency platform.

V. Challenges and Future Directions

A. Technical Challenges

Despite the advantages offered by MSTs, several technical challenges hinder their widespread adoption. One of the primary limitations is thermal management. MSTs, particularly those with high power densities, generate significant heat during operation, which can lead to thermal stress on components and reduced efficiency. Effective cooling systems, such as liquid cooling or advanced heat dissipation materials, are necessary but can increase system complexity and cost.

Material constraints also pose challenges. The performance of MSTs is heavily dependent on the quality and properties of the materials used in components like transformers, power electronic devices, and insulation systems. As RES integration increases, MSTs must handle higher power levels, requiring materials that can withstand greater electrical, thermal, and mechanical

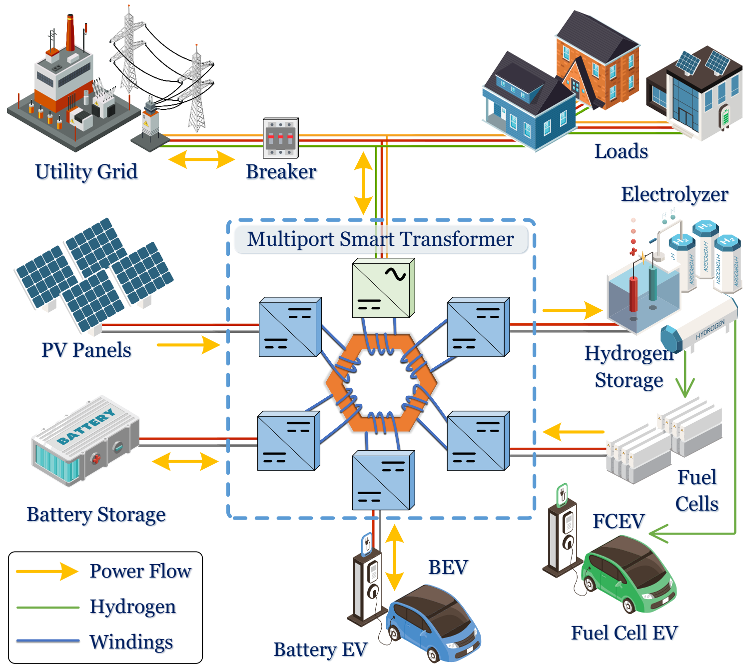

Fig. 6. Illustration of QEERI's 6-port MST.

stresses. However, these materials are often costly, and finding cost-effective, high-performance alternatives remains a challenge.

Control complexities also arise in MSTs, particularly in systems with multiple inputs and outputs. Coordinating power flow efficiently between various renewable sources, storage systems, and the grid requires advanced control algorithms and real-time monitoring. Achieving optimal performance without introducing instability or inefficiency demands significant computational resources, making the design and implementation of control systems more complex. Additionally, ensuring reliable operation under dynamic and fluctuating conditions requires highly responsive control mechanisms, which further complicate the system.

Future advancements in MST systems require further investigation into advanced materials, cost reduction strategies, and AI-driven optimization. Developing high-performance magnetic materials with lower core losses and improved thermal stability can enhance efficiency and reliability. Exploring novel winding techniques and additive manufacturing may further optimize transformer design. Cost reduction strategies should focus on minimizing material usage, improving manufacturing efficiency, and leveraging AI-driven predictive maintenance to reduce operational expenses. Additionally, enhancing AI models for real-time fault detection, adaptive control, and energy management can improve overall system performance. Further research into scalable, modular MST architectures will also support widespread adoption in renewable energy and grid applications.

B. Standardization and Interoperability

The widespread adoption and successful integration of MSTs into existing power infrastructure requires comprehensive standardization efforts that address both hardware interfaces and communication protocols. Several emerging standards are beginning to address specific aspects of MST deployment as shown in Table III.

Despite these developments, significant gaps remain. No comprehensive standard yet exists that specifically addresses MST design, testing, and integration. This may lead to proprietary solutions that hinder interoperability, for example,

- Physical Interfaces: Variations in connector designs and voltage levels complicate equipment replacement and system expansion.
- Communication Protocols: Differences in IEC 61850 implementations limit plug-and-play functionality.
- Control Architectures: Lack of standardized control hierarchies and function blocks prevents system coordination.
- Protection Coordination: Absence of standardized protection schemes complicates protection coordination in hybrid AC-DC systems.

TABLE III

RELEVANT STANDARDS, THEIR DESCRIPTIONS, AND REFERENCES

Standard	**Description**	**Reference**
IEEE 2030.7-2017	Specifies technical requirements for microgrid controllers and MST control functions.	[45]
IEC 61850-90-8	Focuses on communication interfaces for distributed energy resources.	[46]
EN 50160	Defines voltage characteristics for electricity supplied by public networks, impacting MST voltage regulation.	[47]
IEEE 1547.9-2022	Addresses interconnection requirements for distributed resources with electric power systems.	[48]

C. Advancing MST Systems through AI

AI enhances MST systems across design, control, and maintenance. Large Language Models (LLMs) improve topology optimization and material selection, refining core and winding designs. Physics-Informed Neural Networks (PINNs) integrate empirical data with mathematical models to predict electromagnetic, efficiency, and thermal behaviors, enhancing system performance.

For system configuration, Reinforcement Learning (RL) combined with Graph Neural Networks (GNNs) optimizes MST layout and component efficiency, proving effective in complex domains like chip design. In maintenance, AI processes large datasets for proactive fault detection. Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), and Support Vector Machines (SVMs) identify patterns, while Long Short-Term Memory (LSTM) and Gated Recurrent Units (GRUs) analyze temporal data to anticipate issues. Autoencoders (AEs) and Isolation Forests (IFs) further enhance anomaly detection.

AI-driven control strategies use RL, Neural Networks (NNs), and PINNs to dynamically adjust system states for optimal performance. Integrated fault detection enables fault-tolerant controllers, ensuring sustained efficiency and reliability.

VI. Conclusion

This paper highlights the critical role of MSTs in modern power systems, offering enhanced control over power distribution and enabling seamless integration of AC and DC sources. MSTs address key challenges such as fluctuating demand and intermittent renewables, providing efficient energy management and system stability.

Future research should focus on overcoming technical challenges like thermal management, electromagnetic interference, and system complexity. Standardization and real-time optimization will be crucial for enhancing MST performance and interoperability. By addressing these issues, MSTs can become a cornerstone of resilient, sustainable power systems.

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