IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 26 August 2023, accepted 14 November 2023, date of publication 20 November 2023, date of current version 27 November 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3334651

TOPICAL REVIEW

Review of Smart Transformer-Based Meshed Hybrid Microgrids: Shaping, Topology and Energy Management Systems

RAFAEL A. NÚÑEZ R.[1,2], **JOHNNY POSADA**[3], **CLODOMIRO UNSIHUAY-VILA**[4], **AND OMAR PINZÓN-ARDILA**[5]

[1]School of Engineering, Universidad Autónoma de Bucaramanga, Bucaramanga 680003, Colombia
[2]Faculty of Natural Sciences Natural Sciences and Engineering, Unidades Tecnológicas de Santander, Bucaramanga 680005, Colombia
[3]Department of Automatics and Electronics Engineering, Universidad Autónoma de Occidente, Cali 760030, Colombia
[4]Polytechnic Center, Department of Electrical Engineering, Universidade Federal do Paraná, Curitiba 81531-990, Brazil
[5]School of Electrical and Electronic Engineering, Universidad Pontificia Bolivariana, Bucaramanga 680006, Colombia

Corresponding author: Rafael A. Núñez R. (rnunez281@unab.edu.co)

This work was supported in part by the Science, Technology, and Innovation Fund of the General System of Royalties under the Excellence Scholarship Program 2019—Ministry of Science, Technology, and Research—Minciencias, Colombia.

ABSTRACT Microgrids are considered an adequate alternative to overcome the challenges involving integrating distributed energy resources in distribution systems to contribute to the 'Three D' trend in the electricity sector, i.e., decentralize, decarbonize, and digitize electricity. This paper reviews the most relevant works to establish a baseline for advancing and developing smart transformer-based meshed hybrid microgrids and energy management systems. First, the structure of the solid-state transformers as smart transformers and their potential application as energy routers in a microgrid is discussed. Then, the principle of conformation of meshed hybrid microgrids based on a smart transformer and the topologies reported in the literature are reviewed. Finally, power management systems integrated into smart transformers-based meshed hybrid microgrids are studied. According to the findings and conclusions, smart transformers-based meshed hybrid microgrids operated by an optimal energy management system under uncertainty are a potentially feasible technological alternative for adequately penetrating distributed energy resources into local distribution systems.

INDEX TERMS AC/DC microgrid, distributed generation, power management, smart transformer.

NOMENCLATURE

GHG	Greenhouse Gas.
ESS	Energy Storage Systems.
DG	Distributed Generation.
MG	Microgrids.
DER	Distributed Energy Resources.
DS	Distribution System.
PVG	Photovoltaic Generators.
EVs	Electric Vehicles.
V2G	Vehicle To Grid.
AC	Alternating Current.
DC	Direct Current.
HMG	AC/DC Hybrid Microgrids.
IC	Interlinking Converters.
MHM	Meshed Hybrid Microgrids.
SST	Solid-State Transformers.
ST	Smart Transformers.
ER	Energy Router.
PEI	Electronic Power Interface.
EMS	Energy Management System.
GA	Genetic Algorithms.
EI	Energy Internet.
KPI	Key Performance Indicator.
OPF	Optimal Power Flow.
OEMS	Optimal Energy Management Systems.

The associate editor coordinating the review of this manuscript and approving it for publication was Suman Maiti.

PIC	Proportional-Integral Controllers.
PRC	Proportional Resonant Controllers.
PQ	Power Quality.
LV	Low Volage.
MV	Medium Voltage.
LFT	Low-Frequency Transformer.
CCP	Control and Communication Platform.
DAB	Dual Active Bridge.
TP4L	Three-Phase Four-Leg.
DGC	Distributed Generation Converters.
IoT	Internet Of Things.
PEI	Power Electronic Interface.
MAS	Multi-Agent Systems.
GWO	Gray Wolf Optimizer.
ABC	Artificial Bee Colony optimization.
ToU	Time-of-Use.
BESOA	Bald Eagle Search Optimization Algorithm.
SH	Smart Home.
PAR	Peak-To-Average Rate.
IFM	Intelligent Fault Management.
IPM	Intelligent Power Management.
FREEDM	Future Renewable Electric Energy Delivery and Management.
OSI	Open Systems Interconnection.
SoC	State of Charge.
UPQC	Unified Power Quality Conditioner.
RO	Robust Optimization.
MV_{AC}	Medium Voltage AC.
MV_{DC}	Medium Voltage DC.
LV_{AC}	Low Voltage AC.
LV_{DC}	Low Voltage DC.
m_{MV}	Modulation Index.
i_M	Current Injection.
i_q^r, i_d^r	dq References Current.
m_{DAB}	Modulation Index DAB.
m_{LV}	Converter Modulation Index.
m_{MV}	Modulation Index AC-DC.
P_{max}; P_{min}	Maximum Power and Minimum Power.
LC_{PEI}	Local Control Loop.
P_{AC}, Q_{AC}	Active and Reactive Power Setpoint.
V_{AC}, I_{AC}, F_{AC}	Voltage, Current AC, and Frequency AC.
P_{DC}	Active Power DC.
V_{DC}, I_{DC}	Voltage and Current DC.

I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

In line with the needs in terms of reducing Greenhouse Gas (GHG) emissions, it is necessary to promote technological development to increase electricity coverage, integrated Energy Storage Systems (ESS) [1], and Distributed Generation (DG) schemes. Likewise, the strengthening and advancement of Microgrids (MG) [2], [3] create a diversified energy matrix that includes Distributed Energy Resources (DER) [4]. From this point of view, MG is a suitable alternative to overcome the challenges of integrating DER into the Distribution System (DS). Similarly, it is necessary to introduce ESS connected to the DS to cover the load demand in the periods of minimum generation of Photovoltaic Generators (PVG) [5], [6] since this period coincides with the peak of the highest energy demand [7], [8]. This event causes an imbalance in the voltage condition of the DS and waste of the generated energy [9]. It must be noted that considering the electric mobility strategy [10], high penetration of Electric Vehicles (EVs) involving charging system infrastructure and Vehicle To Grid (V2G) is expected and has a direct impact on the performance of DS [11], [12]. These impacts may include increased demand, voltage and phase imbalance of the network, injection of harmonics, power losses and reduction in network stability, among other aspects [13], [14]. These situations deteriorate the quality of service of the DS.

MGs make the integration of DER on a scale into the DS more flexible while improving the reliability and energy efficiency of the electrical grid [15]. Alternating Current (AC) MGs are widely used. However, despite the degree of maturity of control and management techniques, they present the need to introduce DG synchronization and reactive power management schemes [16]. On the other hand, Direct Current (DC) MGs allow the integration of DER and ESS with higher efficiency by using fewer converters and no reactive power. However, incorporating these elements into the common DC bus makes voltage control complex, and power-sharing algorithms are necessary [17], [18]. AC/DC Hybrid Microgrids (HMGs) appear as a typology of great interest since they combine the main advantages of AC and DC MGs [16], [19], [20], with a high degree of reliability, flexibility, and economy [21]. This MG allows combining AC and DC networks in the same distribution network through Interlinking Converters (ICs), which helps the integration of DER, ESSs, AC/DC loads, and V2G with minimal DS modifications, reducing the overall cost [16], [22]. These MG configurations have been conventionally implemented based on radial distribution schemes with satisfactory results. However, they might show low reliability regarding power supply since DER can cause voltage increases and exceed the limit [19].

In contrast, high load demand can cause a significant voltage to decrease at the end of the line and, at the same time, overload distribution lines and connected transformers [23]. Therefore, voltage regulation is challenging, especially for long feeders, and may require voltage regulation devices [22], [24]. Thus, in recent years, Meshed Hybrid Microgrids (MHM) based on Solid-State Transformers (SSTs) or Smart Transformers (STs) [25] have been proposed as a feasible alternative to increase the penetration of DER, ESS, and V2G [26]. Thus, it is necessary to establish a baseline for future studies of EMS systems applied to MHM.

B. RELATED WORKS

ST is an enabler element for hybrid AC/DC loops in MG under the Energy Router (ER) concept [27]. Due to the

TABLE 1. Comparison of findings in the literature review.

Ref.	YEAR	Ref. Type	MG Type	EMS Type	IC	SST	ER	EV/V2G	US
[7]	2023	RS	AC	OPF	-	-	-	-	-
[12]	2023	RS	AC	EU-OPF	-	-	-	V2G	-
[1]	2022	RV	AC	-	-	-	-	Y	-
[2]	2022	RV	HMG	OPF	-	-	-	Y	-
[32]	2022	RS	MHM	RB+ DCTR	-	Y	-	-	-
[17]	2021	RV	DC	EU-OPF	-	-	-	Y	-
[25]	2021	RS	MHM	DCTR	-	Y	-	-	-
[30]	2021	RS	MHM	RB+ DCTR	-	Y	-	Y	-
[33]	2021	RS	MHM	EU-OPF	-	Y	-	-	-
[34]	2021	RS	DC	DCTR	Y	-	-	-	-
[35]	2021	RV	HMG	EU-OPF	Y	-	-	-	-
[36]	2021	RS	MHM	RB- DCTR	-	Y	-	-	-
[37]	2021	RS	MHM	EU-OPF	-	Y	-	Y	-
[38]	2021	RS	MHM	EU-OPF	-	Y	-	-	-
[39]	2021	RV	AC	EU-OPF	-	-	-	Y	Y
[40]	2021	RS	AC	OPF	-	-	-	-	Y
[14]	2020	RS	MHM	DCTR	-	Y	-	-	-
[23]	2020	RS	MHM	DCTR	-	Y	-	-	-
[29]	2020	RS	MHM	RB	-	Y	-	-	-
[31]	2020	RS	MHM	DCTR	-	Y	-	-	-
[41]	2020	RV	AC	OPF	-	-	-	EV	Y
[42]	2020	RV	MHM	EU- DCTR	-	Y	Y	-	-
[43]	2020	RS	AC	DCTR	-	-	Y	-	-
[44]	2020	RV	AC	RB	Y	-	Y	-	-
[45]	2020	RS	MHM	EU-OPF	-	Y	-	-	-
[46]	2020	RS	MHM	DCTR	-	Y	-	-	-
[26]	2019	RS	HMG	-	-	Y	-	-	-
[47]	2019	RS	HMG	DCTR	Y	-	-	-	-
[48]	2019	RS	HMG	DCTR	-	Y	Y	-	-
[49]	2019	RS	HMG	OPF	Y	-	-	Y	-
[50]	2019	RV	HMG	EU-OPF	Y	-	-	Y	Y
[51]	2019	RS	AC	OPF	-	-	-	-	Y
[52]	2019	RS	AC	OF	-	-	-	-	Y
[53]	2019	RV	HMG	EU-OPF	Y	-	-	Y	Y
[15]	2018	RV	HMG	DCTR	Y	-	-	V2G	-
[20]	2018	RS	MHM	DCTR	-	Y	-	-	-
[24]	2018	RS	AC	RB	-	Y	-	-	-
[28]	2018	RV	HMG	DCTR	Y	Y	Y	Y	-
[49]	2018	RV	HMG	EU-OPF	Y	-	-	Y	-
[54]	2018	RS	AC	DCTR	-	Y	-	-	-
[55]	2018	RS	AC	DCTR	-	Y	-	-	-
[56]	2018	RS	AC	OPF	-	-	-	Y	Y
[27]	2016	RS	HMG	DCTR	-	Y	Y	-	-

US: Uncertainty Scenario; RS: Research Paper; RV: Review Paper; OPF: Optimal Power Flow; EU-OPF: OPF Heuristic Techniques; RB: Rule-Based; DCTR: Distribute Controller; Y: Yes; -: No report.

degrees of freedom of the ST, it can be transformed into MHMs by interconnecting the Electronic Power Interface (EPI) of each DER with the ST stages at the DC or AC ports [25]. STs, in addition to eliminating the need for IC [28], shape various energy flow paths and management strategies [25].

Nonetheless, MHMs must integrate supervisory control coupled with an Energy Management System (EMS) to optimize network performance in terms of power quality, reduced line losses, and MG fault management capability [14]. Recently, EMS strategies have been proposed in MHM that integrate ESS and PVG in connection and disconnection maneuvers [29], [30]. Similarly, they have shown that voltage and load profile control can be realized by meshing the network in a ring configuration with bidirectional power flow control [14], facilitating independent active and reactive power management [31]. On the other hand, EMS based on a hierarchical architecture with distributed control [14], centralized control [25], and schemes based on Genetic Algorithms (GA) combined with network reconfiguration algorithms [33], have been proposed. However, despite the promising results reported concerning MHMs and EMS, the proposed algorithms do not consider the variability of DER, ESS, V2G, and linear and nonlinear load management according to Key Performance Indicator (KPI) concerning the power quality of the MG in the DS.

Table 1 summarizes the findings in the review of the main papers reported. Key topics were defined to guide the study of this work. First, we seek to identify the publication date and reference type, whether a review or research results paper.

The kind of microgrid analyzed is also established: AC MG, DC MG, HMG, and MHM. Likewise, we seek to compare the type of key element in each work, such as IC, SST, and ER. On the other hand, EVs and V2G are considered topics, given emerging systems with growing interest in their operating principle and impact on the electricity system. Finally, a scenario under uncertainty is introduced, which seeks to identify the reported works that have presented studies or reports of MG under uncertainty conditions, either in load or DER.

According to the data reported in Table 1, HMGs have shown relevance given the characteristics to flexibly integrate DER and ESS on both the AC and DC sides of DS. These MGs are mainly characterized by integrating ICs for coupling between AC MGs and DC MGs, but the ICs are not considered to fulfill ER functions. Advances in EMS have been oriented towards heuristic optimization techniques and rule-based systems, further integrated with distributed control systems according to the control levels in the AC MG, DC MG, and HMG, under deterministic operating conditions, primarily. SST is considered a key component for forming HMG, but essentially, MHMs. Integrating these converters with suitable EMS allows better integration of DER and EV, both AC/DC, enabling ER functionalities. On the other hand, EVs and V2G have been studied mainly to evaluate their impact on AC MG and the advantages of integrating them in HMG; despite this, EVs have greater relevance given their higher participation in real DS. Few papers have presented the SST as an ER; however, the findings indicate that it is mainly used for HMG and MHM and has excellent potential to develop ER functions under the Energy Internet (EI) concept.

C. CONTRIBUTIONS

Despite the degree of progress in the development of AC MG, HMG, and MHM and the inclusion of new converters, such as the SST, which increase the degrees of freedom for optimal management of MGs, recently reported research has focused on studies of deterministic systems and, in the works that have conducted studies under operating conditions with uncertainties, have not included the SST and, even less, as ER. In this context, a gap exists regarding EMS advances in AC MG, HMG, and MHM that integrate the SST as ER under uncertain operating conditions. This paper reviews the most relevant works to establish a baseline for advancing and developing ST-based MHMs and EMS. The main contributions are the following:

a) Determine the characteristics and functionalities of the SST that allow it to become an ST and its potential application as an ER in HMGs under the concept of EI.
b) Establish the fundamental structure of an ST-based MHM, functionalities, and classification according to the different topologies and objectives of the MG management system.
c) Classify the optimal energy management algorithms of ST-based MHMs according to the objective function, constraints, and solver used to solve the optimization problem in real-time under uncertain operation scenarios.

The works reported in this paper include management mechanisms for Optimal Power Flow (OPF) in ST-based MHM. The proposed alternatives contemplate stationary DER conditions without considering the random behavior and their impact on the grid's overall performance [57], [58]. This scenario allows us to identify a baseline to propose a technological development and innovation alternative for the rapid penetration of DER in MG, whether AC, DC, or hybrid. This alternative involves developing Optimal Energy Management Systems (OEMS) based on robust optimization techniques [41], whose central actuator is established from the ST. The aim is to increase the resilience, reliability, and flexibility of the electricity system that operates under conditions of high uncertainty.

D. ORGANIZATION

The following review is organized as follows. Section II proposes a review of Smart Transformer-Enabled Meshed Hybrid MG, organized according to the Microgrids AC/DC definition (2.A), Smart Transformers (2.B), Smart Transformer-Enabled Energy Router (2.C), and Meshed Hybrid Microgrids (2.D), followed by a review of Energy Management System in ST-based MHM, in Section III. Section IV presents Findings and Contributions, which formulate, among other aspects, a technological alternative platform based on MHM and ST operated by OEMS according to the results and the gap identified throughout the studio. Finally, the conclusions are presented in Section V.

II. ST-ENABLED MESHED HYBRID MICROGRIDS

A generalized review of the control levels and management mechanisms most used in AC MGs, DC MGs, and HMGs is initially proposed to have a broader view of the conformation of ST-based MHMs. Then, the structure and operating principle of the ST, whose characteristics allow for the conception of this multi-stage converter as an ER, are presented. Finally, under this approach, a new HMG topology based on the ST is developed by exploiting the advantages of the classical HMG and the ST as an ER. Thus, the developments, advances, and challenges in implementing this new MG topology in EMS are presented.

A. MICROGRIDS AC/DC

AC MGs have four main components to be coordinated: active power, reactive power, harmonics, and unbalance components of the MG [18]. Similarly, power quality is the main problem of AC MGs compared to DC MGs. These components are set according to the operating mode, on-grid and off-grid.

In AC MGs, the primary control approach can be grouped into two types: a linear controller and a nonlinear controller. Linear controllers are typically Proportional-Integral

Controllers (PIC) and Proportional Resonant Controllers (PRC) according to a synchronous and stationary reference frame. A PIC is used for DC references due to the zero steady-state error, and for AC references, a PRC is selected due to its faster action [47].

Cascade controllers with a primary-secondary structure perform well in regulating voltage and power. In this technique, the primary is used to control the voltage and frequency, and the secondary is used to hold the active and reactive power of the system according to the conditions set by the primary controller [59]. The secondary control regulates the MG power management system, improving Power Quality (PQ) by restoring the MG voltage and frequency. At the same time, it facilitates resynchronization operation between the main grid and DGs [60]. Distributed, multiagent, and predictive model-based approaches are used at this level of control. From a higher approach, tertiary control is used to regulate the power flow between the AC MGs and the main grid to optimize the system performance so that it allows the coordination of the interconnection of multiple MGs and supplies the desired voltage and frequency to the main grid from the reference power component [61].

On the other hand, research on DC MGs has become relevant given the advancement in the development of DC renewable power generation sources and their inherent advantage for DC loads, such as EVs and ESS, in commercial, industrial, and residential applications [34].

The DC MGs have two control techniques predominating in the primary control in a hierarchical structure: centralized and decentralized. At the primary level, droop control, adaptive droop control, droop control with virtual resistance, and artificial intelligence-based schemes are used [35]. In the secondary controller, all primary controllers, such as centralized, decentralized, and distributed, can be implemented to provide voltage and current reference signals to the primary controller level. Reference signals for the primary controller supplied by the secondary controller increase the reliability, proportional power-sharing, voltage regulation, and overall power quality of DC MGs [17].

At the tertiary level, an additional controller is established to achieve economical operation and general regulation of the MG. Typically, the tertiary controller employs various heuristic techniques, such as particle swarm optimization and GA, for microgrid scheduling [62]. Additionally, these structures at the different control levels do not present synchronization and reactive control problems in the DC MGs.

The HMG concept seeks to exploit the advantages of AC MGs and DC MGs by combining AC and DC microgrid architectures under a single structure. Thus, the hybrid microgrid has the benefits of the two individual microgrids [49], allowing more flexibility in terms of the penetration of DER in the MG. A typical HMG is shown in Fig. 1. These are AC and DC microgrids connected through a bidirectional IC [63], a standard configuration of this type of HMG.

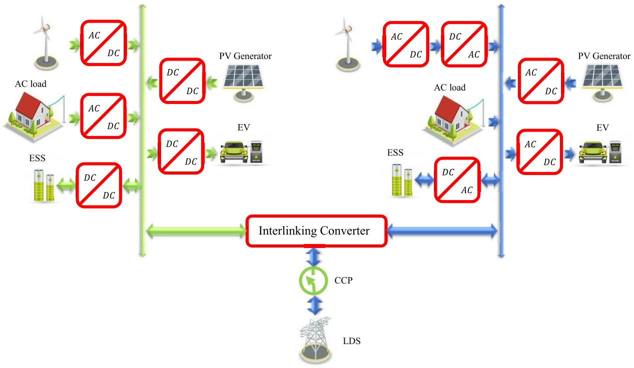


FIGURE 1. HMG architecture.

HMGs facilitate several potential advantages and establish a novel paradigm for future modern power system applications. The benefits of the HMG are related to the combination of AC and DC MG since it is a more flexible structure, reliable, with low complexity, a reduced number of converters, is sustainable, improves power quality, and is profitable [35]. The control algorithms set the operating point of the IC according to the level and focus of the central or distributed controller. In addition to generating significant advantages in terms of DER integration, this structure can present many challenges that are the subject of recent research, such as a more complex control strategy since no global variable can be used for power-sharing and voltage and frequency regulation. Similarly, a power-sharing method must be implemented between the AC and DC MGs independent of the conventional P – F and Q – V droop controller. Finally, an EMS is required to maintain the optimization and reliability of the MG [15]. Additionally, many authors have worked on different control strategies, such as current shaping control, centralized power management approach, hybrid instantaneous theory, and innovative restoration techniques [35], to solve the HMG operation stability problems from the operating and coordination points of the bidirectional converter to improve power quality and system reliability during events with nonlinear and unbalanced loads [64].

According to the results found in the literature, it is observed that HMGs present more significant benefits concerning the independent performance of MG AC and MG DC. Despite this, HMGs present challenges in IC management and control, a scenario that makes it complex to achieve optimal system performance. An alternative to reduce the complexity of the control and management algorithms is integrating a multi-stage converter with more degrees of freedom and greater flexibility to reduce the complexity of the management and control systems in the HMG, such as the ST.

B. SMART TRANSFORMERS

The ST concept is based on integrating the SST and communication-control interface, which allows to take advantage of the benefits of its decoupled structure in both

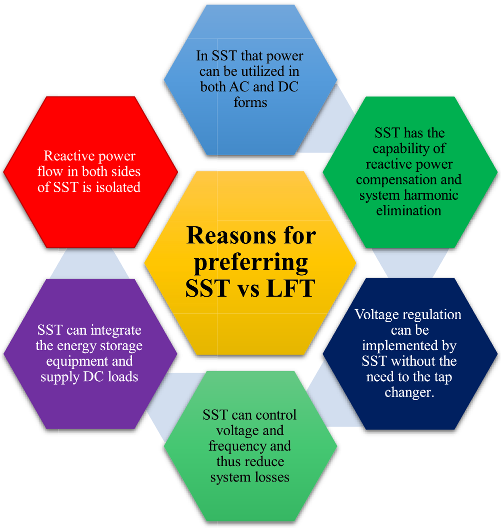


FIGURE 2. **Some of the most reasons for preferring SST vs LFT [73].**

AC and *DC* in a flexible way. The SST is a multi-stage power electronic converter with multiple Low Volage (LV) and Medium Voltage (MV) ports, both ACandDC. The first record of this concept was known in 1970, in which William McMurray proposed a power converter as a high-frequency $AC - AC$ link [65]. Despite this, the first introduction of the term SST was as an alternative to an autotransformer based on an $AC - AC$ buck converter and an $AC - AC$ buck-boost converter. This topology was introduced by J.L. Brooks in 1980 and initially focused on naval systems applications [66], [67].

In 1999, the ability of an SST to fulfill the function of LV distribution transformer was known [68], [69]. In 2001, Lothar Heinemann et al. [50], proposed the use of SST as a universal distribution transformer based on power electronic converters for MV and LV distribution systems. Recently, there has been renewed interest in SSTs due to the growing demand for interconnecting medium voltage AC and DC levels using high power density power converters with high performance and controllability in applications such as traction and future smart grids [42], [70], [71], as well as the formation of the ST [72] and ER [48]. Given the advances in the development and application of the SST in MG and DS, the SST has been considered a potential substitute for the Low-Frequency Transformer (LFT) in MV and LV systems. Although three aspects should be considered: a) The development and implementation cost of SST is much higher than that of LFT. However, with advances in power electronics, the cost of SST may begin to decrease significantly. b) The reliability of the LFT is considerably high with respect to the SST due to the high complexity of the SST structure [73]. c) LFT efficiency is high, between 98.5% and 99.5%, compared to a margin between 90% and 98.1% in the SST [74]. Despite this, the SST presents benefits that make it a key element to conform advanced network topologies that allow the integration of DER, V2G, and ESS flexibly and reliably with the possibility of increasing the degrees of freedom in the EMS of the MGs. Fig. 2 presents the main reasons for preferring ST vs LFT.

Managing DER, ESS, and V2G integrated into an MG requires the development of technology, new MG topologies, and power electronic converters to manage better the power flow and other conditions of AC, DC, or HMGs [26], [75]. Thus, the SST has been developed as a potentially key element for creating MGs since it is a multi-stage power electronic converter that integrates an AC-DC converter, a DC-DC converter with high-frequency galvanic coupling, and a DC-AC converter. These are managed by the electronic Control and Communication Platform (CCP) for interconnection with an MG [76]. This platform allows it to implement a decoupled control whose operating point is set with the EMS and Droop-Control type control layers. Consequently, it will enable the integration of DER into a DS, typically radial topology. The basic structure of a three-stage SST is shown in Fig. 3. The first stage is generally implemented from cascaded H-bridge converter modules, given the flexibility and power capacity offered by this type of converter [77]. This stage enables bidirectional power flow between MV_{AC} and MV_{DC} with unity power factor [78]. The second stage consists of Dual Active Bridge (DAB) modules cascaded with a common LV_{DC}, which allows us to increase the current delivered to the third stage of the SST with a level of LV_{DC} [72]. Finally, the third stage is typically implemented using a Three-Phase Four-Leg (TP4L) converter. This stage allows bidirectional power flow control between LV_{DC} and LV_{AC}, and the management of unbalanced loads by implementing current control in the neutral leg of the converter [79].

Each transformer stage has a decoupled primary control scheme. These controllers can operate in current or voltage mode in a cascade topology. This feature allows setting bi-directional power flow conditions and individual management of each stage based on SST operating modes of the power reference block and operating modes under the requirements of the microgrid's EMS. The first stage voltage controller can work in buck mode and boost mode and sets the Modulation Index (m_{MV}) of the converter. Boost mode is responsible for setting the Current Injection (i_M) MV main grid according to energy quality criteria. Buck mode regulates the MV_{DC} on the primary's DAB. The controller dq References Current (i_q^r, i_d^r) are set by the voltage/frequency restoration mechanism in conjunction with the power flow control, thus bidirectional MV_{AC} to MV_{DC} the transfer is performed in a bidirectional controlled manner. The second stage of the SST serves bidirectional power transfer (Buck mode or Boost mode) between the MV_{DC} and LV_{DC} levels limited by the Maximum Power and Minimum Power (P_{max}; P_{min}), integrating a high-frequency galvanic decoupling between the MV_{DC} and LV_{DC} levels of the SST. The Modulation Index (m_{DAB}) of the DAB sets the direction and magnitude of the power flow. This index is adjusted by the power flow controller according to the required voltage level at both MV_{DC} and LV_{DC} from the conditions set by the power reference

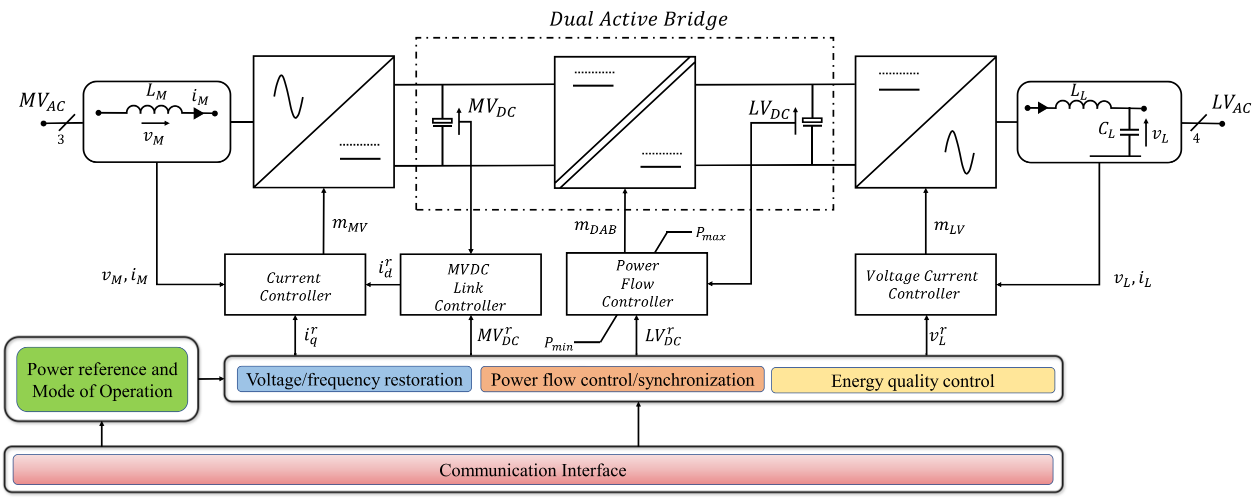


FIGURE 3. The basic structure of a three-stage SST.

block and operating mode of the SST, which set the reference MV_{DC}^r and LV_{DC}^r. The functionality of the DAB coupled to the control layers allows integrating, typically, ESS on the MV_{DC} bus [30], even allowing the form of hybrid $AC - DC$ loops by integrating DER on the LV_{DC} bus port [25]. The third stage of the SST enables the connection of the MG to the SST and bi-directional power transfer between LV_{DC} and LV_{AC}. This allows the SST to function as a grid following, when the MG is connected at one end to the main grid; grid forming, when the MG is fed only from the LV_{AC} bus of the SST and the SST imposes the voltage and frequency conditions on the MG; and grid-forming, when the MG is fed only from the LV_{AC} bus of the SST and the SST imposes the voltage and frequency condition on the MG. Likewise, it allows to take advantage of the availability of the DER in the AC or DC bus to supply the MG demand bidirectionally. The voltage and current controller adjust the Converter Modulation Index (m_{LV}) according to the power quality control mechanism requirements, the power reference block, and the SST mode of operation. For each mode of operation, the reference voltage level (v_L^r) and current (i_L^r) are set to maintain the SST output LV_{AC} at a suitable voltage level and frequency to meet the demands of the MG. The coupling between the primary control layers of each SST stage, the power and operating mode reference, voltage/frequency restoration, power flow control/synchronization, energy quality control mechanisms, and the communication interface make up the SST's electronic DAB CCP's. This structure converts the SST into an ST with multiple functionalities and degrees of freedom that give rise to the conformation of MHM.

The ST is more than a straightforward substitute for the conventional LFT (60 Hz or 50 Hz). This device supplies many services to the intelligent electrical grid. It also eases the integration of new hybrid AC and DC MGs architectures. Thus, the ST plays the role of an ER [48] since it can inject or absorb reactive power, mitigate harmonics [54], mitigate voltage sag [80], and limit current in the event of short-circuit

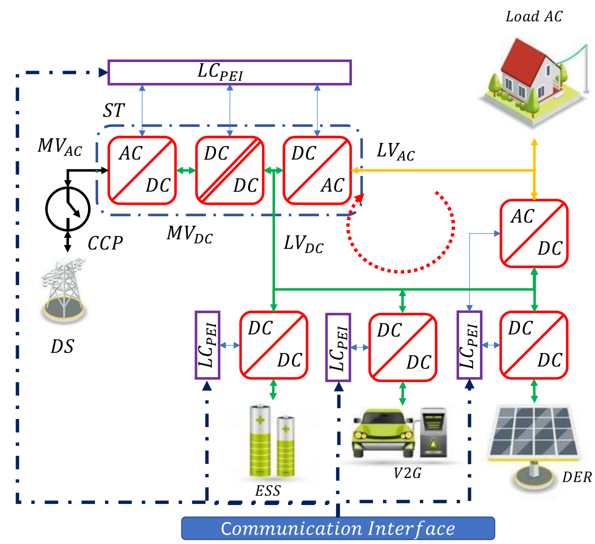


FIGURE 4. Formation of a hybrid meshed DS.

faults [81]. In this context, the communication signal will be the frequency of the AC microgrid [48]. That is, in an ST-commanded grid, distributed resources are connected on the LV_{DC} side or the LV_{AC} side asynchronously with the grid side so that the low-voltage DC or AC frequency can be used as a feedback signal for power flow control, and in this way, the power routing function is effectively achieved.

By taking advantage of the degrees of freedom offered by each stage of the SST, the ST concept [82] was proposed, which provides DC connectivity [83] and reduces the reinforcement in the LV_{AC} distribution network caused by the increasing penetration of DER, ESS, and V2G. The ST also represents a semi-decentralized solution for receiving network information since it is a controllable node to supply the MG demand bidirectionally. The voltage and current controller adjust the Converter Modulation Index of the MV network [26]. The ST allows the formation of a hybrid

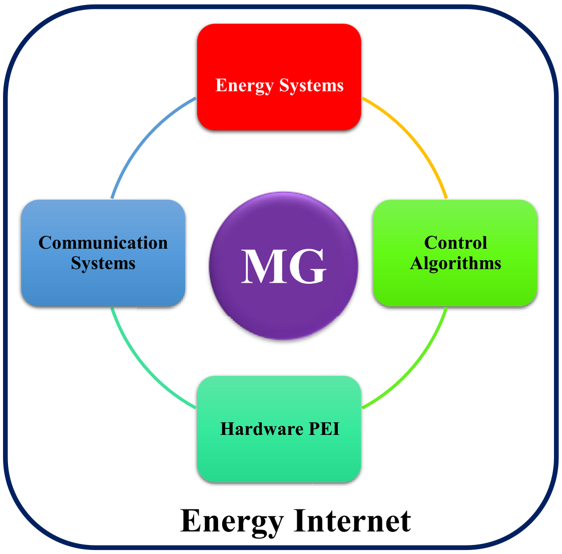


FIGURE 5. Overview of the key layers involved in EI.

meshed DS that provides voltage and power flow control to be achieved simultaneously with a centralized controller, as shown in Fig. 4.

Under this scheme, a LV_{DC} is connected between the LV_{DC} ST link and the Distributed Generation Converters (DGC) DC bus. This additional connection introduces several active power flow paths to support load demand. DGCs supply active power close to the load points in this way, ensuring that line losses are significantly reduced. Better voltage regulation is achieved compared to the conventional radial microgrid. On the other hand, DGCs can draw active power from the LV_{DC} link during the absence of DER to support the load, resulting in better use of these converters. This new scheme reduces the complexity of the DGC control algorithms since the ST controls both LV_{AC} and LV_{DC} line voltages [25]. Similarly, this ST-based MHM topology eliminates the need to introduce IC and allows for various power flow paths and power management strategies [28]. Under this novel approach, the advancement and development of MHM require an EMS to optimize the performance of the network in terms of network voltage limit, overcurrent, and line losses, as well as to manage network operation in the event of failure, avoiding network collapse [14], [84]. Furthermore, the hybrid structure that enables the interconnection of the network with the ports of the ST stages, as shown in Fig. 4, when integrated with appropriate control algorithms, provides functionalities that allow conceiving the ST as an ER that controls the bidirectional flow of power simultaneously on the AC and DC buses. Thus, the new challenges are focused on energy management algorithms to improve the performance of the ST as an ER.

C. SMART TRANSFORMER-ENABLED ENERGY ROUTER

The new actors involved in energy generation and DS based on renewable resources bring up scenarios where not only a technological transformation is needed but also a change in basic assumptions in policy and market practices in the value chain of the electricity sector [85]. Huang [70] argues that to facilitate the penetration of renewable energy sources into DS, the electric power market should be decentralized and deregulated with the active participation of consumers through real-time energy transactions. These ideas converge in a new business paradigm and electric grid infrastructure called the EI.

EI is a cyber-physical system in which the network infrastructures and the distributed resources are interconnected and managed by a cyber-energy network from algorithms employing energy packet management techniques [86]. Consequently, EI needs ER devices, i.e., ST. In that sense, as a transformation of smart grids, EI could be conceived as an application of the Internet Of Things (IoT) to the energy industry [87], [88]. However, in a broader view, EI makes up several layers that can be categorized into three groups based on the structure of the ST proposed in Fig. 3 and the architecture presented in [43]: i) power systems, ii) communication systems, and iii) control algorithms. Fig. 5 shows an overview of the critical layers involved in EI, which can be integrated centrally and flexibly into a decoupled multi-stage hardware architecture such as the ST, making them an ER. The communications system allows for synchronization, monitoring, and remote control of the Power Electronic Interface (PEI). Finally, control and management algorithms are integrated into the EMS, ST, and PEI.

In addition to suitable power electronic converters, the implementation of EI requires a telecommunications and control infrastructure that enables decentralized control systems, where the energy transaction in the different points of the network with high DER penetration is coordinated under global DS performance indicators. In [89], a distributed control scheme with two levels of control operated at the agent of each DER is proposed. Droop control is adopted for localized power sharing and a distributed diffusion algorithm for arbitrary power sharing among the DERs at the secondary level, all supported by Internet protocols. A similar approach is presented in [90]; however, it uses a novel decentralized robust control strategy for Multi-Agent Systems (MASs) governed by MGs in the EI. The objectives are frequency/voltage regulation and proportional reactive/active power sharing for MGs. Other work has integrated IoT technologies and prototypes with heuristic optimization algorithms and distributed control systems for managing MG. In [91], a real-time dispatch architecture based on the Gray Wolf Optimizer (GWO) and Artificial Bee Colony optimization (ABC) algorithm is proposed [91], in which a Time-of-Use (ToU)-based pricing model defines the peak hour rates optimally. Likewise, [92] presents a multi-objective version of a metaheuristic algorithm called the Bald Eagle Search Optimization Algorithm (BESOA) for discovering the optimal scheduling of home appliances at the Smart Home (SH) system level. Under this SH perspective, [93] develops a real-time DER residential load control method based on an input and optimization algorithm to control and schedule loads and

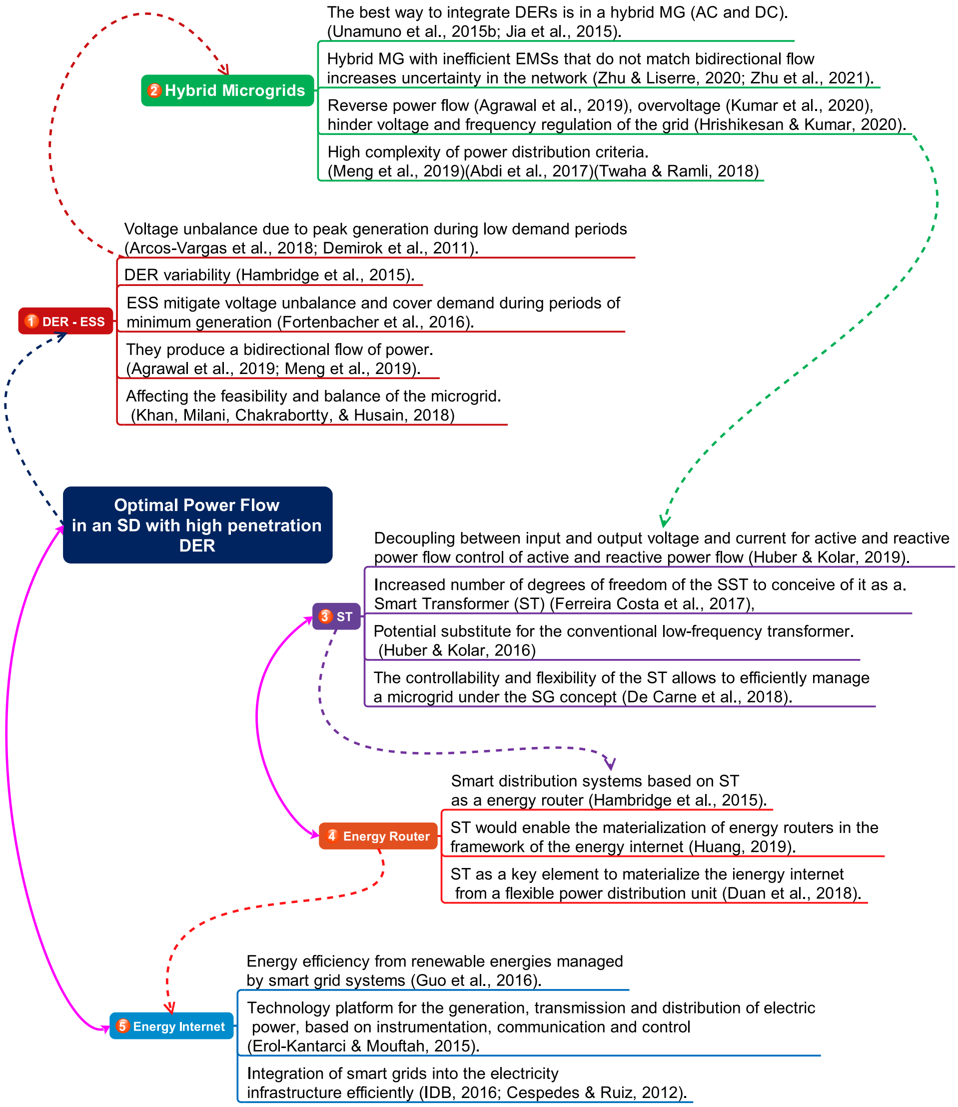


FIGURE 6. **Overview of the key layers involved in EI.**

Peak-To-Average Rate (PAR) savings. The results presented in these papers have shown good performances by integrating key elements such as EMS, IoT, and OPF algorithms. Thus, key components have been identified to conform to MG architectures based on the EI concept. Despite these, the achievements focus on AC MG management and do not introduce ER equipment from multi-stage converters. However, it could be visualized that these advances, plus the integration between the ST as a power router, EMS, IoT, and OPF, could form a flexible, reliable, and efficient MG structure [94].

MGs with high penetration of DER require adequate technology that allows the grid to manage the bidirectional flow of power resulting from the dynamics of supply and demand of the resource at different points of the grid. Intelligent Fault Management (IFM) and Intelligent Power Management (IPM) mechanisms are key elements of a fundamental EI requirement [48]. Therefore, integrating IFM and IPM into specialized hardware devices, such as ST, allows for determining the power routing in MG. This is done on the understanding that energy exchanges are not conducted directly between two points in the microgrid. Instead, the energy exchanges are conceived as a global energy balance in the MG. According to the EMS's automated decision criteria, the injection or absorption at different locations adjusts each PEI's point of operation [95]. In [70], a MG structure is proposed, conceived as the Future Renewable Electric Energy Delivery and Management (FREEDM). In this sense, sustainable MG must integrate plug-and-play interfaces that allow resources to be connected at any time and in any part of the network, thus promoting the modularity and flexibility of the system [96], [97].

Similarly, it should include intelligent EMS for real-time monitoring of loads and other system elements [88]. Additionally, distributed network intelligence algorithms should be implemented in an integrated way, allowing distributed control strategies to efficiently consider operating points between demand, generation, and energy storage at each network node [98]. Under this perspective and given the $DC-AC$ connectivity and degrees of freedom to implement control and power management algorithms in the SST [99], the ST as an ER would enable key tasks to be performed that meet the fundamental requirements of the EI [100].

A more compact and complete architecture concerning the EI paradigm is proposed by Patil [44]. This architecture is based on an analogy between the Open Systems Interconnection (OSI) model of the internet and the EI model. Thus, the physical layer corresponds to the DG and storage system. The link layer is related to the energy flow between network elements. The network layer is equivalent to the interconnection of multiple distribution nodes, and the transport layer is associated with the high-voltage transmission infrastructure of the network. The session layer refers to end-user and prosumer consumption. The presentation layer corresponds to the Internet-based communication infrastructure, and finally, the application layer is related to business and energy market management processes.

The ST-based router can work at the network level or the user level. The information flow is used at the network level to control power flow between different directly connected STs. At the user level, the ST connects and exchanges information directly with users, DER, ESS, and linear and nonlinear loads [101]. To achieve these functionalities, the ST must include a plug-and-play connection mechanism, bidirectional voltage, and current flow control algorithms at each stage of the ST. It must also integrate OPF scheduling, control algorithms, and a layer of real-time communication functions [27].

In Fig. 6, a diagram is proposed based on the findings found in the literature that sets up the interrelationship of DER (1), HMG (2), and ST (3) as an ER (4) based on EI (5). This relationship contributes to alternatives for solving OPF problems in MG with high penetration DER and ST as an ER in MG. DER has random characteristics that are conceived as non-dispatchable units. Therefore, a suitable way to integrate DERs into DS is through MGs. Given the benefits of the ST as an ER, adequate MG management is achieved by simplifying the decision criteria. Furthermore, the ST provides us with the necessary and sufficient elements to form an architecture according to the concept of EI. Finally, it allows us to propose management algorithms that contemplate feasible solutions to power flow problems in MG with high DER penetration.

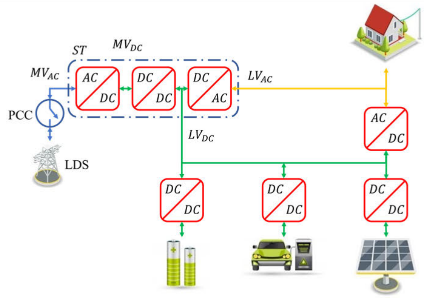
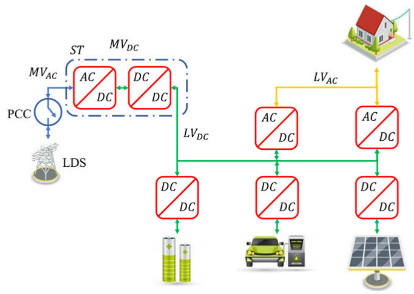
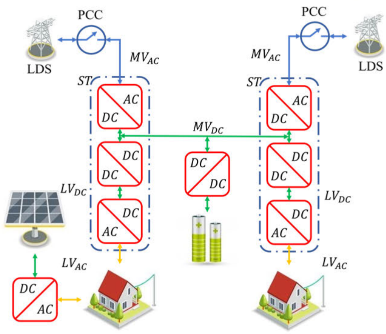
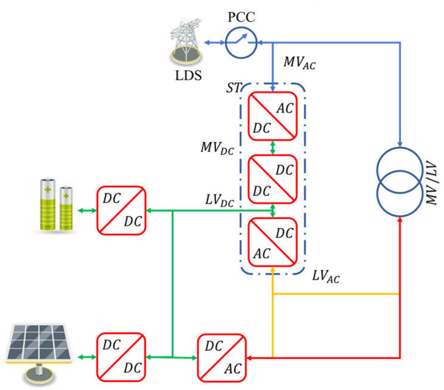
Under this scenario, alternative HMG and EMS schemes have been proposed that would give way to the materialization of the EI paradigm to integrate ST as an ER under a meshed or radial structure. The latter incorporates MG, ESS, and V2G in a flexible, controlled way that keeps the reliable performance of the MG by guaranteeing an optimal operating point based on KPI in terms of power quality. Control algorithms must ensure that the MG behaves as a single-frequency self-controlled entity, as with a synchronous generator. It must also prevent the power flow from exceeding the nominal values of the line by keeping the voltage and frequency within acceptable limits during island mode operation with an energy balance and an adequate scheme to resynchronize with the main grid safely [102], [103]. Under this scheme, authors agree that MHM controllers should regulate voltage and frequency under all operating conditions. They, likewise, shaped control active and reactive power to achieve adequate power-sharing in grid-connected and islanded modes with an appropriate transition. This scenario ensures an optimized DER production and maintains uninterrupted supply to critical loads such as schools, hospitals, and other essential services. In this way, it supports startup capacity in case of grid failure and establishes an optimized operating cost of production and energy exchanges with the main grid, among other aspects [15], [35], [104], [105], [106].

D. MESHED HYBRID MICROGRIDS

Many schemes have used hierarchical structure control strategies in HMG, where the primary loop regulates the MG's impedance, voltage, and current. The secondary loop is used to regulate voltage and frequency. Moreover, for its part, the tertiary control loop is used to hold active and reactive power, which facilitates optimal power exchange with the main grid [107]. Under a hierarchical control structure, several algorithms have been proposed for MG management based on the ST as an ER.

In [29], an ESS-based energy management algorithm for the islanded operation of a hybrid ST-based microgrid is proposed. Since this can control the LV_{AC} port, undervoltage load disconnection is intentionally implemented to reduce the ESS discharge rate during MG islanding operation when the State of Charge (SoC) of the ESS drops below a critical value. With this, it could be shown that the duration of ESS operation in island mode is increased by intentionally decreasing the LV_{AC} voltage by the ST in a MHM. Under this approach in [30], it was possible to demonstrate the conformation of several pathways for the controlled power flow in the system. Compared to AC interconnects, this configuration improves the entire system's performance during various adverse operating conditions, such as reverse power flow, peak power demand, and voltage drop, as the operation of an integrated ESS in an MHM is proposed. Instead of connecting through AC interconnects with normally open breakers, the same line is connected through the MV_{DC} links of the ST. On the other hand, [14] studies the advantages of implementing an ST-based MHM, as well as its operation and control. In this case, it is argued that the meshed MG is a hypernym for different power grid configurations, where each node in the network is fed from at least two sides. The LV_{AC} network can mesh both at the LV_{AC} bus bar and at the feeder end. The latter is also known as a ring network and is a subset of mesh networks. This allows optimizing the power flow in the grid since the MHM network configuration shows a high potential to control the active power flow bidirectionally. Therefore, instead of injecting the excess power generated by the DER into the MV_{AC} network at one of the feeders, the ST can send the excess power back to the feeder at the other end of the mesh.

TABLE 2. Different ST-Based MHM topologies.

Ref.	MHM OUTLINE	Objective
[14]; [25]; [29]; [33]; [37]; [45]; [32]		✓ Minimize losses in AC and DC distribution lines in isolated mode and connected to the DS. ✓ Simultaneous voltage and power flow control with a centralized controller. ✓ Conform an alternate path for power flow that allows for a more efficient reversal of power flow from DERs. ✓ Control MHM that operates in an intelligent and coordinated manner. ✓ Stabilize the voltage at the LV_{DC} from ESS in voltage mode and current mode. ✓ Optimize ST localization while minimizing the power drawn from the grid and keeping the line voltages stable.
[101]; [46]; [38]		✓ Reducing the number of converters from hybrid loops between the DER converters and the LV_{DC} of the two-stage ST. ✓ Reduce the capacity of power converters in the LV_{DC} grid. ✓ Analyze the performance of a Unified Power Quality Conditioner (UPQC) to control AC load voltages and source currents.
[31]; [36]; [30];		✓ Reduce the complexity of the overall MG control since the MV_{DC} the ST controls the bus voltage. ✓ Improve MG performance during reverse power flow conditions, peak power demand, and voltage drop. ✓ Introduce multiple paths for controlled active power flow in the overall microgrid. ✓ Establish an MV_{DC} distribution bus with the integration of an ESS for power balancing.
[23]; [82];		✓ Improve MG performance in terms of power flow control and power quality improvement. ✓ They interconnect multiple AC and DC networks to set up power router actions in power flow control. ✓ Enable structures so that each node of the MG is powered from at least two sides, allowing advanced control of power flow through ST. ✓ Loop power control on the ring network to eliminate the effects of load imbalance and line congestion and keep voltages across the feeder within limits.

Despite this, the ST-based mesh network configuration requires optimization to achieve better performance in energy flow management and network services, usually implemented in a central controller. This aspect is also argued in [31] since the need for MV_{DC} interconnection is raised to improve the flexibility of the controlled power flow in the MG and different power flow conditions. The ST is thus conceived as an interconnection node that supplies decoupled active and reactive power control capability and coordinated operation capability that improves the reliability of power supply for LV_{AC} loads even during voltage dips and avoids introducing more DER resynchronization schemes during grid voltage dips. According to different authors, ST coupled with an MG would give way to forming a new type of MG called a Meshed Hybrid Microgrid based on Smart Transformers (ST-based MHM).

Significant advances in hierarchical management and control algorithms have been documented for the operation and control of an MHM. In [14] and [25], an EMS based on hierarchical architecture and distributed control was obtained to coordinate the ST-based MHM efficiently. These systems can improve network performance by optimizing power flow and grid resilience compared to the radial configuration during grid failures; this is due to a hierarchical architecture, where the local-level control uses a primary control implemented within the local converter control in the MHM. Voltage, current, and power are controlled variables.

The primary control system design aims to satisfy the required dynamic and steady-state performance of the power converters of each ST stage to follow the EMS set points with robust behavior against system disturbances. It should be said that, in an ST-based MHM, there is a controlled power transfer between networks during regular operation. Similarly, it allows the integration of fault management algorithms in the source of the main grid MV_{AC}, these results show an increase in reliability [36]; this is an effect of the integration of a LV_{DC} bus extending in parallel to the LV_{AC} DS, and the DGCs that are integrated into the LV_{DC} line. Similarly, the availability of the ST LV_{DC} bus opens an option to conduct the LV_{DC} DS. This allows a higher degree of freedom for the algorithms required to be proposed and, consequently, the control complexity of the DGC is reduced since they do not need to control the DC link voltages with a noticeable reduction of the LV_{AC} line loading and improvement of the LV_{AC} line voltage profile [25].

Finally, some work has been aimed at solving the optimal energy management problem in ST-based MHM. In [14] and [33], control strategies and management algorithms that generate an additional set point from the EMS level to optimize network performance are formulated, e.g., voltage control considering the impact of line impedance, critical bus voltage control, line loss minimization, and compensation. Similarly, an optimal online problem is formulated to determine the active and reactive power references of the DGC to minimize the power losses on the line. Minimizing the total power loss at each time point is chosen as the objective function and solved using a GA. The total loss in the system is the sum of the losses in the bus LV_{DC} and LV_{AC}. This total loss is calculated using the backward and forward-swept power flow method. This strategy allows achieving benefits associated with the combination of optimal grid source allocation and grid reconfiguration (ST with added LV_{DC} line) to minimize system power losses.

Power loss optimization is possible with the ST configuration due to the presence of the DC line. According to these results, there is room for structuring studies to address the OPF problem in ST-based MHM using multiple approaches to consolidate this new power distribution scheme with high grid penetration. Table 2 summarizes the main ST-based MHM schemes reported in the literature. This study identified common aspects, such as taking advantage of the ST degrees of freedom to couple DC and AC buses as multiple feeders in the MG. Likewise, they allow the creation of hybrid networks that facilitate the integration of the DERs in the MG under an optimal energy management approach. Furthermore, the MHM makes it possible to find feasible solutions that set the operating points of the different PEIs of the DERs connected to the MG.

III. ENERGY MANAGEMENT SYSTEM IN ST-BASED MHM

MGs must be managed by an EMS that eases the minimization of operating costs, emissions, and peak loads so that the technical constraints of MG can be satisfied at the same time [108]. In recent years, the EMSs of the MG have been studied from different perspectives and have recently attracted considerable attention from researchers. As a result, EMSs have been classified into four categories based on the type of standby system used: Non-Renewable Based EMS, ESS-Based EMS, DSM-Based EMS, and Hybrid Systems Based EMS [50].

Non-Renewable Based EMS is the classic MG strategy that does not have a high penetration of renewable DER, using mainly diesel-type energy sources. ESS-Based EMS seeks to maintain the balance between generation and demand by using the ESS to store energy during off-peak hours and discharge it during peak hours [109]. Demand-Side Management based EMS adjusts demand profiles to meet optimal system performance criteria and balance resource availability and the corresponding demand adjustment [110]. This system is characterized by reduced demand consumption, increased efficiency, and dynamic end-user tariffs or incentive payments to reduce consumption during expensive hours or when system reliability is at risk. Finally, Hybrid Systems EMS combines the above categories whose management services, DER variation, and demand response make the EMS decision criteria more complex.

To solve this type of problem, it is suggested to determine uncertain parameters for prediction, model uncertainties, mathematically formulate objective functions and constraints, choose the optimization technique to solve the problem, and validate the performance of the EMS based on optimization algorithms [111]. These can have a deterministic or stochastic approach; however, the stochastic one presents higher complexity and computational cost, but the solutions are less conservative.

An EMS can operate in three modes: centralized, decentralized, and hierarchical [112]. In a centralized way, EMS is characterized by providing global optimization, reduction in overall operating cost, and uniformity for the whole network, so it is easy to implement [113]; however, it presents little flexibility and expandability, with a high computational cost due to the need for a dedicated high bandwidth communication channel. Decentralized EMS, on the other hand, presents a more efficient distributed computational load with flexibility compared to centralized; EMS; however, an exact optimization is not possible and requires the integration of synchronization algorithms that make the management rules complex [114]. Finally, in hierarchical EMS, the control loops grouped by levels improve the reliability and accuracy of the management system and are considered more suitable for ADS management; however, this architecture makes the

TABLE 3. Different OEMS in ST-Based MHM.

Ref.	Mode	Objective Function	Constraints	Solver
[37]	Off-Grid	$\min f = P_{loss}(t)$ $P_{los}(t) = \sum_{k=1}^{n_{acl}} \left(I_{ac}^{k}(t)\right)^2 R_{ac}^{k} + \sum_{w=1}^{n_{dcl}} \left(I_{dc}^{w}(t)\right)^2 R_{dc}^{w}$	$P_{EES}(t) = P_{LV_{ac}}(t) + P_{LV_{dc}}(t)$ $V_{LV_{ac}}^{min}(t) \leq V_{LV_{ac}}^{x}(t) \leq V_{LV_{ac}}^{max}(t)$ $P_{PV_{x_{inv}}}^{*} \leq S_{PV_{x_{inv}}}^{rated}$ $SoC_{EV}^{min}(t) \leq SoC_{EV}^{x}(t) \leq SoC_{EV}^{max}(t)$ $SoC_{ESS}^{min}(t) \leq SoC_{ESS}^{x}(t) \leq SoC_{ESS}^{max}(t)$ $P_{EV_x}^{c}(t) \leq P_{EV_x}^{c,max}(t);\ P_{EV_x}^{d}(t) \leq P_{EV_x}^{d,max}(t)$ $P_{ESS_x}^{c}(t) \leq P_{ESS_x}^{c,max}(t);\ P_{ESS_x}^{d}(t) \leq P_{ESS_x}^{d,max}(t)$	Genetic Algorithm
[45]	On-Grid	$\min f = E_{grid}(t) + dp$		
[33][38]	On-Grid	$E_{grid}(t) = \left(\sum_{i=1}^{n_l} P_l^{i}(t) + P_{ac-loss}(t)\right) T_c - \left(\sum_{j=1}^{n_{dg}} P_{dg}^{j}(t) + P_{dc-loss}(t)\right) T_c$	$P_{grid}(t) = P_{lvac}(t) + P_{lvdc}$ $V_{min} \leq V_l^{i}(t) \leq V_{max}$ $\sqrt{\left(P_{dgc-ref}^{j}(t)\right)^2 + \left(Q_{dgc-ref}^{j}(t)\right)^2} \leq S_{dgc-rated}^{j}$ $pf_{dgc-min} \leq pf_{dgc}^{j}(t) \leq 1$	

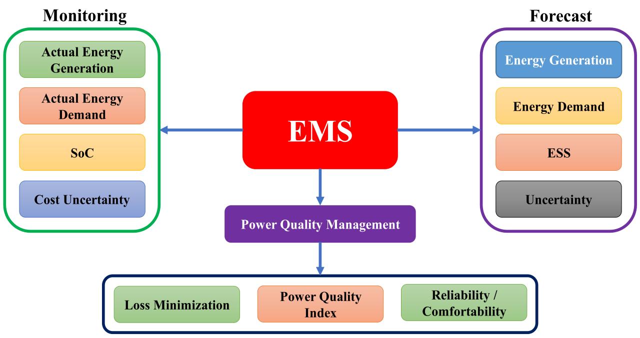


FIGURE 7. Overview of the EMS.

EMS implementation more complex, leading to a high cost and computational level [115].

An overview of the key elements of an EMS is shown in Fig. 7, in which topics related to optimization algorithms, power flow analysis, bidirectional communication schemes, and computational tools are framed. The EMS performs monitoring tasks for real-time operation and forecasting tasks for daily planning of the MG based on the projection of available DER, dispatchable resources, and demand projection. Additionally, it adopts power quality control mechanisms to increase system reliability and dependability. These elements, when integrated, allow setting optimal set points for the control loops at the different control levels of the AC, DC, or HMG [39]. The EMS are multi-objective systems, focusing on technical, economic, and social-environmental objectives. The economic objectives include investment, operation, and reinforcement cost plans. On the other hand, the technical purposes seek the optimal management of DER penetration, MG losses, load balance, voltage and frequency stability, and power quality [39].

For the modeling of the EMS, it is necessary to introduce uncertainty models of the DER, which can be built from stochastic, Fuzzy Logic (FL), and robust optimization-based techniques. In the case of the stochastic approach, the Monte-Carlo scenario's generation and simulation are used. The mathematical formulation of the EMS can be formulated from objective functions based on operating costs, the number of emissions, and even technical requirements. Similarly, constraints should be included, which may be associated with distributed generation, power balance, technical criteria, and ESS [50]. Finally, one approach that has gained significant relevance in recent years is oriented toward techniques considering the stochasticity of DER and V2G [56]. Within this topic, algorithms considering the demand management problem have started to be formulated through demand and supply response mechanisms in MGs, taking the uncertainty of renewable energy generation. On the power generation other hand, the scheduling problem in an MG is considered, considering the uncertainties of DER in combination with electricity prices [41]. The resolution of these problems is framed within an optimization problem since it allows minimizing or maximizing a cost function according to the merit figures of the system and the associated constraints [116]. Stochastic optimization techniques are considered in conjunction with robust optimization techniques to solve problems related to demand management in MGs with a high penetration of DER. These techniques make it possible to find optimally scheduled demand and supply profiles that minimize the costs associated with fuel consumption over the entire time horizon. The variability of the DERs is formulated from a reference distribution function to limit uncertainty [117].

Under the scheduling problem of power generation in an MG with high penetration of DER, the stochasticity of the MGs must be considered, and optimization problems based on heuristic and robust techniques must be formulated. The scheduling problem of power generation in a microgrid scenario is solved to minimize the cost and keep the system's stability. In these, distribution uncertainty sets are defined to reduce the fluctuations range and uncertainty in the electricity price by limited random variables [118] according to statistical analysis concerning environmental conditions data, generation profiles, and load profiles in the MG [50].

Multiple approaches have been proposed for ST-based MHMs that seek to apply optimization problems to energy management based on performance indicators. Table 3 classifies the references that report EMS based on the objective function, constraints, and optimization problem-solving techniques.

In [37], an OEMS for off-grid mode operation, a low voltage ST-based MHM, is defined. The main objective is to minimize line losses in the system from the formation of DC line connections and ESS by taking advantage of LV_{DC} ST port's, under a stochastic approach and heuristic techniques, GA. The EMS adjusts the operating points of the PEIs of each DG, ESS, and ST stages. Each stage of the ST has a decoupled control loop that controls the injection or absorption of active and reactive power, thus controlling the state of charge of the ESS and voltage balance en LV_{DC} and LV_{AC}. This EMS ensures the system has the maximum uptime possible with available DG sources, ESS, and EV. A similar approach is reported in [45]. In this, an optimization problem is formulated for determining the active and reactive power references of DG converters in real-time for minimized power losses in the line in both AC and DC side MG. In the issues reported in [37] and [45], the total loss in the system is the sum of the losses on the AC and DC lines. The two approaches differ in the inclusion of an ESS in the LV_{DC} port of the ST. Thus, despite having the same objective function, the constraints of the problem are different depending on the type of ESS and the mode of operation, off-grid, and on-grid. In [45] the inequality constraints are defined according to voltage deviation, power factor variation and power balance. In [37] the inequality constraints are defined according to the SoC of the ESS and EV, the SoC and discharge of the ESS, and the rated power of the DG. In both cases, GA-based optimization techniques are used.

In [32] and [38], an OEMS is proposed to determine the active and reactive power references of DG converters. This system maintains the LV_{AC} load bus voltages within the limits of the grid and considering the constraints of the DG converters. The minimization of the energy withdrawn from the ST MV_{AC} port is regarded as an objective function and is solved using a GA. Despite having the same objective function and set of constraints, the ST structure in [38] has two stages; thus, a further objective for the EMS is to find the best location for the third stage. This approach is valid since the ST is a decoupled multi-stage converter.

The three stages of ST allow decoupled control loops to be established for each of the stages, as shown in the following figure Fig. 3. Given this characteristic, some works are reported that propose rule-based EMS and distributed control for ST-based MHM, which allows taking better advantage of the functionalities and degrees of freedom of ST and MHM in connected, isolated or fault scenarios [36]. In [32], a rule-based EMS is proposed to establish the reconnection of the MHM to the MV_{AC} grid while keeping the ST converter running, thus initiating the power flow and establishing the transition from isolated to grid-connected mode of the MHM. A similar approach is presented in [29] and [30], in which MHM management mechanisms are proposed to operate the integrated ESS and ST in an MHM. Instead of connecting through AC interconnects with normally open circuit breakers, the same line is connected through the MV_{DC} ST DC links introduce several ways for the controlled flow of power in the system in an optimal way. In this way, a hierarchical structure for the management of the MHM can be identified based on the operating conditions of the ST. These works present a similar architecture concerning the control of the ST, which, despite having different objectives, gives the same management mechanism as the MHM. In Fig. 8, a schematic of the architecture used for the ST-based MHM EMS is presented. Functionalities are identified in terms of the mode of operation of each stage of the ST, hence of the MHM, and functionalities introduced in Fig.7.

The EMS consists of three levels and is presented in Fig. 8. At the top level, management is based on MG operating conditions/problems. Suppose conditions require reducing line losses, operating faults, feeder voltage deviation, or overloading. In that case, the EMS can choose the most appropriate network configuration to minimize the above effects and improve performance based on KPIs. Depending on the selected configuration, the priority of the control target under optimum conditions is set by setting the setpoint at the medium level, MV_{AC} and MV_{DC}, and the ST voltage control strategy at the low level, LV_{AC} and LV_{DC}.MHMs are a set of new MG topologies in which the benefits of ST are appropriately exploited. As Table 2 below presents, the reported references focus mainly on centralized primary and secondary control systems in the ST stages. According to Table 3, few works have been developed on OEMS in ST-based MHMs. The analyzed results show good indicators and adequate OEMS performance. However, genetic algorithms have been used to solve the optimization problem to minimize system line losses or maximize DG power injection under maximum operating point conditions.

In the issues reported, the variability of the resource and the uncertainty associated with the generation profiles and behavior of the ESS, which finally condition the formulation of the constraints related to the optimization problem, are not considered. This formulation requires different solution alternatives to GA, such as robust optimization or stochastic programming [41].

IV. FINDINGS AND CONTRIBUTION

Decarbonizing the electricity generation, transmission, and DS is one of the main challenges proposed based on the results of the report of Goal 7 of the UN. In this sense, as a mitigation measure, efforts have been made to promote the

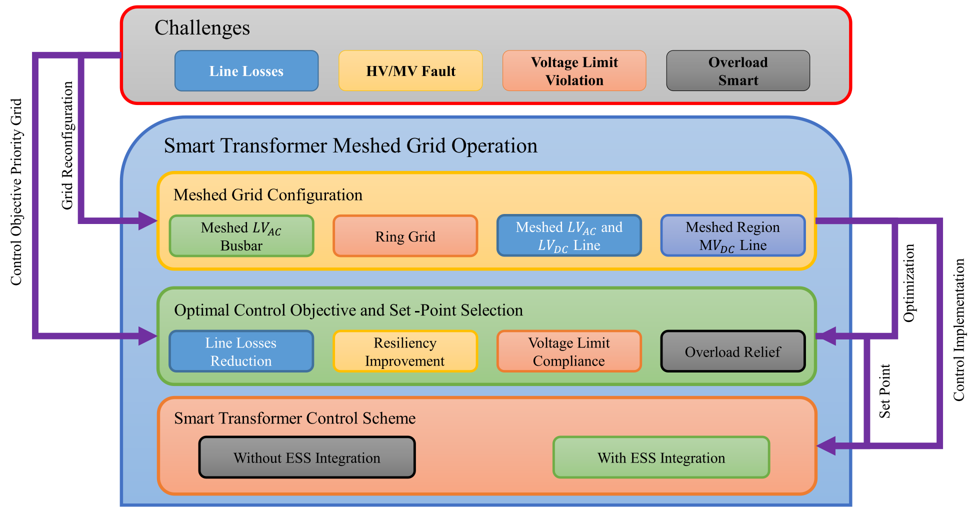


FIGURE 8. **An overview of ST management under a MHM operation [23], [119].**

integration of renewable energy sources into DS, such as DG and ESS, as elements of diversification and flexibility of the energy matrix. However, this new scenario generates collateral effects regarding power quality and energy efficiency due to the resource's variability, the grid's low inertia, and the bidirectional power flow. In response to these effects, we seek to propose OEMS schemes based on robust optimization algorithms that consider the dynamics and uncertainties of DG, ESS, V2G, and the management of linear and nonlinear loads in MHM. This OEMS is according to the KPIs that account for power quality in DS, in an approach in which DS with high grid penetration is visualized as an Active Distribution System (ADS). The main objective is geared toward the optimal operation of the DER regarding economic benefits and safe operation that guarantees an uninterrupted and reliable power supply [40].

Fig. 8 shows the conceptual model of a technological hardware platform with an ST-based MHM controlled by OEMS, which can work in isolated mode or interconnected mode through the Common Coupling Point (CCP) in MV_{AC} of the ST. The OEMS inputs are defined based on the variables measured at the operating point of the different elements of the MG, both in AC and DC (weather forecast data, demand projection, and economic criteria for system operation). In addition, parameters that set the references for the MG's primary and secondary control levels have been specified for the outputs. For the latter, active and reactive power criteria are set, and for the primary control, operating points of voltage, current, and frequency levels are developed for each PEI control loop.

Under a scenario of uncertainty in MG by the variability of DER, an approach based on robust optimization for the OEMS is proposed to find a feasible operating point according to the operational constraints of the MG. That finally responds to the economic dispatch problems of the ADS [41]. This scheme is proposed based on a hybrid-meshed structure, which adds more degrees of freedom for MG operation. Still, it increases the degree of complexity regarding the requirements to find the solution in an expected time horizon for the proper operation of the MHM.

The mesh structure of the MG is formed from a DC bus that starts at the LV_{DC} of the ST and ends at the output of the $DC-DC$ converter of the DER connected at the end of the MG. In addition, a hybrid ring bus interconnects an AC bus segment with a DC bus segment through bidirectional $AC-DC$ converters, which eases power exchange between the two buses and the DERs connected to the DC bus. This hybrid structure allows the PEIs to obtain power from the MV_{AC} network through the LV_{DC} bus in case they do not have enough power from the DERs. Similarly, the PEIs do not control their DC link voltage, as the ST takes care of this. The DERs inject power to the DC links through the $DC-DC$ and $AC-DC$ converters, respectively. These converters help the DERs to operate at maximum power point most of the time [55]; likewise, the $DC-AC$ converters are responsible for supplying power to the LV_{AC} line. This bidirectional power-flow control mechanism is the main strength of MHMs, which could be exploited and improved with a radial structure such as the DS's.

As for the PEIs, each one is connected to a Local Control Loop (LC_{PEI}) and communication interface so that its elements act at the primary control level of the MG. That is defined based on the input information, composed of operational parameters of the MG, environmental conditions, demand forecast, and market information, being the input for the demand projection and estimation of the generation profiles of the DERs connected to the MHM. Subsequently, a probabilistic model of the DERs and a stationary model of the PEIs are proposed to construct an objective function that minimizes the power flow in the MG, considering the associated restrictions. Therefore, robust optimization or stochastic programming algorithms can be proposed, as detailed in [41]

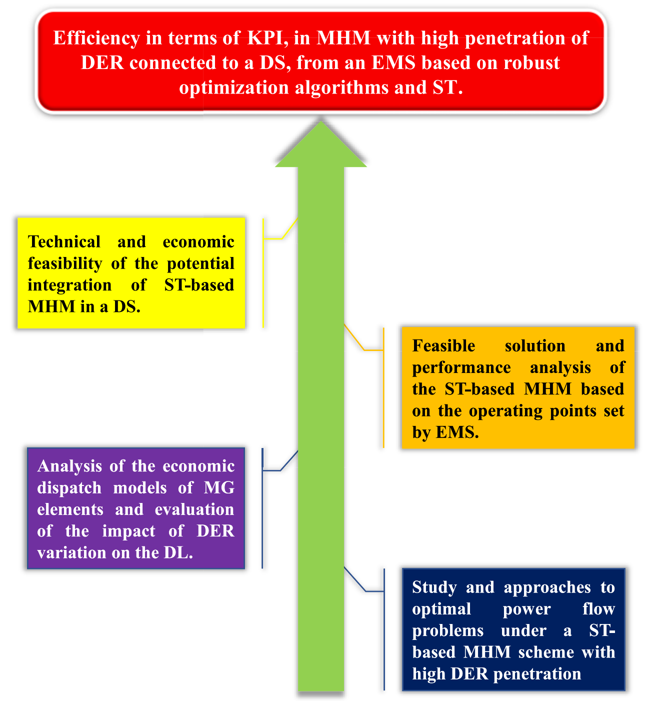


FIGURE 9. Development of optimal EMS algorithms.

and [120], to obtain a set of feasible solutions that set the operating point of the secondary and primary control levels of the MHM, employing the AC bus Active and Reactive Power Setpoint (P_{AC}, Q_{AC}), as well as the Voltage, Current AC, and Frequency (V_{AC}, I_{AC}, F_{AC}). For the DC bus, the Active Power (P_{DC}), Voltage, and Current DC (V_{DC}, I_{DC}) are set. Similarly, the feasible operating points are set for the operational conditions of the ST that functions as an ER between the DC and AC bus of the MHM.

The energy management algorithm is proposed as a centralized tertiary controller for the MG. Its input parameters are a function of the variables measured at the operating point of the different MG elements, AC, and DC (weather forecast data, demand projection, and economic criteria for system operation) [41]. The output is defined from parameters that seek to set the references of the MG's primary and secondary control levels [121]. Active and reactive power criteria are set for the latter, translated into voltage-frequency references for the primary control loops. According to this structure, it should be noted that a 24 H horizon is defined for the OEMS with control windows of the order of minutes for the secondary control and in the order of milliseconds for the primary controller [106]. However, the OPF problem of reducing voltage-frequency deviation focuses on a steady-state analysis of the microgrid under uncertain conditions in DER and the different ST stages.

For OEMS, optimization techniques are defined that consider the uncertainty of the REDs in the solution of the power flow optimization problem, whose objective is to minimize a cost function by the KPIs in the microgrid. According to the taxonomy of optimization proposed in [41], in optimization problems involving uncertainty in decision variables, one can opt for stochastic programming or robust optimization techniques. Stochastic Programming (SP) defines the optimization problem based on probability distribution functions, and under a discrete approach with N samples, a Monte Carlo approach could be considered. [122]. On the other hand, Robust Optimization (RO) defines an uncertainty set U, to which the variables with uncertainty must belong so that any feasible solution such that $u \in U$, even the Worst-Case, guarantees that all constraints are respected.

According to weather station data, the probability distribution functions of irradiance and temperature variation for PVG in some areas do not fully describe the random variable. Therefore, applying the SP optimization techniques proposed in [90] is not recommended. On the other hand, the set of feasible solutions presented by RO techniques tends to be more conservative than stochastic optimization. However, this depends on the choice of the worst-case scenario to be included in U, whose adjustment can reduce the risk level according to the quantification of the feasible solution [123], which finally establishes the operating point of the microgrid. Therefore, applying RO techniques for developing the energy management algorithm is proposed based on these two criteria. Under this type of optimization, it is possible to formulate a multi-stage $min - max$ formulation that minimizes the combination of a first-stage objective function and the second-stage worst-case scenario, defined as the maximum cost over the uncertainty set U [124], [125].

Allowing the structure shown in Fig. 8, an alternative way to develop algorithms for OEMS in MHM is demonstrated in Fig. 9. Under this approach, the starting point is a stationary model analysis of the PEIs of each DER. The variability of PVG and wind turbine generators are characterized by probabilistic models proposed in [51] and [126]. As for ESS, they are modeled based on the SoC as proposed in [127] and [126] and V2Gs as proposed in [56], [128], and [129]. These probabilistic models determine the constraints when presenting the RO problem, whose solution must be feasible in the uncertainty space defined by each DER of the MHM [52], [53]. By determining the set of feasible solutions through solving the optimization problem, the performance of the target MHM can be evaluated under an emulation scheme with specialized hardware as proposed in [29], [30], [46], and [55].

Finally, according to the results achieved at the pre-feasibility level, we seek to establish the technical and economic feasibility of the potential integration of an ST-based MHM with high penetration of DG, V2G, and ESS in a DS operated by an OEMS.

One feasible way to assess the impact of DER penetration in the DS to address the optimization algorithms proposed in Fig. 9 is to mesh a section of the DS. This meshed structure ensures optimal operation, starting from selecting and analyzing information recorded by the network operator in the

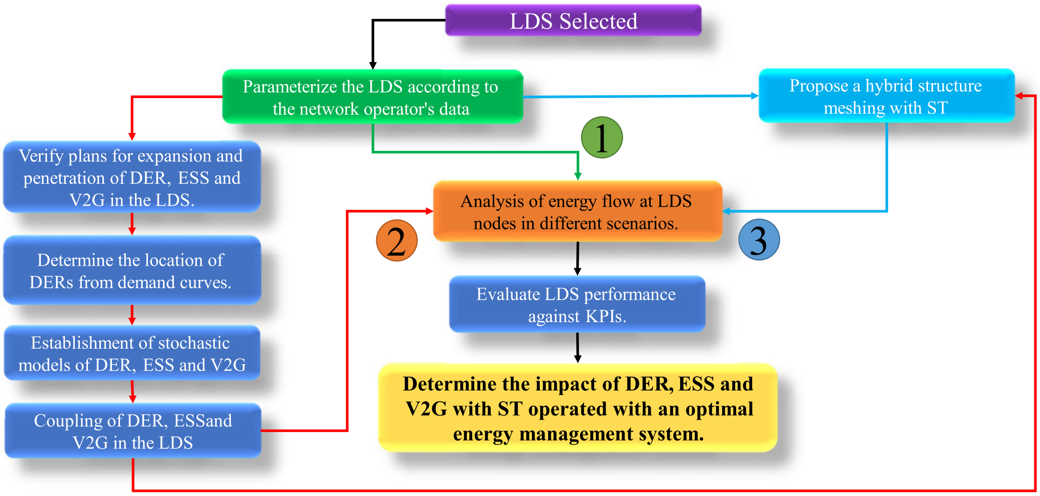


FIGURE 10. The flow chart to evaluate the performance of a section of the DS with high penetration of DER.

area with the highest potential for DER resource availability and highest demand in terms of controlled load, uncontrolled load, V2G systems, and the need to incorporate ESS. Next, stochastic models or spaces of the uncertainty of the energy potential of the DERs are proposed for their connection with the different nodes in the DS area of interest. By incorporating these models with the network parameters, the power flow is analyzed under various scenarios, including DS, without integrating DER and models with high penetration of DER to get a baseline with the worst-case scenario results. Additionally, the interconnection of the DS section with high penetration of DER is improved by using an ST to analyze the three approaches to contrast the network's performance from indicators that reveal the system's power quality.

This method is shown in Fig. 10, where a flow chart is proposed to evaluate the performance of a section of the DS with high penetration of DER and a technological alternative that meets economic, environmental, political, and social needs.

According to the literature findings, the alternative technology platform and the workflows illustrated in Fig. 8 and Fig. 9 are highly feasible for materialization under real DS-integrated MG operating conditions. The SST has presented reliable results in flexibility and bidirectional power control in radial MGs by acting as an ST. The results presented in the literature, the technological alternative proposed in Fig. 8, and the methodologies proposed in Fig. 9 and Fig. 10 show that the SST could provide ER services in MHM with high penetration of DER, V2G, and ESS. OEMS drives this to improve efficiency in terms of KPI. Under this approach, ST projects as a key element in the MGs of future distribution networks or ADSs as it significantly enhances network operation's flexibility.

Similarly, it enables interconnection between AC and DC distribution grids, making MHM's operation possible. The power flows can be controlled, and more efficient direct integration of distributed DC resources, such as PVG and EV charging stations [82]. In this way, technological development strategies could be proposed to improve the KPIs of an MHM with high penetration of DG, V2G, and ESS connected to a DS when using ST commanded from an OEMS based on robust optimization algorithms.

Finally, the ST is presented as a three-stage electronic converter with multiple degrees of freedom that allow the forming MHM and is considered a suitable structure to materialize the EI as a new electric sector paradigm by integrating the ST as an ER. These concepts have gradually gained interest in the scientific community for algorithm development and performance analysis of new MG topologies such as MHM, specifically in controlled environments using simulation and emulation schemes with promising results. Therefore, since 2017, technical and economic feasibility studies of ST-commanded MGs have been conducted in a pilot project in a DS in the UK [130]. This project would become a milestone for the electrical sector with multiple fields of application and general interest regarding incorporating a SST in DS to form MGs with a higher degree of controllability, efficiency, and reliability.

V. CONCLUSION

This review summarizes the most important contributions reported in the literature concerning ST-based MHM, which allows for determining the conformation of this type of MG, the new topologies and EMS used, and identifying the gap on these topics. The revision also introduces an alternative technology platform based on ST-based MHM, operated by OEMS. Similarly, it allows the introduction of a workflow to evaluate the performance of a section of the DS with high DER penetration. Finally, the possibility of meshing the MG through the multi-port structure of the ST is studied according to deterministic scenarios.

Although ST-based MHM topologies are relatively new, significant contributions to managing these MGs have been identified under different operating scenarios. The main benefit of this type of MG is the flexibility of DER penetration in the DSs under a meshed topology. This provides greater possibilities for increased EMS performance and optimal MG operation. Nevertheless, further research and innovation are needed to develop OEMS under uncertain conditions since ST-based MHMs are highly conditioned by the random behavior of DERs and the demand profile, leading to uncertain operation scenarios. Therefore, RO techniques are suitable to meet the new challenges in EMS for MHM.

REFERENCES

[1] M. A. Judge, A. Khan, A. Manzoor, and H. A. Khattak, "Overview of smart grid implementation: Frameworks, impact, performance and challenges," *J. Energy Storage*, vol. 49, May 2022, Art. no. 104056, doi: 10.1016/j.est.2022.104056.

[2] F. R. Badal, S. K. Sarker, Z. Nayem, S. I. Moyeen, and S. K. Das, "Microgrid to smart grid's evolution: Technical challenges, current solutions, and future scopes," *Energy Sci. Eng.*, vol. 11, no. 2, pp. 874–928, Oct. 2022, doi: 10.1002/ese3.1319.

[3] J. Viola and C. Aceros, "Smart grids and their applicability for the development of the electricity sector for Colombia in the year 2050," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 138, Jul. 2016, Art. no. 012010, doi: 10.1088/1757-899x/138/1/012010.

[4] G. Chicco, "Introduction—Advances and challenges in active distribution systems," in *Planning and Operation of Active Distribution Networks*, vol. 826. Cham, Switzerland: Springer, 2022, pp. 1–42.

[5] P. Fortenbacher, M. Zellner, and G. Andersson, "Optimal sizing and placement of distributed storage in low voltage networks," in *Proc. Power Syst. Comput. Conf. (PSCC)*, Jun. 2016, pp. 1–7, doi: 10.1109/PSCC.2016.7540850.

[6] UPME. (2015). *Plan de Expansión de Referencia Generación Transmisión 2015–2029*. Unidad de Planeación Minero Energética, Bogotá. [Online]. Available: http://www1.upme.gov.co/Energia_electrica/Planes-expansion/Plan-Expansion-2015-2029/Plan_GT_2015-2029_VF_22-12-2015.pdf

[7] K. Gholami, A. Azizivahed, A. Arefi, and L. Li, "Risk-averse volt-VAr management scheme to coordinate distributed energy resources with demand response program," *Int. J. Electr. Power Energy Syst.*, vol. 146, Mar. 2023, Art. no. 108761, doi: 10.1016/j.ijepes.2022.108761.

[8] M. Auguadra, D. Ribó-Pérez, and T. Gómez-Navarro, "Planning the deployment of energy storage systems to integrate high shares of renewables: The Spain case study," *Energy*, vol. 264, Feb. 2023, Art. no. 126275, doi: 10.1016/j.energy.2022.126275.

[9] E. Demirok, P. C. González, K. H. B. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, "Local reactive power control methods for overvoltage prevention of distributed solar inverters in low-voltage grids," *IEEE J. Photovolt.*, vol. 1, no. 2, pp. 174–182, Oct. 2011, doi: 10.1109/JPHOTOV.2011.2174821.

[10] A. A. D. O. Filho, T. B. Rodríguez, A. C. Navarro, F. L. Consoni, E. Barassa, and E. Lacusta Jr., "Institutional framework and the advance of electromobility: The case of South America," *Int. J. Automot. Technol. Manage.*, vol. 22, no. 3, p. 277, 2022, doi: 10.1504/ijatm.2022.124830.

[11] J. Quirós-Tortós, L. Victor-Gallardo, and L. Ochoa, "Electric vehicles in Latin America: Slowly but surely toward a clean transport," *IEEE Electrific. Mag.*, vol. 7, no. 2, pp. 22–32, Jun. 2019, doi: 10.1109/MELE.2019.2908791.

[12] F. Alfaverh, M. Denaï, and Y. Sun, "Optimal vehicle-to-grid control for supplementary frequency regulation using deep reinforcement learning," *Electr. Power Syst. Res.*, vol. 214, Jan. 2023, Art. no. 108949, doi: 10.1016/j.epsr.2022.108949.

[13] H. S. Das, M. M. Rahman, S. Li, and C. W. Tan, "Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review," *Renew. Sustain. Energy Rev.*, vol. 120, Mar. 2020, Art. no. 109618, doi: 10.1016/j.rser.2019.109618.

[14] R. Zhu and M. Liserre, "Operation and supervision control in smart transformer-based meshed and hybrid grids," in *Proc. 6th IEEE Int. Energy Conf. (ENERGYCon)*, Sep. 2020, pp. 1019–1023, doi: 10.1109/ENERGYCon48941.2020.9236572.

[15] S. K. Sahoo, A. K. Sinha, and N. K. Kishore, "Control techniques in AC, DC, and hybrid AC–DC microgrid: A review," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 6, no. 2, pp. 738–759, Jun. 2018, doi: 10.1109/JESTPE.2017.2786588.

[16] E. Unamuno and J. A. Barrena, "Hybrid AC/DC microgrids—Part I: Review and classification of topologies," *Renew. Sustain. Energy Rev.*, vol. 52, pp. 1251–1259, Dec. 2015, doi: 10.1016/j.rser.2015.07.194.

[17] F. S. Al-Ismail, "DC microgrid planning, operation, and control: A comprehensive review," *IEEE Access*, vol. 9, pp. 36154–36172, 2021, doi: 10.1109/ACCESS.2021.3062840.

[18] E. Planas, J. Andreu, J. I. Gárate, I. M. de Alegría, and E. Ibarra, "AC and DC technology in microgrids: A review," *Renew. Sustain. Energy Rev.*, vol. 43, pp. 726–749, Mar. 2015, doi: 10.1016/j.rser.2014.11.067.

[19] L. Jia, Y. Zhu, and Y. Wang, "Architecture design for new AC–DC hybrid micro-grid," in *Proc. IEEE 1st Int. Conf. DC Microgrids (ICDCM)*, Jun. 2015, pp. 113–118, doi: 10.1109/ICDCM.2015.7152020.

[20] Y. Li, Q. Sun, T. Dong, and Z. Zhang, "Energy management strategy of AC/DC hybrid microgrid based on power electronic transformer," in *Proc. 13th IEEE Conf. Ind. Electron. Appl. (ICIEA)*, May 2018, pp. 2677–2682, doi: 10.1109/ICIEA.2018.8398163.

[21] A. Garcés-Ruíz, "Small-signal stability analysis of DC microgrids considering electric vehicles," *Revista Facultad de Ingeniería Universidad de Antioquia*, vol. 89, pp. 52–58, Jan. 2018, doi: 10.17533/udea.redin.n89a07.

[22] M. Nour, J. P. Chaves-Ávila, G. Magdy, and Á. Sánchez-Miralles, "Review of positive and negative impacts of electric vehicles charging on electric power systems," *Energies*, vol. 13, no. 18, p. 4675, Sep. 2020, doi: 10.3390/en13184675.

[23] R. Zhu, M. Liserre, M. Langwasser, and C. Kumar, "Operation and control of the smart transformer in meshed and hybrid grids: Choosing the appropriate smart transformer control and operation scheme," *IEEE Ind. Electron. Mag.*, vol. 15, no. 1, pp. 43–57, Mar. 2021, doi: 10.1109/mie.2020.3005357.

[24] C. Kumar, X. Gao, and M. Liserre, "Smart transformer based loop power controller in radial power distribution grid," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT-Eur.)*, Oct. 2018, pp. 1–6, doi: 10.1109/ISGTEurope.2018.8571844.

[25] D. Das, V. M. Hrishikesan, C. Kumar, and M. Liserre, "Smart transformer-enabled meshed hybrid distribution grid," *IEEE Trans. Ind. Electron.*, vol. 68, no. 1, pp. 282–292, Jan. 2021, doi: 10.1109/TIE.2020.2965489.

[26] R. Zhu, G. De Carne, M. Andresen, and M. Liserre, "Control of smart transformer in different electric grid configurations," in *Proc. 10th Int. Conf. Power Electron. ECCE Asia (ICPE-ECCE Asia)*, May 2019, pp. 1668–1675.

[27] H. Guo, F. Wang, J. Luo, and L. Zhang, "Review of energy routers applied for the energy internet integrating renewable energy," in *Proc. IEEE 8th Int. Power Electron. Motion Control Conf. (IPEMC-ECCE Asia)*, May 2016, pp. 1997–2003, doi: 10.1109/IPEMC.2016.7512602.

[28] A. Gupta, S. Doolla, and K. Chatterjee, "Hybrid AC–DC microgrid: Systematic evaluation of control strategies," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3830–3843, Jul. 2018, doi: 10.1109/TSG.2017.2727344.

[29] D. Das, H. V. M., and C. Kumar, "BESS-PV integrated islanded operation of ST-based meshed hybrid microgrid," in *Proc. IEEE 9th Int. Power Electron. Motion Control Conf. (IPEMC-ECCE Asia)*, Nov. 2020, pp. 2122–2128, doi: 10.1109/IPEMC-ECCEAsia48364.2020.9367663.

[30] V. M. Hrishikesan and C. Kumar, "Operation of meshed hybrid microgrid during adverse grid conditions with storage integrated smart transformer," *IEEE Open J. Ind. Electron. Soc.*, vol. 2, pp. 315–325, 2021, doi: 10.1109/OJIES.2021.3073142.

[31] V. M. Hrishikesan and C. Kumar, "Smart transformer based meshed hybrid microgrid with MVDC interconnection," in *Proc. IECON 46th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2020, pp. 4961–4966, doi: 10.1109/IECON43393.2020.9255284.

[32] D. Das and C. Kumar, "Partial startup scheme for smart transformer in meshed hybrid islanded grid operation," *IEEE Trans. Ind. Appl.*, vol. 58, no. 1, pp. 142–151, Jan. 2022, doi: 10.1109/TIA.2021.3124862.

[33] C. Kumar, R. Manojkumar, S. Ganguly, and M. Liserre, "Impact of optimal control of distributed generation converters in smart transformer based meshed hybrid distribution network," *IEEE Access*, vol. 9, pp. 140268–140280, 2021, doi: 10.1109/ACCESS.2021.3119349.

[34] A. Eisapour-Moarref, M. Kalantar, and M. Esmaili, "Power sharing in hybrid microgrids with multiple DC subgrids," *Int. J. Electr. Power Energy Syst.*, vol. 128, Jun. 2021, Art. no. 106716, doi: 10.1016/j.ijepes.2020.106716.

[35] B. Sahoo, S. K. Routray, and P. K. Rout, "AC,DC,and hybrid control strategies for smart microgrid application: A review," *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 1, pp. 1–53, Jan. 2021, doi: 10.1002/2050-7038.12683.

[36] M. V. Hrishikesan, C. Kumar, and M. Liserre, "An MVDC-based meshed hybrid microgrid enabled using smart transformers," *IEEE Trans. Ind. Electron.*, vol. 69, no. 4, pp. 3722–3731, Apr. 2022, doi: 10.1109/TIE.2021.3071683.

[37] D. Das, R. Manojkumar, C. Kumar, and S. Ganguly, "Optimal power management for islanded operation of ST-based meshed hybrid LV microgrid," in *Proc. IEEE 12th Energy Convers. Congr. Expo. Asia (ECCE-Asia)*, May 2021, pp. 183–188, doi: 10.1109/ECCE-Asia49820.2021.9479110.

[38] C. Kumar, R. Manojkumar, and S. Ganguly, "Optimal placement of smart transformer low voltage converter in meshed hybrid distribution network," in *Proc. IEEE 12th Energy Convers. Congr. Expo. Asia (ECCE-Asia)*, May 2021, pp. 1795–1800, doi: 10.1109/ECCE-Asia49820.2021.9479233.

[39] S. Hussain, C. Z. El-Bayeh, C. Lai, and U. Eicker, "Multi-level energy management systems toward a smarter grid: A review," *IEEE Access*, vol. 9, pp. 71994–72016, 2021, doi: 10.1109/ACCESS.2021.3078082.

[40] M. O. De Lara Filho, R. S. Pinto, A. C. De Campos, C. U. Vila, and F. H. Tabarro, "Day-ahead robust operation planning of microgrids under uncertainties considering DERs and demand response," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Latin Amer. (ISGT Latin America)*, Sep. 2021, pp. 1–5, doi: 10.1109/ISGTLatinAmerica52371.2021.9543063.

[41] S. K. Rangu, P. R. Lolla, K. R. Dhenuvakonda, and A. R. Singh, "Recent trends in power management strategies for optimal operation of distributed energy resources in microgrids: A comprehensive review," *Int. J. Energy Res.*, vol. 44, no. 13, pp. 9889–9911, Oct. 2020, doi: 10.1002/er.5649.

[42] F. Ruiz, M. A. Perez, J. R. Espinosa, T. Gajowik, S. Stynski, and M. Malinowski, "Surveying solid-state transformer structures and controls: Providing highly efficient and controllable power flow in distribution grids," *IEEE Ind. Electron. Mag.*, vol. 14, no. 1, pp. 56–70, Mar. 2020, doi: 10.1109/MIE.2019.2950436.

[43] Y. Wang, T. L. Nguyen, M. H. Syed, Y. Xu, E. Guillo-Sansano, V.-H. Nguyen, G. M. Burt, Q.-T. Tran, and R. Caire, "A distributed control scheme of microgrids in energy internet paradigm and its multisite implementation," *IEEE Trans. Ind. Informat.*, vol. 17, no. 2, pp. 1141–1153, Feb. 2021, doi: 10.1109/TII.2020.2976830.

[44] A. Joseph and P. Balachandra, "Energy Internet, the future electricity system: Overview, concept, model structure, and mechanism," *Energies*, vol. 13, no. 16, p. 4242, Aug. 2020, doi: 10.3390/en13164242.

[45] C. Kumar, R. Manojkumar, S. Ganguly, and M. Liserre, "Power loss minimization in smart transformer based meshed hybrid distribution network," in *Proc. IECON 46th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2020, pp. 1670–1675, doi: 10.1109/IECON43393.2020.9254324.

[46] C. Kumar, H. VM, D. Das, and S. Ghosh, "Control and sizing of two-stage smart transformer in meshed hybrid distribution grid," in *Proc. IEEE 9th Int. Power Electron. Motion Control Conf. (IPEMC-ECCE Asia)*, Nov. 2020, pp. 2129–2134, doi: 10.1109/IPEMC-ECCEAsia48364.2020.9368198.

[47] I. Roasto, O. Husev, M. Najafzadeh, T. Jalakas, and J. Rodriguez, "Voltage source operation of the energy-router based on model predictive control," *Energies*, vol. 12, no. 10, p. 1892, May 2019, doi: 10.3390/en12101892.

[48] A. Q. Huang, "Solid state transformers, the energy router and the energy internet," in *The Energy Internet*, W. Su and A. Q. Huang, Eds. Sawston, U.K.: Woodhead Publishing, 2019, pp. 21–44.

[49] M. Manbachi, *Energy Management Systems for Hybrid AC/DC Microgrids: Challenges and Opportunities. Challenges and Opportunities*. Amsterdam, The Netherlands: Elsevier, 2018.

[50] H. Shayeghi, E. Shahryari, M. Moradzadeh, and P. Siano, "A survey on microgrid energy management considering flexible energy sources," *Energies*, vol. 12, no. 11, p. 2156, Jun. 2019, doi: 10.3390/en12112156.

[51] Y. Li, Z. Yang, G. Li, D. Zhao, and W. Tian, "Optimal scheduling of an isolated microgrid with battery storage considering load and renewable generation uncertainties," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 1565–1575, Feb. 2019, doi: 10.1109/TIE.2018.2840498.

[52] J. S. Giraldo, J. A. Castrillon, J. C. López, M. J. Rider, and C. A. Castro, "Microgrids energy management using robust convex programming," *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 4520–4530, Jul. 2019, doi: 10.1109/TSG.2018.2863049.

[53] M. Pourbehzadi, T. Niknam, J. Aghaei, G. Mokryani, M. Shafie-khah, and J. P. S. Catalão, "Optimal operation of hybrid AC/DC microgrids under uncertainty of renewable energy resources: A comprehensive review," *Int. J. Electr. Power Energy Syst.*, vol. 109, pp. 139–159, Jul. 2019, doi: 10.1016/j.ijepes.2019.01.025.

[54] I. Syed, V. Khadkikar, and H. H. Zeineldin, "Loss reduction in radial distribution networks using a solid-state transformer," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 5474–5482, Sep. 2018, doi: 10.1109/TIA.2018.2840533.

[55] G. De Carne, G. Buticchi, Z. Zou, and M. Liserre, "Reverse power flow control in a ST-fed distribution grid," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3811–3819, Jul. 2018, doi: 10.1109/TSG.2017.2651147.

[56] Y. Li, Z. Yang, G. Li, Y. Mu, D. Zhao, C. Chen, and B. Shen, "Optimal scheduling of isolated microgrid with an electric vehicle battery swapping station in multi-stakeholder scenarios: A bi-level programming approach via real-time pricing," *Appl. Energy*, vol. 232, pp. 54–68, Dec. 2018, doi: 10.1016/j.apenergy.2018.09.211.

[57] O. Smith, O. Cattell, E. Farcot, R. D. O'Dea, and K. I. Hopcraft, "The effect of renewable energy incorporation on power grid stability and resilience," *Sci. Adv.*, vol. 8, no. 9, Mar. 2022, Art. no. eabj6734, doi: 10.1126/sciadv.abj6734.

[58] H. Nosair and F. Bouffard, "Economic dispatch under uncertainty: The probabilistic envelopes approach," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2017, p. 1, doi: 10.1109/PESGM.2017.8273988.

[59] J. A. P. Lopes, C. L. Moreira, and A. G. Madureira, "Defining control strategies for MicroGrids islanded operation," *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 916–924, May 2006, doi: 10.1109/tpwrs.2006.873018.

[60] J. M. Guerrero, J. C. Vasquez, and R. Teodorescu, "Hierarchical control of droop-controlled DC and AC microgrids—A general approach towards standardization," in *Proc. 35th Annu. Conf. IEEE Ind. Electron.*, Nov. 2009, pp. 4305–4310, doi: 10.1109/IECON.2009.5414926.

[61] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Cañizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. A. Jiménez-Estévez, and N. D. Hatziargyriou, "Trends in microgrid control," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, Jul. 2014, doi: 10.1109/TSG.2013.2295514.

[62] A. Basati, M. B. Menhaj, and A. Fakharian, "GA-based optimal droop control approach to improve voltage regulation and equal power sharing for islanded DC microgrids," in *Proc. Electr. Power Quality Supply Rel. (PQ)*, Aug. 2016, pp. 145–150, doi: 10.1109/PQ.2016.7724104.

[63] M. Ahmed, L. Meegahapola, A. Vahidnia, and M. Datta, "Stability and control aspects of microgrid Architectures—A comprehensive review," *IEEE Access*, vol. 8, pp. 144730–144766, 2020, doi: 10.1109/ACCESS.2020.3014977.

[64] B. Sahoo, S. K. Routray, and P. K. Rout, "A novel centralized energy management approach for power quality improvement," *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 10, Aug. 2020, Art. no. e12582, doi: 10.1002/2050-7038.12582.

[65] W. McMurray, "Power converter circuits having a high frequency link," U.S. Patent 3 517 300 A, Jun. 23, 1970.

[66] J. L. Brooks. (1980). *Solid State Transformer Concept Development, California E.E.U.U.* [Online]. Available: https://apps.dtic.mil/sti/citations/ADA089299

[67] J. C. Bowers, S. J. Garrett, H. A. Nienhaus, and J. L. Brooks, "A solid state transformer," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 1980, pp. 253–264, doi: 10.1109/PESC.1980.7089456.

[68] S. D. Sudhoff, "Solid state transformer," U.S. Patent 5 943 229 A, Aug. 24, 1999.

[69] M. Kang, P. N. Enjeti, and I. J. Pitel, "Analysis and design of electronic transformers for electric power distribution system," *IEEE Trans. Power Electron.*, vol. 14, no. 6, pp. 1133–1141, Nov. 1999, doi: 10.1109/63.803407.

[70] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, and S. J. Dale, "The future renewable electric energy delivery and management (FREEDM) system: The energy internet," *Proc. IEEE*, vol. 99, no. 1, pp. 133–148, Jan. 2011, doi: 10.1109/JPROC.2010.2081330.

[71] J. E. Huber and J. W. Kolar, "Solid-state transformers: On the origins and evolution of key concepts," *IEEE Ind. Electron. Mag.*, vol. 10, no. 3, pp. 19–28, Sep. 2016, doi: 10.1109/MIE.2016.2588878.

[72] L. Ferreira Costa, G. De Carne, G. Buticchi, and M. Liserre, "The smart transformer: A solid-state transformer tailored to provide ancillary services to the distribution grid," *IEEE Power Electron. Mag.*, vol. 4, no. 2, pp. 56–67, Jun. 2017, doi: 10.1109/MPEL.2017.2692381.
[73] H. Shadfar, M. G. Pashakolaei, and A. A. Foroud, "Solid-state transformers: An overview of the concept, topology, and its applications in the smart grid," *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 9, pp. 1–24, Sep. 2021, doi: 10.1002/2050-7038.12996.
[74] R. P. Londero, A. P. C. d. Mello, and G. S. da Silva, "Comparison between conventional and solid state transformers in smart distribution grids," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Latin Amer. (ISGT Latin Amer.)*, Sep. 2019, pp. 1–6, doi: 10.1109/ISGT-LA.2019.8895327.
[75] F. Baronti, S. Vazquez, and M.-Y. Chow, "Modeling, control, and integration of energy storage systems in E-Transportation and smart grid," *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6548–6551, Apr. 2018, doi: 10.1109/TIE.2018.2810658.
[76] J. P. Contreras, J. M. Ramirez, J. V. Marin, and G. R. E. Correa, "Distribution systems equipped with power electronic transformers," in *Proc. IEEE Grenoble Conf.*, Jun. 2013, pp. 1–6, doi: 10.1109/PTC.2013.6652154.
[77] F. Z. Peng, J.-S. Lai, J. McKeever, and J. VanCoevering, "A multilevel voltage-source inverter with separate DC sources for static VAr generation," in *Proc. Conf. Rec. IEEE Ind. Appl. Conf. 13th IAS Annu. Meeting*, vol. 3, Oct. 1995, pp. 2541–2548, doi: 10.1109/IAS.1995.530626.
[78] J. E. Huber and J. W. Kolar, "Applicability of solid-state transformers in today's and future distribution grids," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 317–326, Jan. 2019, doi: 10.1109/TSG.2017.2738610.
[79] A. Abu-Siada, J. Budiri, and A. Abdou, "Solid state transformers topologies, controllers, and applications: State-of-the-Art literature review," *Electronics*, vol. 7, no. 11, p. 298, Nov. 2018, doi: 10.3390/electronics7110298.
[80] R. B. Jeyapradha and V. Rajini, "Investigations on service extensions of solid state transformer," in *Proc. 5th Int. Conf. Elect. Energy Syst. (ICEES)*, May 2019, pp. 1–6, doi: 10.1109/ICEES.2019.8719315.
[81] V. N. Jakka, S. Acharya, A. Anurag, Y. Prabowo, A. Kumar, S. Parashar, and S. Bhattacharya, "Protection design considerations of a 10 kV SiC MOSFET enabled mobile utilities support equipment based solid state transformer (MUSE-SST)," in *Proc. IECON 44th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2018, pp. 5559–5565, doi: 10.1109/IECON.2018.8592886.
[82] R. Zhu, M. Andresen, M. Langwasser, M. Liserre, J. P. Lopes, C. Moreira, J. Rodrigues, and M. Couto, "Smart transformer/large flexible transformer," *CES Trans. Electr. Mach. Syst.*, vol. 4, no. 4, pp. 264–274, Dec. 2020, doi: 10.30941/CESTEMS.2020.00033.
[83] R. Zhu, G. Buticchi, and M. Liserre, "Investigation on common-mode voltage suppression in smart transformer-fed distributed hybrid grids," *IEEE Trans. Power Electron.*, vol. 33, no. 10, pp. 8438–8448, Oct. 2018, doi: 10.1109/TPEL.2017.2779803.
[84] L. Meng, E. R. Sanseverino, A. Luna, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Microgrid supervisory controllers and energy management systems: A literature review," *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1263–1273, Jul. 2016, doi: 10.1016/j.rser.2016.03.003.
[85] A. Q. Huang, "Solid state transformers, the energy router and the energy internet," in *The Energy Internet*. Amsterdam, The Netherlands: Elsevier, 2019, pp. 21–44.
[86] H. M. Hussain, A. Narayanan, P. H. J. Nardelli, and Y. Yang, "What is energy internet? Concepts, technologies, and future directions," *IEEE Access*, vol. 8, pp. 183127–183145, 2020, doi: 10.1109/ACCESS.2020.3029251.
[87] K. Zhou, S. Yang, and Z. Shao, "Energy internet: The business perspective," *Appl. Energy*, vol. 178, pp. 212–222, Sep. 2016, doi: 10.1016/j.apenergy.2016.06.052.
[88] K. Wang, J. Yu, Y. Yu, Y. Qian, D. Zeng, S. Guo, Y. Xiang, and J. Wu, "A survey on energy internet: Architecture, approach, and emerging technologies," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2403–2416, Sep. 2018, doi: 10.1109/JSYST.2016.2639820.
[89] B. N. Alhasnawi, B. H. Jasim, Z.-A.-S. A. Rahman, J. M. Guerrero, and M. D. Esteban, "A novel internet of energy based optimal multi-agent control scheme for microgrid including renewable energy resources," *Int. J. Environ. Res. Public Health*, vol. 18, no. 15, p. 8146, Jul. 2021, doi: 10.3390/ijerph18158146.
[90] B. N. Alhasnawi, B. H. Jasim, B. E. Sedhom, E. Hossain, and J. M. Guerrero, "A new decentralized control strategy of microgrids in the internet of energy paradigm," *Energies*, vol. 14, no. 8, p. 2183, Apr. 2021, doi: 10.3390/en14082183.
[91] B. N. Alhasnawi, B. H. Jasim, Z.-A.-S. A. Rahman, and P. Siano, "A novel robust smart energy management and demand reduction for smart homes based on internet of energy," *Sensors*, vol. 21, no. 14, p. 4756, Jul. 2021, doi: 10.3390/s21144756.
[92] B. N. Alhasnawi, B. H. Jasim, P. Siano, H. H. Alhelou, and A. Al-Hinai, "A novel solution for day-ahead scheduling problems using the IoT-based bald eagle search optimization algorithm," *Inventions*, vol. 7, no. 3, p. 48, Jun. 2022, doi: 10.3390/inventions7030048.
[93] B. N. Alhasnawi and B. H. J. Jasim, "A novel hierarchical energy management system based on optimization for multi-microgrid," *Int. J. Electr. Eng. Informat.*, vol. 12, no. 3, pp. 586–606, Sep. 2020, doi: 10.15676/ijeei.2020.12.3.10.
[94] Z. Yixin, Z. Zhiwei, Z. Chenxi, and W. Haoyu, "Power flow optimization method research for the AC/DC distribution network with energy routers," in *Proc. Annu. Conf. China Electrotechnical Soc.*, Singapore: Springer, 2023, pp. 396–405.
[95] S. Chen, T. Zhang, H. B. Gooi, R. D. Masiello, and W. Katzenstein, "Penetration rate and effectiveness studies of aggregated BESS for frequency regulation," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 167–177, Jan. 2016, doi: 10.1109/TSG.2015.2426017.
[96] C.-W. Yang, J. Yan, and V. Vyatkin, "Towards implementation of plug-and-play and distributed HMI for the FREEDM system with IEC 61499," in *Proc. IECON 39th Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2013, pp. 5347–5353, doi: 10.1109/IECON.2013.6700005.
[97] E. M. Najm, Y. Xu, and A. Q. Huang, "Low cost plug-and-play PV system for DC microgrid," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2015, pp. 4236–4242, doi: 10.1109/ECCE.2015.7310258.
[98] F. Meng, R. Akella, M. L. Crow, and B. McMillin, "Distributed grid intelligence for future microgrid with renewable sources and storage," in *Proc. North Amer. Power Symp.*, Sep. 2010, pp. 1–6, doi: 10.1109/NAPS.2010.5618963.
[99] F. Cao, Y. Zhang, C. Liu, and R. Qian, "Location model and algorithm of solid state transformer considering distribution network reconfiguration," in *Proc. 2nd IEEE Conf. Energy Internet Energy Syst. Integr. (EI)*, Oct. 2018, pp. 1–6, doi: 10.1109/EI2.2018.8582429.
[100] Y. Xu, J. Zhang, W. Wang, A. Juneja, and S. Bhattacharya, "Energy router: Architectures and functionalities toward energy internet," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Oct. 2011, pp. 31–36, doi: 10.1109/SmartGridComm.2011.6102340.
[101] T.-H. Chang, M. Alizadeh, and A. Scaglione, "Real-time power balancing via decentralized coordinated home energy scheduling," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1490–1504, Sep. 2013, doi: 10.1109/TSG.2013.2250532.
[102] J. M. Guerrero, P. C. Loh, T.-L. Lee, and M. Chandorkar, "Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1263–1270, Apr. 2013, doi: 10.1109/TIE.2012.2196889.
[103] A. Hirsch, Y. Parag, and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," *Renew. Sustain. Energy Rev.*, vol. 90, pp. 402–411, Jul. 2018, doi: 10.1016/j.rser.2018.03.040.
[104] R. Zamora and A. K. Srivastava, "Controls for microgrids with storage: Review, challenges, and research needs," *Renew. Sustain. Energy Rev.*, vol. 14, no. 7, pp. 2009–2018, Sep. 2010, doi: 10.1016/j.rser.2010.03.019.
[105] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," *IEEE Power Energy Mag.*, vol. 6, no. 3, pp. 54–65, May 2008, doi: 10.1109/mpe.2008.918702.
[106] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1963–1976, Dec. 2012, doi: 10.1109/TSG.2012.2197425.
[107] Q. Shafiee, J. M. Guerrero, and J. C. Vasquez, "Distributed secondary control for islanded microgrids—A novel approach," *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 1018–1031, Feb. 2014, doi: 10.1109/TPEL.2013.2259506.
[108] S. A. Helal, M. O. Hanna, R. J. Najee, M. F. Shaaban, A. H. Osman, and M. S. Hassan, "Energy management system for smart hybrid AC/DC microgrids in remote communities," *Electr. Power Compon. Syst.*, vol. 47, nos. 11–12, pp. 1012–1024, Jul. 2019, doi: 10.1080/15325008.2019.1629512.
[109] M. M. Alam, M. H. Rahman, H. Nurcahyanto, and Y. M. Jang, "Energy management by scheduling ESS with active demand response in low voltage grid," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2020, pp. 683–686, doi: 10.1109/ICTC49870.2020.9289284.

[110] D. Ramin, S. Spinelli, and A. Brusaferri, "Demand-side management via optimal production scheduling in power-intensive industries: The case of metal casting process," *Appl. Energy*, vol. 225, pp. 622–636, Sep. 2018, doi: 10.1016/j.apenergy.2018.03.084.

[111] A. K. Erenoğlu, İ. Şengör, O. Erdinç, A. Taşcıkaraoğlu, and J. P. S. Catalão, "Optimal energy management system for microgrids considering energy storage, demand response and renewable power generation," *Int. J. Electr. Power Energy Syst.*, vol. 136, Mar. 2022, Art. no. 107714, doi: 10.1016/j.ijepes.2021.107714.

[112] S. K. Rathor and D. Saxena, "Energy management system for smart grid: An overview and key issues," *Int. J. Energy Res.*, vol. 44, no. 6, pp. 4067–4109, May 2020, doi: 10.1002/er.4883.

[113] D. E. Olivares, C. A. Cañizares, and M. Kazerani, "A centralized energy management system for isolated microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1864–1875, Jul. 2014, doi: 10.1109/TSG.2013.2294187.

[114] X. Zhou, Z. Ma, S. Zou, J. Zhang, and Y. Guo, "Distributed energy management of double-side multienergy systems via sub-gradient averaging consensus," *IEEE Trans. Smart Grid*, vol. 14, no. 2, pp. 979–995, Mar. 2023, doi: 10.1109/TSG.2022.3201814.

[115] N. Bazmohammadi, A. Tahsiri, A. Anvari-Moghaddam, and J. M. Guerrero, "A hierarchical energy management strategy for interconnected microgrids considering uncertainty," *Int. J. Electr. Power Energy Syst.*, vol. 109, pp. 597–608, Jul. 2019, doi: 10.1016/j.ijepes.2019.02.033.

[116] R. Wang, P. Wang, and G. Xiao, *Intelligent Microgrid Management and EV Control Under Uncertainties in Smart Grid*, 1st ed. Singapore: Springer, 2018.

[117] S.-J. Kim and G. B. Giannakis, "Scalable and robust demand response with mixed-integer constraints," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 2089–2099, Dec. 2013, doi: 10.1109/TSG.2013.2257893.

[118] D. Bertsimas, E. Litvinov, X. A. Sun, J. Zhao, and T. Zheng, "Adaptive robust optimization for the security constrained unit commitment problem," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 52–63, Feb. 2013, doi: 10.1109/TPWRS.2012.2205021.

[119] M. A. Rahman, Md. R. Islam, K. M. Muttaqi, and D. Sutanto, "Data-driven coordinated control of converters in a smart solid-state transformer for reliable and automated distribution grids," *IEEE Trans. Ind. Appl.*, vol. 56, no. 4, pp. 4532–4542, Jul. 2020, doi: 10.1109/TIA.2020.2972507.

[120] A. Hussain, V.-H. Bui, and H.-M. Kim, "Robust optimal operation of AC/DC hybrid microgrids under market price uncertainties," *IEEE Access*, vol. 6, pp. 2654–2667, 2018, doi: 10.1109/access.2017.2784834.

[121] L. C. Blanco et al., *Control Jerárquico en Micro-Redes AC*, 1st ed. Pereira, Colombia: Universidad Tecnológica de Pereira, 2021.

[122] G. Calafiore and M. C. Campi, "Uncertain convex programs: Randomized solutions and confidence levels," *Math. Program.*, vol. 102, no. 1, pp. 25–46, Jan. 2005, doi: 10.1007/s10107-003-0499-y.

[123] S. Claeys, M. Vanin, F. Geth, and G. Deconinck, "Applications of optimization models for electricity distribution networks," *WIREs Energy Environ.*, vol. 10, no. 5, pp. 1–35, Sep. 2021, doi: 10.1002/wene.401.

[124] R. S. Pinto, C. Unsihuay-Vila, and F. H. Tabarro, "Coordinated operation and expansion planning for multiple microgrids and active distribution networks under uncertainties," *Appl. Energy*, vol. 297, Sep. 2021, Art. no. 117108, doi: 10.1016/j.apenergy.2021.117108.

[125] L. A. Roald, D. Pozo, A. Papavasiliou, D. K. Molzahn, J. Kazempour, and A. Conejo, "Power systems optimization under uncertainty: A review of methods and applications," *Electr. Power Syst. Res.*, vol. 214, Jan. 2023, Art. no. 108725, doi: 10.1016/j.epsr.2022.108725.

[126] S. M. Muyeen, S. M. Islam, and F. Blaabjerg, *Variability, Scalability Stability Microgrids*, 11st ed. London, U.K.: Institution of Engineering and Technology, 2019.

[127] H. T. Kim, Y. G. Jin, and Y. T. Yoon, "An economic analysis of load leveling with battery energy storage systems (BESS) in an electricity market environment: The Korean case," *Energies*, vol. 12, no. 9, p. 1608, Apr. 2019, doi: 10.3390/en12091608.

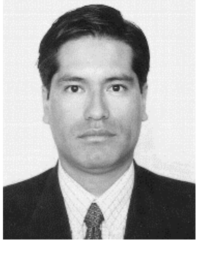
[128] Z. Zhou and T. Lin, "Spatial and temporal model for electric vehicle rapid charging demand," in *Proc. IEEE Vehicle Power Propuls. Conf.*, Oct. 2012, pp. 345–348, doi: 10.1109/VPPC.2012.6422675.

[129] R. Leou, J. Teng, and C. Su, "Modelling and verifying the load behaviour of electric vehicle charging stations based on field measurements," *IET Gener., Transmiss. Distrib.*, vol. 9, no. 11, pp. 1112–1119, Aug. 2015, doi: 10.1049/iet-gtd.2014.0446.

[130] A. Donoghue. (2022). *LV Engine*. SP Energy Networks. [Online]. Available: https://www.spenergynetworks.co.uk/pages/lv_engine.aspx#tablist1-tab5

RAFAEL A. NÚÑEZ R. received the B.S. degree in electronics engineering from Unidades Tecnológicas de Santander, Bucaramanga, Colombia, in 2011, the M.Sc. degree in electronics engineering from Universidad Pontificia Bolivariana, Bucaramanga, in 2018, and the Ph.D. degree from Universidad Autónoma de Bucaramanga, Bucaramanga, in 2023. He joined the Department of Automatics and Electronics Engineering, Unidades Tecnológicas de Santander, in 2012, where he is currently a full-time Professor. He is also a Researcher/Associate Professor with the GICAV Research Group. His research interests include power electronics, microgrids, smart grid applications, and power systems planning and operation.

JOHNNY POSADA received the B.S. degree in electronics engineering from Universidad Autónoma de Occidente, Cali, Colombia, in 2001, the M.Sc. degree in electronics engineering from Universidad del Valle, Valle, in 2007, and the D.Sc. degree in electrical engineering from CINVESTAV, Guadalajara, Mexico, in 2013. He joined the Department of Automatics and Electronics Engineering, Universidad Autónoma de Occidente, in 2002, where he is currently a full-time Professor. He is also a Researcher/Associate Professor with the GIEN Research Group. His research interests include power electronics, microgrids, and smart grid applications.



CLODOMIRO UNSIHUAY-VILA received the degree in electrical engineering from the National University of the Center of Peru (UNCP), Peru, in 2000, validated by the Federal University of Minas Gerais, Brazil, the M.Sc. degree in electrical engineering from the Federal University of Maranhão, Brazil, in 2003, and the Ph.D. degree in electrical engineering from the Federal University of Itajubá, Brazil, in 2009. Since March 2010, he has been an Associate Professor with the Electrical Engineering Department, Federal University of Parana (UFPR), Brazil. His current research interests include power systems planning and operation, energy planning, renewable energy, energy management, smart grids and microgrids, and market and regulation of power systems. He completed the Sandwich-Doctoral Fellowship from the Pontifical University of Comillas, Madrid, Spain, from 2007 to 2008.

OMAR PINZÓN-ARDILA received the B.S. degree in electrical engineering from Universidad Industrial de Santander, Bucaramanga, Colombia, the M.Sc. degree in electrical engineering from Universidad de los Andes, Bogotá, Colombia, and the Ph.D. degree from the Department of Electronics and Control Engineering, Universidad Pontificia Comillas, Madrid, Spain. Currently, he holds the position of a Titular Professor with the Department of Electrical and Electronic Engineering, Universidad Pontificia Bolivariana, Bucaramanga. His research interest includes the application of power electronics in electric energy systems, with a particular interest in smart grids.