Transactive Energy: State-of-the-Art in Control Strategies, Architectures, and Simulators

ADEIZA J. ONUMANYI[1], (Member, IEEE), **SHERRIN J. ISAAC**[1], (Member, IEEE), **CAREL P. KRUGER**[1], **AND ADNAN M. ABU-MAHFOUZ**[1,2], (Senior Member, IEEE)

[1]Advanced IoT, Next Generation Enterprises and Institutions, Council for Scientific and Industrial Research (CSIR), Pretoria 0001, South Africa
[2]Department of Electrical and Electronic Engineering Science, University of Johannesburg, Johannesburg 2092, South Africa

Corresponding author: Adeiza J. Onumanyi (aonumanyi@csir.co.za)

ABSTRACT The concept of transactive energy (TE) in smart grid systems is gaining increased research attention for its potential to optimize distributed energy resources, improve system reliability, as well as provide a balanced ecosystem for fair economic transaction between prosumers. TE is defined by the GridWise Architecture Council as a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter. With control mechanisms being a key part of TE systems, in this article, we discuss the state-of-the-art in TE control strategies, architectures, and relevant simulators for designing, evaluating, and analysing TE systems. Most importantly, existing TE control strategies are examined and discussed via a hierarchical structure comprising four different levels wherein TE control strategies/controllers can be deployed. Architecture-wise, we highlight the different types of TE architectures including the centralized, decentralized, distributed, and hierarchical architecture. In terms of existing and potential simulators for designing and evaluating TE models, we discuss and compare notable software across different characteristics of interest. We conclude this article by highlighting the basic components of a typical TE controller and other future research directions spanning across security concerns, privacy issues, communication challenges, simulation and validation demands. As a main contribution, different from existing survey articles, this article presents a synthesis of existing works regarding TE control strategies, architectures, and TE-based simulators for the benefit of the budding researcher whose interest may lie in the study of TE systems.

INDEX TERMS Energy, microgrid, power, smart, transactive.

I. INTRODUCTION

Since the early 2000s, many private and public electric utilities around the world have been steadily migrating from traditional power grid systems to the more enterprising concept of smart grid (SG) networks [1]. The embrace of SG networks over traditional power grid systems follows from key comparative advantages, which are presented in Table 1 [2]. Following Table 1, it is seen that SG systems are typically more advantageous than existing traditional grid systems, and for such reasons they are being adopted and deployed speedily worldwide.

SG networks are composed of many independent and geographically distributed power generation sites that are capable

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of being integrated into the main grid. Such independent and distributed power generation sites are typically referred to as microgrids (MGs). Specifically, MGs are able to island (i.e. disconnect) from the central main grid during downtime in order to supply locally generated energy to nearby customers, and such operations are typically provided via intelligent controllers [3]. MGs comprise several distributed energy resources (DER) and loads such as solar panels, wind turbines, combined heat and power generators, electric vehicle (EV) charging stations, and energy storage facilities like batteries. These energy sources are responsible for generating and storing power locally within an MG. Spatial-wise, MGs may serve discrete geographical footprints, such as college campuses, hospital complexes, business/industrial centres, or neighbourhoods [4]. Consequently, MGs are envisioned primarily to provide both economic and operational benefits

Traditional Main Grid	Smart Grid
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distributed generation
Few sensors	Sensors throughout
Manual monitoring	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

both to the power producers (i.e. owners of legacy grid systems) as well as to power consumers/prosumers by providing a fair balance between the supply of and demand for electric power.

One key advantage of MGs in SG networks is that they provide the capability to control when and how energy is generated and used locally, which can lower the demand and strain on the main grid system during peak periods. MGs can also help to stabilize the main grid by providing resilient and sustained power supply even during downtimes, for example during severe weather and disaster conditions. However, questions have arisen as to how will MG owners be compensated for providing services such as power, frequency, and voltage control to the main grid? How can economic incentives and signals be used to achieve the operational goals of the main grid to ensure system reliability?

Such questions as mentioned above are being answered via transactive energy (TE). Technically, TE is defined by the GridWise Architecture Council (GWAC) as "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter" [5]. Essentially, TE refers to any approach that allows energy to be managed efficiently and traded between different prosumers and consumers as well as between prosumers and producers. In this case, a prosumer refers to a customer that can both produce and consume energy with demand response capabilities [6]. Demand response refers to the tools and strategies that provide the capacity for an energy consumer to change its power consumption rate in order to match the demand for power with supply [7]. TE can thus be used alongside demand response mechanisms to ensure that DERs in MGs are integrated easily into existing networks via control mechanisms that use market-based solutions to manage energy. Being a relatively new paradigm, it is understandable to have many different perceptions about the entire concept of TE. Thus, in this article, we provide a survey of TE focusing specifically on control strategies from the viewpoint of structure and architecture. By this, the present article is noted to contribute in the following ways:

- We discuss TE control strategies from a structural point of view, dwelling on the different levels wherein such strategies can be implemented. Specific approaches in the literature are presented based on the different levels in which they are implemented.

- The different architectures noted for the deployment of TE systems are discussed extensively, with focus on transactive and control lines that differentiate the different architectures.

- With little or no summaries available on the potential simulators for designing, testing, and evaluating TE systems, we present an overview of notable state-of-the-art simulators for TE. We highlight and contrast their different characteristics in order to aid researchers in the choice of potential TE simulators for their use.

- We highlight potential requirements for the development of TE controllers and conclude with future research challenges and directions for improvement.

A general outline of the rest of this article is given as follows: section II provides a discussion of related survey articles as a means to distinguish the present article from existing survey articles. Section III introduces the general definition and attributes of TE, while section IV introduces control strategies and their different classifications. In section V, we discuss the different basic architectures for supporting the deployment of TE systems in SG networks. Different possible simulators for designing and testing TE systems are highlighted in section VI. Section VII mentions the basic components required towards the realization of TE controllers, while section VIII highlights the future research directions towards the realization of effective, efficient, and secured TE systems. Conclusions are drawn in section IX. The abbreviations used in this article are presented in the Appendix.

II. RELATED SURVEY ARTICLES

In this section, we aim to distinguish the present article from existing survey articles, as well as to introduce interested readers to other relevant facets of TE and where such summaries can be found. For details regarding the basics and general idea of TE, readers can find comprehensive presentations in [2] and [17]. Such topics regarding what is TE? How does TE work? Why do we need TE? and concerns with TE are treated exhaustively in these articles (see [2], [17]). Although most survey articles would typically present some level of background about TE, nevertheless, our attention in this section is drawn only to the specific areas of TE covered in such survey articles. A summary of notable and related TE survey articles is provided in Table 2.

A thorough treatment of TE market structures and business models for TE is presented in [8]. Specifically, the authors provided a foundation for comparing TE market structures, which entails how wholesale and retail sellers and buyers of energy services can transact effectively with each other. They also discussed business models for TE, covering models such as state-regulated, investor-owned, and electric distribution cooperative utilities. Generally, the contents of [8] will be beneficial to readers who may be interested in the economic details and models of TE.

Details about existing TE pilot projects can be found in [9], [10], [12], [14]. Specifically, authors in [9] provided a

TABLE 2. Summary of existing survey articles and their main focus areas with regards to TE.

Survey articles	Year	Specific focus of discussion
Cazalet *et al.* [8]	2016	• TE market structures • Business models for TE • TE models used/deployed in different countries
Liu *et al.* [9]	2017	• Summarizes the different pilot projects that use transactive control • Bibliographic review of articles that study transactive control for power system operations
Lian *et al.* [10]	2017	• Extensive review of major projects in US and Europe that use transactive approaches • Role of microeconomics in the design and analysis of TE systems • Theoretical basis for TE systems
Abrishambaf *et al.* [11]	2019	• Transactive network management • Decentralize transactive control • Peer-to-peer markets • Existing implemented TE projects
Muhanji *et al.* [12]	2019	• TE and existing projects that have implemented TE strategies • Potential use cases of energy IoT (eIoT) with TE strategies • TE applications for utilities and DSOs • Customer applications of TE: at Industrial, commercial, and residential levels
Zia *et al.* [13]	2020	• General functional architectures for designing TE systems • Distributed ledger technologies • Peer-to-peer and community-based energy markets
Lee *et al.* [14]	2020	• Discusses the challenges faced in notable TE experimental projects • Focuses on risk perceptions, user and system readiness, and economic feasibility of each TE project
Mollah *et al.* [15]	2020	• Background to blockchain and blockchain methods • Through discuss of blockchain in different areas of smart grid networks • Practical projects and trials implementing blockchain in smart grid • Software platforms for implementing blockchain in power systems
Khorasany *et al.* [16]	2020	• Requirements to design effective market mechanism for TE markets • Case study of TE implementation: The Monash MG

summary of the different pilot TE projects and then summarized a number of articles where transactive control techniques in power system operations have been used. In [10], different existing TE pilot projects were classified and discussed based on the different countries wherein such projects were conducted. In addition, the authors also focused on the role of microeconomics in the design and analysis of TE systems. They also provided a theoretical basis for the development of TE systems. In a separate survey article, the authors in [12] discussed existing TE projects as well as some use cases for the application of the concept of energy Internet of Things (eIoT) in TE. They highlighted how eIoT can be integrated with TE applications for use in utilities and distributed system operators (DSOs). Lee *et al.* in addition to discussing existing TE projects in [14], also focused mainly on the different challenges encountered in such TE-based projects. They discussed a number of existing challenges based on the risk perception, user and system readiness, and economic feasibility of each TE project.

With regards to TE network management, the survey article in [11] sheds great light on both network management techniques, decentralized transactive control, and peer-to-peer

market studies. They exhaustively discussed the above mentioned areas in addition to highlighting some existing TE projects implemented across the world. Zia *et al.* in [13] provided an extensive survey regarding the general functional and high-level layers for the design of TE systems. They focused on distributed ledger technologies as well as peer-to-peer and community-based energy markets. A more thorough and specific survey article regarding blockchain methods in TE can be found in [15]. Here, the authors provided a background to blockchain and blockchain methods. They then discussed blockchain in different areas of SG networks and mentioned practical projects that have implemented blockchain in SG. A discussion of software platforms for implementing blockchain in power systems was also presented. In a separate article, Khorasany *et al.* in [16] discussed the requirements for designing an effective market mechanism for TE markets and then provided a popular case study of the Monash MG.

The above mentioned survey articles have focused on diverse areas of TE, yet leaving more to be desired. Consequently, different from the foregoing articles, in the present article we focus on discussing TE control strategies from a

structural and architectural point of view. By this, readers are better informed about where TE control strategies can be deployed as well as the different TE control strategies that have been deployed at such layers. Another important question that may interest budding and established TE researchers is, what are the potential simulators available for the design and evaluation of TE systems prior to deploying them in real-time? In this regard, we discuss state-of-the-art software for TE purposes, while highlighting their areas of application and characteristics. We conclude by summarizing some key issues concerning the development of TE control systems in SG networks.

III. TRANSACTIVE ENERGY: A GENERAL OVERVIEW

There are many competing concepts across the academic, industrial, and business world regarding the meaning and scope of TE. This can be observed following the many different definitions of TE, for which a few notable examples are listed as follows:

"*A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter.*" - by the GWAC [5]

"*A software-defined grid managed via market-based incentives to ensure grid reliability and resiliency. This is done with software applications that use economic signals and operational information to coordinate and manage devices' production and/or consumption of electricity in the grid. Transactive energy describes the convergence of technologies, policies, and financial drivers in an active prosumer market where prosumers are buildings, electric vehicles, microgrids, virtual power powers (VPPs) or other assets.*" - [18]

"*Techniques for managing the generation, consumption, or flow of electric power within an electric power system through the use of economic or market-based constructs while considering grid reliability constraints.*" - [19]

"*An internet-enabled free market, where customer devices and grid systems can barter over the proper way to solve their mutual problems, and settle on the proper price for their services, in close to real time.*" - [20]

By examining the above definitions, it is safe to summarize TE as referring to a class of approaches, mechanisms, and/or techniques that engage consumers, prosumers, and producers of electric energy in a symbiotic and interactive framework for the economic and operational benefits of all involved parties. In other words, TE suffices as an interactive mechanism between the central (i.e. traditional) grid system and the distributed MGs, such that economic rewards are offered to the owners of MGs in a bid to guarantee the stability and reliability of the entire SG network.

There are many unknowns to be resolved concerning the concept of TE since it is still a contemporary area of research within the global energy domain. For example, it is essential to arrive at a unified TE framework for all parties involved in the SG. It is also necessary to ensure that TE frameworks are

realized in real-time, and there is need to develop functional operating and control mechanisms. Lastly, it is also necessary to establish fair market policies for equitable participation of all involved parties. Towards unifying the concept of TE, the GWAC has made great strides to highlight a number of essential TE attributes for which further research and development efforts are required. These attributes are represented in Figure 1, and a brief summary of each aspect is noted as follows [5]:

1) **Architecture**: This refers to all TE tools and methodologies, which are described as components or subsystems of a system framework.

2) **Extent**: This refers to the space/size that a TE system must cover in terms of some geographic, organizational, political, or other measures of extent.

3) **Transacting parties**: In most cases, this refers to automated systems, which act as a replacement for human participants. Nevertheless, in some cases, humans may still be involved in the loop. Essentially, all entities that are party to transactions must be explicitly described in a TE system.

4) **Transaction**: A transaction must be clearly defined in a TE system typically within the context of that system. A number of questions must be answered to be clear about what a transaction means, such as: who are the transacting parties? What information is exchanged during a transaction? What are the rules governing transactions? What mechanisms are used to reach an agreement during a transaction?

5) **Transacted commodities**: In essence, the primary commodity to be transacted is energy, but any other derived product(s) must be clearly defined.

6) **Temporal variability**: The time scale or period of transaction between transactive systems must be well specified and analysed particularly to guarantee
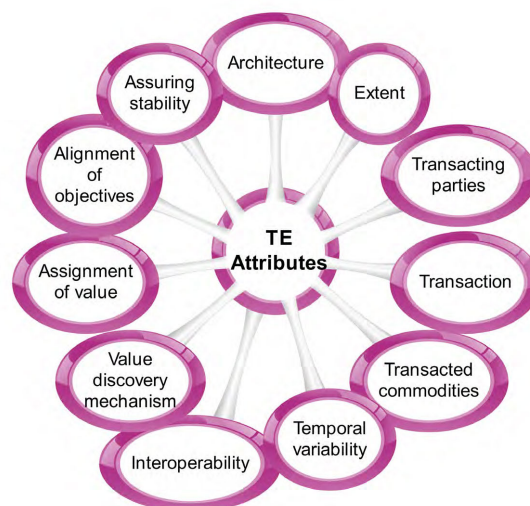

FIGURE 1. The different attributes of TE.

compatibility and interoperability between transactive systems.

7) **Interoperability**: This describes the requirement for transactive systems to link and interchange information (accenting format and syntactic) and the need to understand such interchanges in the setting that is required to support work-flows and constraints.

8) **Value discovery mechanism**: This refers to any means of demonstrating economic or engineering value (in terms of profit or accomplishment) that can be associated with a transaction. In other words, it describes the procedure by which transacting participants agree on a preassigned value.

9) **Assignment of value**: This describes the means by which value is assigned to specific objectives (sometimes non-quantitative in nature), which can then be processed using a discovery method.

10) **Alignment of objectives**: This encompasses the continuous need to align many objectives to produce better outputs as the system works. This requires maximising the benefits of the whole transactive system, objectives, variables, and constraints to accomplish both the economic and engineering benefits of TE systems.

11) **Assuring stability**: The reliability of grid control and market-based instruments is required and has to be guaranteed. This refers to guaranteeing stability both from the perspective of control systems and the assurance with respect to existing grid stability limits.

Thus, having briefly mentioned a number of TE attributes that are important for successfully realizing TE systems, in the next sections we focus on three key areas, namely, the state-of-the-art in control strategies, architectures, as well as on existing simulators that can be used for testing, evaluating, and analysing TE systems.

IV. TRANSACTIVE ENERGY: CONTROL STRATEGIES

As noted in Section III, TE is expected to address both the economic and engineering concerns of an SG system. In this case, the engineering aspect of TE refers to the processes involved in guaranteeing reliable and proper functioning of an SG system. Whereas, the economic aspect of TE aims to financially reward all participating prosumers (typically MG owners) for their services rendered towards the stability of an SG system. In order to achieve both concerns, it is pertinent to develop and implement effective and efficient control strategies. Thus, in this section, we will discuss the possibilities and existing attempts at the development of TE control strategies. First, we present a hierarchical classification structure that describes the different levels in which TE control strategies can be implemented in the classic hierarchical structure of the traditional main grid network. Then, we discuss the different TE control strategies per control level.

There are many types of TE control strategies/controllers aimed at achieving different goals. In this context, whenever we mention TE control strategies, we are simply referring to the different methods, schemes, and/or techniques used to
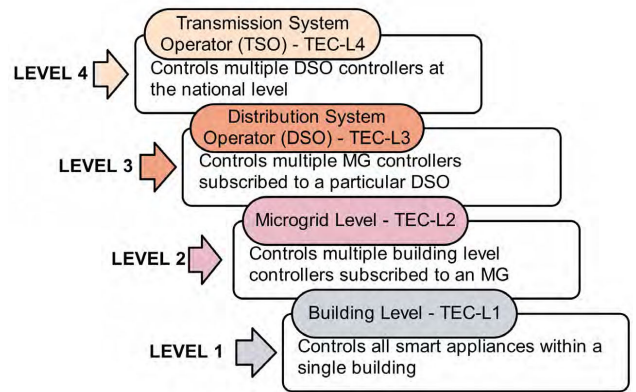

FIGURE 2. The different levels at which TE control strategies/controllers can be implemented.
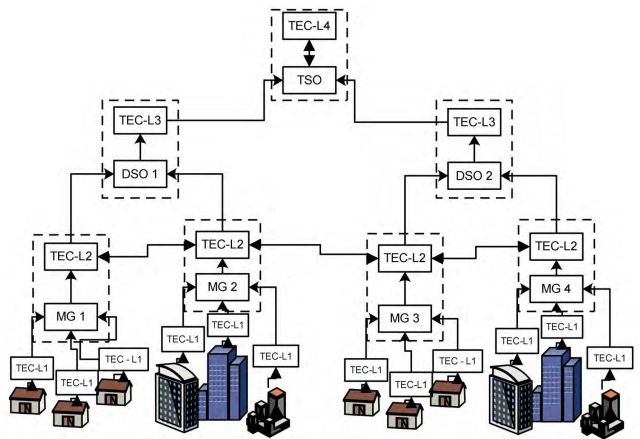

FIGURE 3. Hierarchical representation of TE controllers implemented at different levels of an SG network.

manage the different TE attributes of an SG system. Whereas by TE controllers, we imply the different software/hardware technologies that implement such control strategies. Thus, simply put, TE controllers implement TE control strategies. Consequently, whenever both terms are used (often interchangeably in this article), we simply mean to denote the presence of some TE control mechanism in an SG network.

In terms of understanding TE control strategies, it is important to identify the classification structure of an SG system before delving into the possible implementable control strategies. In this regard, a hierarchical classification model of an SG system has been proposed by the GWAC in [17], [21], and we adopt such a similar structure in this article as presented in Figure 2. We shall therefore discuss existing control strategies/controllers based on the hierarchical structure of Figure 2.

In Figure 2, we present the different levels wherein TE controllers or control strategies can be deployed, namely, at the building (i.e residential), microgrid (i.e community), distribution system operator (DSO) (i.e state/municipal), and transmission system operator (TSO) (i.e national) levels of control. These different control levels are briefly discussed as follows:

1) **Level 1 (Residential level)**: This represents the first level wherein TE control strategies can be deployed. Any TE controller (TEC) deployed at this level is termed a TEC level 1 (TEC-L1) controller. Essentially, it is envisaged that each building/residence within an MG will consist of smart appliances, DERs, and energy storage devices, which will be connected to and controlled by a TEC-L1 controller.

2) **Level 2 (Microgrid level)**: An MG may comprise many buildings, thus forming a community comprising either a neighbourhood, campus, industrial, hospital, or business environment. Any TEC deployed at this level is termed a TEC level 2 (TEC-L2) controller, whose function is to aggregate information and implement control strategies across different TEC-L1 controllers installed at the level l layer.

3) **Level 3 (Distribution System Operator level)**: Any controller installed at the DSO level (i.e at the municipality level) is termed a TEC level 3 (TEC-L3) controller, whose function is to aggregate and control market and reliability signals and transactions across multiple TEC-L2 controllers subscribed to a specific DSO.

4) **Level 4 (Transmission System Operator level)**: This represents the fourth level of control, which is considered to be the highest point of control, typically at the national level. Any control strategy/controller deployed at this level is referred to as a TEC Level 4 (TEC-L4) controller, whose function is to manage all control messages and transactions across multiple DSOs.

A general schematic depicting a more detailed interconnection between the different controllers and control levels is shown in Figure 3. Essentially, the different TEC-L1 controllers are depicted as installed within the different buildings, which are then aggregated and controlled by a TEC-L2 controller at a single MG level. Then, the different MGs with their respective TEC-L2 controllers are aggregated and controlled by a TEC-L3 controller located at a single DSO level. And finally, multiple TEC-L3 controllers are aggregated and controlled by a single TEC-L4 controller situated at the TSO level. It is worth noting that this model can be extrapolated to higher levels particularly when energy is transacted at international levels between countries. Next, we shall discuss the different specific TE control methods per control level.

A. LEVEL 1 CONTROL STRATEGIES

The essential function of a TEC-L1 controller is to coordinate, communicate, and ensure the stability of all performance parameters of an MG, such as balancing the operating voltage, frequency, and power flow in response to some price signal. Such functions are often performed by many home energy management systems (HEMS), which are typically classed as TEC-L1 controllers. In some other articles, such Level 1 functions are also referred to as the primary control layer functions [22]. However, while the primary control layer in [22] focuses mainly on providing technical functions,

our description of a TEC-L1 controller in terms of TE applications typically forwards only the bids and offers from a prosumer to a level 2 controller (at the MG level). And in return, it will communicate instructions from higher level controllers to specific smart devices, for example, to inform an HVAC (Heating, Ventilation Air Conditioning) system to either decrease or increase its temperature value. Nevertheless, technically, a TEC-L1 controller will perform similar functions to the primary control layer described in [22] such as:

1) To stabilize the voltage and frequency levels of an MG particularly during the periods before and after islanding.

2) To provide plug and play capabilities for DERs to connect and disconnect seamlessly from the central grid.

3) To mitigate circulating currents away from the MG network in order to prevent over-current flow from destroying power electronic devices and DC-link capacitors.

Although this article focuses on TE controllers/control strategies, nevertheless, interested readers can find in [22] and relevant references therein additional details about the different methods for controlling the technical performance parameters of an MG. Such methods typically include the active load sharing method and the droop characteristic techniques [23].

In terms of TE, any TEC-L1 controller, being deployed at the residential level should be capable of providing the following functions [11]:

1) Ability to modify the consumption rate of smart devices within a building based on some market clearing price,

2) Calculate the cost that a consumer should to pay for purchased energy, and

3) Bid a targeted amount of electricity to be purchased.

Furthermore, TEC-L1 controllers are expected to interact with smart appliances, HVACs, and energy storage devices. From our study, we have observed that TEC-L1 controllers or control strategies can be categorized into two broad classes, namely, predictive or non-predictive-based control models, which we discuss as follows:

1) **Predictive control strategy**: Such strategies are based mainly on model predictive control (MPC) frameworks, which are designed to account for parameters such as price and weather. It also forecasts energy from renewable sources, as well as the effectiveness of power storage devices within a building. An MPC framework is typically characterized by optimization models that depend on predicted prices. Many home energy management systems (HEMS) are based on such optimization-based models. For example, authors in [24] developed a stochastic, multi-objective optimization algorithm that uses an MPC architecture for timing the operation of smart residential appliances optimally. Essentially, their design entails that a higher level TE node would typically provide price signals

to the HEMS (which acts as a TEC-L1 controller), which then provides the operating set points for smart appliances within a building (or home). By adopting such a predictive model, some authors have discovered that their predictive-based HEMSs could reduce energy cost paid by consumers by approximately 5% over a ten-day simulation period [24].

Similarly, a predictive-based HEMS was proposed in [25] to ascertain the ideal operational schedule of smart appliances within a building functioning alongside renewable energy sources. Their objective function was designed to minimize the weighted sum of discomfort (i.e. customer's thermal comfort), maximum electricity consumed, energy cost, and carbon footprint. A numerical test approach was used to evaluate the system's performance, and it was found that in contrast to the non-optimized case, their proposed model can reduce daily energy cost by 28%.

Authors in [26] proposed an application that manages demand response in real-time based on price signals. Their application can be installed in smart meters and automated in an online manner to ascertain the optimum operating condition of residential appliances. They analysed their system's performance via a numerical approach and found that a household's electricity bill payment could be reduced by about 26.63%.

Optimal energy consumption scheduling schemes were studied in [27] wherein an optimal and automatic residential energy consumption scheduling framework was proposed to achieve some trade-off between minimizing electricity payment and the waiting time for the operation of each appliance. They demonstrated via simulation that the combination of their energy scheduler and price predictor led to significant reduction in users' payments, which encourages the users to participate in residential load control programs.

Indeed, there is a large body of research works on the study of predictive-based control methods and for further studies such valuable articles can be found in [28]–[30] and other key references therein.

2) **Non-predictive control strategy**: This refers to control strategies that are based on managing the power consumption rate of smart appliances by simply reacting to an instantaneous (i.e. actual) price signal sent from a higher level controller. Such a strategy/model is sometimes referred to as a passive or static controller model. A number of such models are noted in the literature, for example, authors in [31] used this approach to control the HVAC of an office building based on real-time market prices of TE systems. In their model, a passive controller was developed to adjust the internal set point of selected building loads by responding to an external price signal. For example, they suggested that when the current market clearing price (MCP) is higher than the mean price, then the cooling set point temperature of an HVAC should be increased. Conversely, when the MCP is lower than the mean price, then the cooling set point can be decreased.

Authors in [32] introduced a transactive control mechanism for integrating and managing electric vehicles (EV) efficiently into the grid. Their goal was to minimize the charging cost of EVs and to mitigate their effects on the grid. In their design, the DSO (i.e the higher level controller) generates a marginal price, which is then sent to the TEC-L1 controller at the customer's house. The passive TEC-L1 controller then controls the EV's charging cycle and sends a feedback to the DSO to validate the effectiveness of the economic and control signal that was sent. Authors demonstrated that the proposed approach significantly reduced the electricity bills of EV owners by about 60 - 70 %.

Similarly, a distributed control strategy was developed in [33] for air conditioning loads (ACLs) to mitigate their effects on MG tie-line power fluctuations. Their proposed controller simply allocates a targeted power level to each ACL based on an algorithm derived from the principle of low-pass filtering. They showed that their control strategy was able to reduce power fluctuations on the line significantly as compared to non-controlled load schemes.

Summarily, many control strategies at level 1, i.e within home/residential buildings, are usually either passive (non-predictive) or predictive-based models and we present in Table 3 a qualitative comparison of both classes.

B. LEVEL 2 CONTROL STRATEGIES

Level 2 TE control strategies are typically concerned with establishing the market clearing price (MCP) between multiple MGs while guaranteeing the reliability of the wider SG network. TEC-L2 controllers can operate in a centralized hierarchical structure under the control of a higher-level controller (see Figure 3) towards either purchasing/selling power or obtaining an MCP from the DSO to be used for trading between multiple MGs. In other cases, TEC-L2 controllers will also cater for the case of distributed ad hoc transactions between multiple MGs. Such ad hoc networks between multiple TEC-L2 controllers may arise when MGs operate in an islanded mode. It may also arise when MG operators decide to operate independently of the main grid. Thus, in such cases where ad hoc operations are needed, it is expected that multiple interconnected TEC-L2 controllers should be able to broker prices between themselves as well as to ensure that the wider MG network operates under reliable conditions.

Many research articles have explored and investigated different level 2 control strategies, for example, the authors in [34] developed a secure distributed transactive energy management (S-DTEM) scheme for multiple interconnected MGs. Based on their scheme, the S-DTEM is designed to be a higher level controller, which connotes a TEC-L3 controller. However, going by their structure, each MG is controlled by a distributed MG energy management system (MG-EMS),

TABLE 3. Qualitative comparison of predictive and non-predictive TEC models.

	Level 1 TE Control Strategy	
	Predictive (P)	**Non-predictive (NP)**
Design Complexity	Higher than NP	Low
Computational Demand	Higher than NP	Low
Number of Load Control	Multiple loads	Multiple loads
Memory demand	Larger than NP	Small
Pricing Errors	Susceptible to errors	Error-free (uses actual price)
Energy savings	Higher than NP	Depends on number of loads
Development Cost	Costlier than NP	Lower than P

which refers to a TEC-L2 controller in the context of our article. The MG-EMS (i.e TEC-L2 controller) then shares information regarding market quantities and prices with other MGs to ensure that information is kept private and preserved. Whenever an MG operates as a price taker, its S-DTEM will actively optimize its energy selling price and then auto-tune its operating time towards minimizing its local cost by buying and selling with other MGs or the DSO. In the same article [34], the authors also introduced some security measures to prevent any rogue TEC-L2 controller from negatively affecting the convergence performance of an SG. Following their simulation results for the case of a 4-MG network, it was shown that their scheme successfully reduced the local cost of each MG particularly under conditions of fraudulent behaviour.

An optimal operation of multiple MGs was investigated in [35] via cooperative energy and reserve scheduling. Therein, authors used the well-known *Shapely* value in cooperative game theory to allocate benefits to each MG. Comparison was made between the operation of cooperative MGs and isolated MGs, and it was shown that the cooperative case outperformed the isolated case in terms of operation cost and energy conservation rates.

Authors in [36] proposed a real-time interactive energy management system (EMS) framework that can be deployed for and used by many integrated MGs and the utility. They considered a bi-level control scheme having only primary and secondary level controllers. At the primary level, the EMSs (i.e TEC-L2 controllers) operate separately per MG in order to address problems, power operating points of generating sources, and possible power surpluses or shortages within each MG. Then, any shortage or surplus of power from any MG will be forwarded to a central EMS at the secondary level, which in our case refers to a TEC-L3 controller. They showed via simulation results that their proposed bi-level scheme can dispatch energy from different generation resources optimally between multiple MGs.

Indeed, the literature on level 2 layer control strategies is quite rich and still growing with a number of economic and technical benefits for both the operators of MGs as well as for the DSOs. In this regard, some other level 2 control schemes can be found in [37], [38] and the references therein, and they all aim to coordinate both the economic and energy trading processes between MGs. They also intend to interface with higher level controllers at the DSO.

C. LEVEL 3 AND 4 CONTROL STRATEGIES

Both level 3 and 4 control strategies are discussed in this section since it is possible for both control levels to be managed by the same national energy commission or company. However, in cases where both levels are independent, then the functions at level 4 are often an abstraction of the functions at level 3. Essentially, level 3 control strategies are straddled with aggregating dispersed DERs and flexible loads across multiple MGs, while coordinating and balancing the supply and demand of energy in a transactive manner at the distribution level. It is also responsible for linking both wholesale and retail electricity markets.

A few notable examples of control strategies at level 3 are noted, for example, authors in [39] proposed a framework that enables multiple DSOs to bid in a TE market. Their framework allows DSOs (level 3 controllers) to interact with a TSO (level 4 controller) as well as with prosumers (i.e MGs) at the level 2 control layer. Specifically, the DSO is modeled to use a distribution locational marginal price (DLMP) algorithm, which provides price signals that will be forwarded to lower control levels to control the power consumption rates of consumer devices and for fair market bidding among prosumers. Their simulation outcome showed that their scheme could reduce the cost of energy supply rendered by the entire system.

In a separate article, a hierarchical electric vehicle (EV) management system was proposed wherein three actors were considered, namely, the DSO (level 3 controller), fleet operators, and EV owners [40]. The fleet operator (similar to a level 2 controller) manages centrally the battery charge time of EVs, while the DSO uses transactive control techniques (i.e. comprising price signals) to regulate the combined charging behaviour of fleet operators. It was affirmed via simulation results that their scheme provides optimized charging schedules for EVs while guaranteeing the safe operation of the entire network.

A TE system was developed in [41], [42] for integrating transmission and distribution systems. The integrated transmission and distribution (ITD) system was used to investigate the proficiency of a non-commercial DSO to regulate the

power consumed by DER devices, while offering services in return for suitable financial compensation. Following their designs [see [41], [42]], it was noted that the particular aim of a DSO is to closely monitor the daily amount of power used by an household and to ensure that it tracks a corresponding targeted daily summed load profile. In order to achieve this goal, authors used a "six-step power matcher design", which relies on a bid-based design that realizes good efficiency within a short space of time. Such a design guarantees that wholesale prices can be matched to retail prices towards reflecting accurate marginal costs.

Summarily, most control strategies at levels 3 and 4 (i.e. at the DSO and TSO level) are geared towards establishing the selling and buying price (i.e the market clearing price) for trading between producers, prosumers, and consumers. They are typically in charge of maintaining equilibrium between the supply and demand of energy. A summary of the different functions at the different control levels is provided in Table 4.

V. TRANSACTIVE ENERGY ARCHITECTURES

Prior to discussing the different types of TE architectures, it is pertinent to understand the difference between the control strategies discussed in Section IV and the architectures to be discussed in this section. Essentially, the concept of control strategy presented in Section IV highlights the classic hierarchical structure of the traditional main grid network with emphasis on identifying the different levels wherein TE mechanisms can be deployed. However, on the other hand, the term architecture as discussed in the present section refers to the different configurations/methodologies in which these different control levels are deployed. In this regard, the different levels could interact differently and each subset of the entire control framework would denote a different type of architecture.

To this effect, the literature presents a number of different TE architectures, which can be classified based on the parties involved in the SG network as well as by the manner in which the different parties interact. In this regard, the term "parties"

refers to the MGs and main grid operators (MGOs) [8], [43]. According to the GWAC, these parties are automated systems, possibly acting as surrogates for human parties, although in some cases, humans may be in the loop [5]. Furthermore, an MGO typically encompasses both the DSOs and the TSOs, whereas MGs comprise the consumers and prosumers. Thus, many TE architectures can be classified based on how these parties interact, specifically based on whether an MG transacts with a DSO/TSO or not.

When an MG transacts with a DSO, then a hierarchical and centralized architecture may suffice, however when an MG operates independently of a DSO, then a decentralized and distributed architecture may arise. In some cases, a hybrid architecture may be adopted based on the demands and goals of the participating parties. Consequently, the following TE architectures are discussed in the succeeding subsections, namely the centralized, decentralized, hierarchical, and distributed architectures.

Furthermore, we use two different lines, namely the transaction and control lines, to distinguish the different types of architectures. The transaction lines depict the potential exchange of "value" in monetary terms (or economic benefits) between parties. Such transactive actions are depicted by the purple lines used in the different architectural diagrams depicted in Figures 4, 5, and 6, respectively. On the other hand, the control lines depicted by the red dotted lines in the same figures refer to the actual flow of different possible instruction sets from some source to some destination. Such instruction sets are not limited only to the control of physical parameters (such as voltage, power, and frequency), but also to initiate potential transactions between different parties. For example, a control signal can be sent containing a clearing price, which can be used for transaction purposes between prosumers.

A. CENTRALIZED ARCHITECTURE

A centralized architecture typically comprises a single point of control wherein data collected from different residential

TABLE 4. Summary of the functions at the different TE control levels.

TE Control Level	Functions
Level 1	• Located at the residential level, i.e. within any building • Coordinates, regulates, and controls the power consumption rate of smart appliances, DERs, and storage devices within a building • Communicates with higher level controllers to maintain grid stability • Calculates cost of purchased energy for a customer based on MCP, i.e. forward bid and offers
Level 2	• Located at the MG level, which typically comprises many buildings • Establishes the MCP between multiple MGs • Communicates with higher level controllers towards purchasing/selling electricity • Manages multiple lower TEC-L1 controllers • Ensures stability of the entire MG network
Level 3 and 4	• Located at the main grid level, i.e. at the municipal and national (DSO/TSO) level • Manages multiple MGs to ensure the stability and reliability of the entire SG network • Links both wholesale and retail electricity markets • Prescribes and manages the MCP dispatched through the entire SG network i.e determine selling and buying prices • Ensures the balance between the supply and demand of energy in the SG network

buildings are processed and from which control instruction sets are initiated. In the case of a single MG operating in an islanded mode, such a single processing point could be a microgrid central controller (MGCC) [3], which resides at control level 2. Such a centralized architecture thus consists of only two layers, i.e. levels 1 and 2. On the other hand, if an MG or number of MGs operate in a grid-tied mode, then there will be a controller situated at the distribution level (i.e. TEC-L3 controller) where control instructions are initiated. In this case, the centralized architecture can be classified into three layers based on the number of levels and geographical areas under control, i.e consisting of the DSO, MGCC and TEC-L1 controllers.

A general representation of a centralized architecture is depicted in Figure 4, which shows how both the transaction and control lines interact between the different parties involved in an SG network. Essentially, it is noted that different buildings would consist of different smart appliances and DERs, which are typically controlled by an MGCC often associated with a single MG. In this case, information sent to an MGCC from the different residential building controllers i.e TEC-L1 controllers, are collected via high speed communication channels and processed at the MGCC. In islanded mode, control information would originate from an MGCC and these will be sent to the different TEC-L1 controllers towards either controlling some physical parameters or initiating economic transactions between consumers and the MG operator. In this case, control instructions would typically originate from the MGCC to the TEC-L1 controllers at the residential buildings (as seen by the control lines in Figure 4). Transaction lines would be open between the consumers and the MG operators, for example, towards making payments for electricity, negotiating clearing prices with the MG operator, and/or the MG operator paying for DER services rendered by the residential buildings to the grid.

Similarly, in the case of the 3-layer centralized architecture, it is expected to have a central TEC-L3 controller situated at the DSO being responsible for initiating control instructions towards the MGCC for use at the residential level. Under such an architecture, all information accessed by the MGCC from the different residential buildings are passed to the DSO controller, which becomes responsible for processing and taking decisions based on the general state of the entire SG network. In this case, while transaction lines can be initiated between consumers and the MG operator, such lines can as well as be initiated between the MG operators and the DSO. However, ultimately, all processing and control instruments would typically take place at a central DSO unit.

Summarily, Figure 4 shows that in a centralized architecture, although transaction lines may occur in a bidirectional manner between participating parties, nevertheless, control information typically originates and are sent from a single higher controller. Then such information typically heads towards lower level controllers with an aim to optimize the production and consumption rates of smart appliances and DERs situated within residential buildings.

B. DECENTRALIZED ARCHITECTURE

In a decentralized architecture, processing and control decisions are typically conducted at any level based on some locally collated measurements and pre-defined constraints. In most cases, decentralized architectures often comprise only two relevant conceptual levels, namely, an upper and a lower level [3]. The upper level resides with the MGO whereas the lower level consists of MGCC controllers. Such an architecture can be realized through various artificial intelligence concepts, for example multi-agent systems (MASs) and swarm intelligence. In this regard, MASs make measurements locally at the different residential buildings and then communicate such measurements directly to an MGCC for immediate action on the best operating condition to be used by smart residential appliances. Furthermore, an MGCC can negotiate its own TE contract terms with other MGCCs through the DSO operator and communicate contract terms to lower TEC-L1 controllers. These are depicted by the transaction lines connecting the different MGCCs via the DSO.
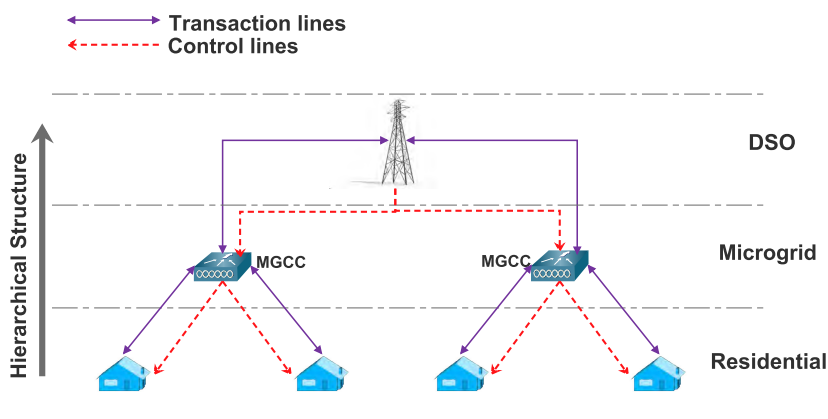

FIGURE 4. Centralized Architecture: Control information originates from a single controller typically situated at the MGO level.

In this case, the DSO brokers the clearing prices between the different MGCCs towards ensuring the stability and reliability of the entire SG network.

In a decentralized architecture, the design of TE controllers are often more complex than in the centralized model because of the need to accommodate potential local decisions. In order to guarantee the potential to make local decisions, the use of fog computing technologies can be deployed so that the data storage and computing power of MGCCs are distributed in efficient places to reduce complexity [44]. Fog computing refers to a decentralized computing infrastructure in which data, computing, and storage facilities are located somewhere between the data source and the cloud [45]. Thus, a fully decentralized architecture will require independent MGs to operate in a distributed manner, which often leads to the close interrelationship between decentralized and distributed architectures. In some cases, it is noted that fully decentralized architectures can be realized using distributed ledger technology (DLT), similar to the way it is used in bitcoin for realizing a decentralized financial system [13].

One realistic demonstration of a decentralized architecture can be seen in the Brooklyn MG project deployed by the LO3 Energy company as a pilot study in Brooklyn, US [46]. It consists of residents and business owners who produce energy via solar arrays and who wish to sell their excess solar energy to consumers. Participants are able to access the market via the Brooklyn MG mobile app. Then, they can purchase solar energy credits through the app via an auction scheme. Consumers determine their energy sources via the mobile software and can then set their daily budget, whereas prosumers can decide whether to trade their excess energy or not. Such a decentralized model has presented quite a number of benefits, such as improving domestic economies and reducing local air contamination through emitted gases in their environs.

Summarily, Figure 5 illustrates the schematic of a decentralized architecture, wherein transaction lines would typically take place in a bidirectional manner between all parties.

However, control information would originate independently from the different MGCCs towards optimizing the power generation and consumption rates of DERs and smart appliances located at the residential level. It is difficult to ascertain which architecture will best suffice for a customer between the centralized and decentralized models, as choice of the best architecture will depend on the specific goals and demands of an SG project. Nevertheless, a qualitative comparison of both architectures is presented in Table 5.

C. DISTRIBUTED ARCHITECTURE

A distributed architecture is simply an extension of a decentralized model, wherein lower level controllers can communicate amongst themselves in a collaborative manner towards achieving the design goals of an SG project. In this case, decentralized controllers will collate local measurements and interact with neighbouring controllers towards arriving at both an optimal MCP in order to ensure that the SG network is kept reliable.

There are notable instances wherein distributed architectures have been deployed, for example, the authors in [3] classified a distributed architecture into three layers, namely the droop/lower, secondary/intermediate, and auxiliary/upper layers. However, such an architectural structure was aimed at managing physical parameters such as voltage, frequency, and power. Essentially, such control functions were expected to be conducted at all controllers in the network, thus accounting for the distributed nature of their architecture.

The POWERWEB architecture in [47] also employs a scalable distributed architecture that runs many processes on multiple computers. Such computers are considered to be physical models of distributed TE controllers since they can be located at different geographical areas and linked via the internet. In their model, four basic types of server processes were deployed to include a web, database, computational and load balancing proxy server. We note that such a distributed model as presented in [47] can be leveraged as an emulative platform to test and evaluate the performance of TE designs.
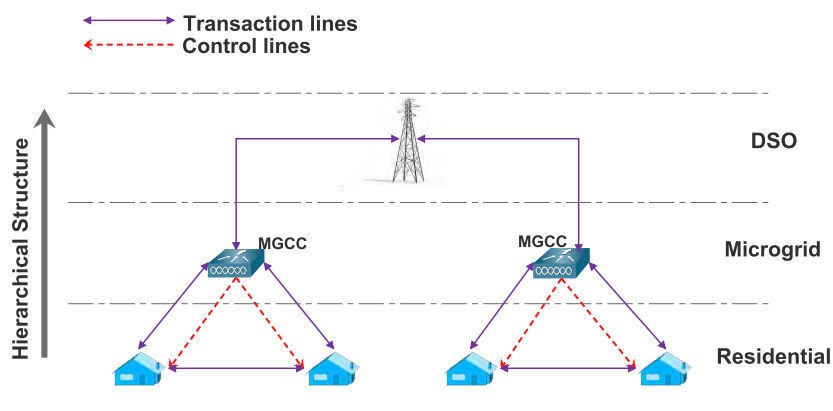

FIGURE 5. Decentralized Architecture: Control information originates from the different MGCC controllers.

Summarily, Figure 6 shows that decentralized and distributed architectures are typically similar except for the fact that all transacting parties are able to intercommunicate across all levels to trade energy in a distributed architecture. In some cases, the decision to control DERs and smart appliances in a distributed architecture may be actioned by local MASs situated at the residential level [46].

D. HIERARCHICAL ARCHITECTURE

A hierarchical architecture typically comprises multiple control and operation levels within a grid network. In this case, lower control levels are designed to report the status of their operational variables and other control parameters to some higher level of control. Such an interaction assumes a bidirectional communication link where lower levels report device information to upper levels and receive operational directives in return. Thus, it suffices to say that most centralized architectures are typically hierarchical in structure. Furthermore, decentralized and distributed architectures can be structured in a hierarchical manner as well. Consequently, a hierarchical architecture can be considered to be an overarching structure of all other architectures as indicated across Figures 4 - 6 (see the hierarchical line of direction within each figure). In terms of energy management, a thorough discussion can be found in [48]–[51], which discuss and propose different energy management schemes for use in TE-SG systems.

E. TRANSACTIVE MECHANISMS FOR THE DIFFERENT ARCHITECTURES

In terms of transactive mechanisms within the different architectures, peer-to-peer (P2P) as well as centralized trading (community-based market) schemes can be used. Essentially, P2P schemes, which are based on distributed ledge technologies can be used in a decentralized/distributed architecture, whereas central trading schemes would typically suffice for the centralized architecture. In the centralized architecture, parties can transact with each other in the islanded mode using a hierarchical scheme [13]. In this scheme, under the

TABLE 5. Centralized and Decentralized control Architecture [3].

Factors	Centralized Control	Decentralized Control
Goals	A clear single task	Uncertain tasks
Personnel	Available	Not available
Flexibility	Less	More
Plug-and-play	Not possible	Possible
Optimality	Optimal solutions	Suboptimal usually
Expansion	Difficult	Easy
Communication	High	Lower
Set-up Cost	High	Lower
Critical operation	Possible	Not possible
Failure occurs	If one point is faulty	If many points are faulty

island mode, an MGCC will typically receive all energy bids and offers from the different MG participants and then proceed to determine the market clearing price (MCP) to be used within the MG. In the grid-tied mode, the TEC-L3 controller will be responsible for receiving all energy bids from the participants within the SG network. During the process of determining the MCP, the MGCC or TEC-L3 controller will also ensure that all technical and operational constraints are satisfied. Once the MCP is determined, it will forward this price (as depicted by the control line) to all participants towards initiating energy transactions (as indicated by the transaction lines).

In the distributed/decentralized mechanism, the different MGCCs broadcast their initial energy prices to all participants in the network towards initiating a further bidding process. Then, they continue to update their respective energy prices and rebroadcast these prices to all participants until convergence is reached. Thus, convergence rate and optimal solutions are a key factor in determining the efficiency and effectiveness of distributed transactive mechanisms.

A notable study regarding the economic benefits of the P2P scheme on consumers and prosumers can be found in [52]. The authors discovered that TE trading between consumers and prosumers, using solar generation in Portugal, achieves economic gains of 28% for consumers and 55% for prosumers. In a different article in [13], we find a detailed
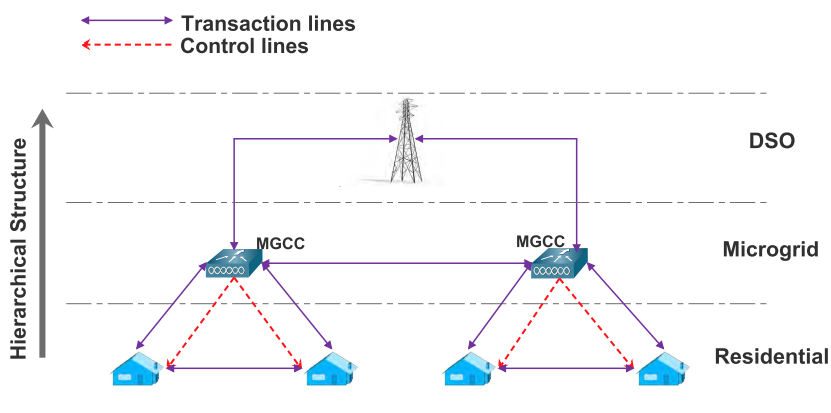

FIGURE 6. Distributed Architecture: Although control information originates from the different MGCC controllers, nevertheless transaction lines occur between all parties.

discussion of transactive mechanisms and their economic benefits. Following these articles, we mention specific methods associated with the P2P approach, which are suited for both decentralized and distribute architectures. In this regard, a P2P approach based on a multi-bilateral economic dispatch (MBED) formulation was proposed in [53]. The authors introduced a relaxed consensus plus innovation approach to solve the MBED problem in a fully decentralized manner. They showed that their proposal allows for more pro-active consumer behaviour such as favouring local power generation as well as the use of clean energy sources. A different approach termed the continuous double auction P2P market framework was proposed in [54]. Their approach allows prosumers to alternate between being sellers and buyers of energy. They argue that this approach makes it more attractive for people to invest in personal renewable energy generation. In [55], authors proposed a user-centric P2P energy trading mechanism for residential MGs. Their approach aims to maximize the profit of small-scale DERs while considering user convenience. There are other studies aimed at developing P2P transactive mechanisms, and these can be found in [4], [43], [56], [57].

Another class of TE market approaches is the hierarchical transactive mechanism, also referred to as the community-based market, which is designed for the centralized architecture [13]. In this case, different MGs would send their different prices to a centralized controller, which then determines the appropriate MCP. An example of this approach is the auction-based approach presented in [58]. Specifically, a joint energy storage ownership sharing scheme was developed between multiple facility controllers. Their aim was to enable prosumers decide on the appropriate fraction of their energy storage that they would want to share with the entire community. The authors showed that their proposed method possesses incentive compatibility and improves energy performance. A community-based electric power market with multi-agent simulation was studied in [59]. Authors assumed that the community shares a battery from which individual homes would obtain power. Centralized power management models were developed and transactions were conducted via the central controller. In another article, authors presented a novel energy exchange model and a trading agent for community energy market [60]. A central market system was designed with intelligent trading agents to ensure balance between supply and demand of energy. They showed that maximizing local energy transactions also maximizes the overall utility. Essentially, most community-based methods such as in [56], [61], [62] typically focus on developing effective ways to optimize the MCP to be used between participants to optimize the balance between the demand and supply of energy.

VI. TRANSACTIVE ENERGY: STATE-OF-THE-ART SIMULATORS

There are many research efforts aimed at studying and realizing TE in SG networks. However, many of these works are often realized, tested, and analysed via simulation platforms since at the moment, physical test-beds and real-time projects are extremely expensive to develop and execute. Furthermore, much software, individually developed, exists for studying TE methods in MGs/SGs since the objectives of an MG power market will typically vary from one case to another. Thus, it is often difficult to generalize all possible TE use cases into a single commercial software design. Consequently, this section discusses some notable state-of-the-art simulators (not in any order of importance) that can be used to design, test, and analyse TE systems. In addition to the simulators to be mentioned next, we note that a large collection of potential open source software for training, teaching, and research regarding an electricity market can be accessed via http://www2.econ.iastate.edu/tesfatsi/ElectricOSS.htm.

A. GridLAB-D

GridLAB-D is a power distribution system simulation software developed by the US Department of Energy at Pacific Northwest National Laboratory (PNNL) in collaboration with the industry and academia [63]. GridLAB-D is a robust simulator characterized by a number of interesting features, such as [63]:

- It provides models of several household equipment, which are implemented with contemporary agent-based approaches,
- It models a number of DERs such as load shedding, distributed generators and storage models,
- It provides modelling tools for retail markets, which allows for the deployment of tools such as SCADA control, choice of different contracts, and metering technologies,
- It enables the possibility to link up with other software such as MATLAB, Excel, and MySQL, and other notable text-based tools,
- It provides the capacity to execute the software on multicore and multiprocessor machines.

GridLAB-D provides for the behavioural study of DSO systems within predefined time periods ranging from a few seconds to decades, it helps to simulate how physical phenomena interact within a business system, as well as to study how consumers behave within markets and regional economics. It is capable of generating different power system statistics including reliability and business metrics.

GridLAB-D includes many tools such as:

- Tools for creating models that can evolve over time.
- Tools for creating and validating rate structures and how other technologies interact with wholesale markets.
- Tools that allow suitable interaction with industry-standard power system tools
- Tools for conducting different power system analyses.

It is noted that GridLAB-D is more likely to find problems with programs and business strategies than any other tool available [63]. Summarily, we consider GridLAB-D to be one of the most popular and versatile simulators for

designing, evaluating, and analysing power systems and TE solutions, as evidenced in the number of research articles that have used the software (see [24], [31], [33], [41], [43], [64]). Full details about GridLAB-D, its resources, downloads, projects, and help documentations can be accessed via https://www.gridlabd.org/index.stm.

B. MATPOWER

MATPOWER is an open-source MATLAB-based power system simulation package that provides high-level sets of power flow, optimal power flow (OPF), and other tools targeted at research and educational purposes [65]. It allows for auction markets based on OPF to be simulated and co-optimized with DERs, which makes it tenable for TE research purposes.

MATPOWER comprises a set of MATLAB M-files containing simple, understandable, and customizable codes for use. It provides functions that can be used to form standard network bus matrices, to calculate power transfer, line factors, and to efficiently compute the first and second derivatives of power flow formulas, among others. It is also extensible, which allows for the addition of user-defined variables, costs, and linear constraints.

While there are many MATLAB-based packages for simulating power systems, MATPOWER is distinguished as being one of the first open-source packages with an extensible architecture for OPF formulation, as well as its easy-to-use toolbox that can be incorporated into personal programs. It can also be used alongside Octave.

MATPOWER has found use in many research works, such as in [32] to calculate the distribution location marginal price via an AC (alternating current) OPF, which is essential for determining the price of energy amongst TE market players. Authors in [64] used MATPOWER to address simulation demands regarding bulk electric power system designs. In their work, MATPOWER was used to publish both the locational marginal price at a substation bus and the positive sequence three-phase voltage at the bus. Summarily, MATPOWER is suitable for modelling OPF-based electricity auction clearing mechanisms for small-sized markets. A version of the open-source MATLAB OPF solver and further detailed documentation of its different algorithms can be accessed via https://matpower.org/.

C. POWERWEB

POWERWEB is a web-based electric power market simulation package [65]. It is very much suited for the study of TE systems since it suffices as a tool for studying and evaluating the economic impacts and dependability of different market designs. POWERWEB can be used to characterize important physical network properties, while incorporating human decision makers within a market simulation environment.

Experiments in POWERWEB typically comprise a set of participants involved in running tests within a computer laboratory. A web-based interface allows experiments to be conducted without gathering all participants within a single physical space. Thus, owing to its web interface capability,

the only requirement is an internet-connected computer running a web browser without the need for any supplementary software.

POWERWEB uses a client-server architecture that deploys a web browser as the client to send requests to the POWERWEB server. Architectural details and examples of how to create new experiments can be found in [65]. It is based on open industry standard protocols such as MySQL, Apache, Perl, MATLAB, and MATLAB web server, thus making use of many well-developed open source platforms.

Summarily, POWERWEB is a cost effective option to analyse newly designed market rules and to steer market designs optimally to save social cost. It requires proper authorization to be used and when using POWERWEB for the first time, it is required to register to obtain a user ID and password for future access authorizations. Full details about how to access POWERWEB can be gleaned from the working manual available at https://pserc.wisc.edu/documents/publications/papers/1997_general_publications/PWebMan.pdf.

D. EnergyPlus

EnergyPlus^{TM} is a whole building energy simulation program for modelling both energy consumption and water use in buildings. Such energy-consuming appliances may include heating, cooling, ventilation, lighting, and plug and process loads. The development of the software was financed by the U.S. Department of Energy's (DOE) and thus freely downloadable.

Some of the notable features of EnergyPlus include, but are not restricted to the following:

- It solves thermal zone conditions in HVAC systems in an integrated and simultaneous manner.
- It provides sub-hourly, user-definable time steps for interaction between thermal zones and the environment.
- It comprises many built-in HVAC and lighting control strategies and scripts for running user-defined controls.

EnergyPlus has been used in a few research works, for example, authors in [61] used EnergyPlus and GridLAB-D to model a distribution system, particularly being able to model building loads such as PV panels and HVAC systems. Similarly, authors in [31] used EnergyPlus to simulate a building based on the DOE model for a small commercial office space located in Maryland, USA. EnergyPlus was used to study load schedules and other building metrics, which were then fed to GridLAB-D for onward use.

Essentially, EnergyPlus is a console-based program that populates text files via read and write operations. It boasts of graphical interfaces that can interact with OpenStudio and other suite of applications. EnergyPlus is an free cross-platform software that runs on Windows, Mac OS X, and Linux operating systems. Further details about EnergyPlus including downloads, documentation, support and training can be accessed via https://energyplus.net/.

E. POWERWORLD

PowerWorld is an interactive power system software that simulates high voltage operation on a time frame ranging from several minutes to several days. It is able to solve systems ranging up to 250000 buses [66]. In addition to a number of features such as an intuitive and user-friendly GUI, model explorer, interactive and animated diagrams, modelling capabilities, there are still other add-ons to the base simulator package such as OPF analysis tool, transient stability, integrated topology processing, and a host of other packages.

PowerWorld was used in [67] to solve a problem with regards to the optimal dispatch of power. It was used to design single-line diagrams, after which the impedance data and length of each line was read. DER bids were defined using the cubic cost model. Then, authors validated their optimal dispatch problem using MATLAB and showed that more powerful analytical and visualization solutions can be realized using PowerWorld over MATLAB. PowerWorld is most suited for the study of competitive MG power markets that contain inverter-interfaced DERs [67].

It is worth noting that PowerWorld is a commercial power system simulator, it is not cross platform, and it runs only on Microsoft Windows OS. Further details about the simulator, downloads, services, and online support can be accessed via https://www.powerworld.com/products/simulator/overview.

F. TRANSACTIVE ENERGY SIMULATION PLATFORM (TESP)

The Transactive Energy Simulation Platform (TESP) is a simulation platform that uses a framework for network co-simulation (FNCS) to enable time synchronized messages to be exchanged between other software modules [43]. It is an upgrade on the GridLAB-D simulator towards addressing a wider variety of use cases. It was developed by the PNNL and funded by the U.S. DOE specifically to simulate transactive system approaches.

TESP has different simulation modules federated within a single framework. For example, it adopts GridLAB-D for the design of electric power distribution feeder and residential buildings [24]; it also integrates PYPOWER, MATPOWER/MOST and AMES to cover TSO designs. It deploys OpenDSS as an alternative program that can be used for realizing distribution power flow designs. It also uses EnergyPlus, which can be used to model large commercial buildings. It adopts network simulator 3 (ns-3) as its communication system simulator to host software agents. TESP consists of an integrating message bus that uses either a Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) or FNCS to manage time step synchronization and exchange of messages amongst all its federated simulation modules [68]. Consequently, it is worth noting that TESP is built upon well proven components, thus mitigating the risk in software development. More technical details about TESP can be found at https://tesp.readthedocs.io/en/latest/TESP_Overview.html.

Research-wise, authors in [61] have improved upon TESP towards studying security scenarios under different cyber-attack use-cases. Specifically, they integrated TESP with ns-3 towards creating stable communication channels between prosumers with an aim to simulate cyber-attacks. Consequently, they were able to introduce a TE system (TES) test-bed that can simulate the operation of both centralized and decentralized TES platforms. In another article, TESP was used in a co-simulation framework with the Hyper ledger Fabric software to simulate the integration of blockchain networks to coordinate MG markets [43]. Therein, agents were developed using Python and communicated with blockchain networks through application programming interface (API) calls. Consequently, they were able to demonstrate the advantages of introducing blockchain models in TES.

Summarily, the TESP software can be said to have achieved the following objectives:

- Integrate separate TE agents that can encapsulate the behaviour of different market mechanisms and participants.
- Implement an open-source platform that works on Windows, Linux, and Mac operating system (OS).
- Define a growth model for multi-year TE simulations.

The source code, design documents, and examples for TESP can be accessed with minimal restrictive open-source license terms via https://github.com/pnnl/tesp/.

G. RIAPS AND TRANSAX

Resilient Information Architecture Platform for Smart Systems (RIAPS) is a component-based decentralized software platform developed to provide a software foundation for building distributed applications [69]. It depends on an underlying OS that comprises two major components: a component framework and a suite of platform managers. The component framework comprises software libraries that are linked dynamically to the different components of the application, while the platform managers are specific OS processes with daemons implemented in Linux systems. Thus, RIAPS is not a cross-platform-based software. It is funded in part by the U.S. DOE and greater details about RIAPS can be accessed via https://riaps.isis.vanderbilt.edu/redmine/projects/riaps.

A number of authors have used RIAPS in their research works. For example, authors in [70], [71] proposed a distributed control algorithm for the optimal consumption of apparent power in islanded MGs. Their algorithm was implemented in RIAPS and validated on a real-time MG test-bed. In a different article, a demo to implement TE systems was realized using RIAPS [72], while a similar demo was documented in a separate article for edge computing purposes using RIAPS [73].

An important extension to RIAPS is the TRANSAX software platform built for studying blockchain-based decentralized energy exchanges in TE MGs [74]. TRANSAX is a transactive decentralized platform built over RIAPS, wherein RIAPs is used to isolate the details of any embedded hardware

from its underlying algorithms as well as to provide useful mechanisms to manage resources, tolerate faults, and guarantee security [74]. TRANSAX enables the capacity to simulate distributed ledger and smart contracts to achieve consensus and trust in TE systems. Although not readily available for download and use at the moment (to our best knowledge), nevertheless, greater technical details about TRANSAX can be accessed in [74].

H. PSAT

The power system analysis toolbox (PSAT) is an open source MATLAB and GNU/Octave-based software package for the analysis and design of small to medium size electric power systems [75]. PSAT provides a many easy-to-use graphical interfaces in addition to a Simulink-based editor for constructing one-line network diagrams. It is noted that PSAT is not originally designed to cater for TE systems since market transaction features are typically non-available within the software. However, it is mention here as a potential software capable of integrating TE mechanisms to compliment its already well-established power system functionalities.

There are many other power system tools that have been developed in MATLAB for commercial, research, and educational purposes, however, only MATPOWER and PSAT are open source and freely downloadable. PSAT is made to run on GNU/Octave, which is a free MATLAB clone. PSAT can be downloaded via http://faraday1.ucd.ie/psat.html.

Since most TE approaches are expected to run and interact with existing power grid systems, it is thus essential to mention typical power system tools. Such tools should be able to analyse power system parameters such as power flow (PF), continuation power flow (CPF) and/or voltage stability analysis (CPF-VS), optimal power flow (OPF), small-signal stability analysis (SSA), time-domain simulation (TDS), and electromagnetic transients (EMT). A number of power system simulation packages have been compared in [75] with regards to the above-mentioned parameters along with "aesthetic" features such as having a graphical user interface (GUI) and a graphical network editor (GNE). A summary of the comparison made in [75] is provided here in Table 6 for completeness, where the packages compared include Power System Toolbox (PST) [76], MATPOWER, Voltage Stability Toolbox (VST) [76], MatEMTP [77], SimPowerSystems (SPS) [78], Power Analysis Toolbox (PAT) [79], and Educational Simulation Tool (EST) [80]. Researchers involved in the integration of power systems in TE will find the comparison of Table 6 worthwhile towards the choice of a suitable power analysis software package. In addition, we have provided in Table 7 a qualitative comparison of the TE simulators discussed in this section. Essentially, there are still a number of research gaps and key requirements to be considered towards the development of TE controller, for which a few will be discussed in the next section.

TABLE 6. MATLAB-based packages for power system analysis [75].

Package	PF	CPF	OPF	SSA	TDS	EMT	GUI	GNE
EST	✓	×	×	✓	✓	×	×	✓
MatEMTP	×	×	×	×	✓	✓	✓	✓
MATPOWER	✓	×	✓	×	×	×	×	×
PAT	✓	×	×	✓	✓	×	×	✓
PSAT	✓	✓	✓	✓	✓	×	✓	✓
PST	✓	✓	×	✓	✓	×	×	×
SPS	✓	×	×	✓	✓	✓	✓	✓
VST	✓	✓	×	✓	✓	×	✓	×

VII. KEY CONSIDERATIONS TOWARDS IMPLEMENTING TRANSACTIVE ENERGY CONTROLLERS

As noted in the preceding sections, TE controllers can be deployed at the different levels of an SG network. However, for practical purposes, a decentralized approach suffices since it supports a simple bi-level control structure, where controllers are needed only at the residential and MG levels. Essentially, a microgrid controller needs to measure the demands, generation rates, and status of each MG asset at various locations across the MG network. Thus, this requires knowledge of the following:

1) Modelling and realization of the power network comprising the smart DERs, loads, and storage devices.
2) Communication network to carry data, required commands and information across the various resources.
3) A TE controller capable of interacting with the operators and the smart DERs, loads, and storage devices.
4) A transacting market framework that optimizes the economic costs of running the network subject to the technical constraints of guaranteeing the reliability of an SG network.

Thus, in order to achieve the above requirements, first, a local controller (TEC-L1 controller) needs to be developed at level 1 (within residential buildings). Such a control needs to possess automation engines and control functions that can apply different commands to DERs and control their parameters at the desired level. Next, a supervisory controller (more like an MGCC at level 2) will be required to maintain optimal energy dispatch to the main grid, while ensuring that reserve margins are maintained in the event of DER failure. An MGCC, being a transactive controller, must determine the MCP via well established market transaction policies. We now discuss these different level controllers and provide a high level summary of their requirements as follows:

A. LOCAL (TEC-L1) CONTROLLER

A TEC-L1 controller will require both hardware and software components to receive signals from an external transducer embedded in DERs, loads, and storage systems. Such signals will then be converted to some digital format for use as required. Thus, relevant converters must be identified for analogue/digital conversion purposes. A local controller must

TABLE 7. Characteristics of different simulators for TE power system design, development, and analysis.

Simulators	Open Source	Web based	Stand-alone Installer	Comprises Multiple Simulators	Cross platform	Power System Analysis	Economic Market Analysis	User Manual
GridLAB-D	✓	✕	✓	✕	✓	✓	✓	✓
MATPOWER	✓	✕	✓	✕	✓	✓	✕	✓
POWERWEB	✓	✓	✕	✕	✓	✓	✓	✓
EnergyPlus	✓	✕	✓	✕	✓	✓	✕	✓
PowerWorld	✕	✕	✓	✕	✕	✓	✕	✓
TESP	✓	✕	✓	✓	✓	✓	✓	✓
RIAPS	✓	✕	✓	✕	✕	✓	✕	✓
PSAT	✓	✕	✓	✕	✕	✓	✕	✓

be programmed based on the DER characteristics. Thus, the specific DERs to be controlled must be identified and suitably programmed. A number of specific control functions will also be required such as proportional integral derivative (PID) controllers, which can be used to control the generating power of generators as well as other specific DERs. Other control mechanisms will need to explored such as rate controllers, pulse width modulators, towards identifying how such local TEC-L1 controllers will be built.

B. THE COMMUNICATION COMPONENT

It is most probable that DERs, loads, smart appliances, and storage systems will be situated at different locations across an MG. Consequently, the most suitable communication mode will be wireless communication since it suffices in terms of topography, reliability, cost, and ease of installation. Owing to the high cost of deploying a physical testbed, an emulation platform may be required, which can be interfaced with well known power grid simulators to test and evaluate TE systems. The concept of fog computing may also be leveraged to ease the computing needs of such TE controllers. In this regard, the best wireless communication technologies that can be explored may include Zigbee, Wifi, and low power wide area network brands such as Sigfox and LoRa technologies. Other technological advances in communication networks, such as the use of cognitive radio, can be introduced in future technologies to improve bandwidth utilization and spectra efficiency [81], [82]. A number of desirable characteristics such as data rate, reliability, and latency will need to be considered and studied towards choosing a suitable and reliable wireless communication technology for use in a TE controller.

C. MICROGRID CENTRAL CONTROLLER

An MGCC (i.e. TEC-L2 controller) will be required to connect local TEC-L1 controllers to a larger MG communication system. Such an MGCC will be expected to monitor all MG assets via local controller, which entails monitoring the status of each asset and the load demands and generation of the DERs. It will also be equipped with an optimization model that will determine the optimal contribution of each generation/storage device and the power imported/exported to and from the SG over time. Such an optimization framework will need to be developed and adopted towards the successful design of an MGCC.

VIII. FUTURE RESEARCH DIRECTIONS

It is widely accepted that SG is the future of the power grid system and TE will play a major role in the success of SG systems. Consequently, a number of tools are required to help design useful TE systems and researchers are at the forefront of developing such tools. Furthermore, researchers are expected to instil confidence in those who are responsible for applying and regulating these systems. Thus, innovative TE systems must be improved upon by testing them first in simulation environments, then in pilot studies before being deployed in real life.

There are a number of technical challenges that must be addressed towards the successful realization and deployment of TE systems, and a few of such challenges are listed as follows:

1) **Simulators**: There is a lot to be desired in terms of the availability of robust simulation tools for TE studies. It is clear that no single simulator has all the requirements for modelling, designing, evaluating, and analysing TE systems in SG networks. Consequently, more robust tools are required to address practical challenges such as implementation costs, device and communication failures, network assets response time, physical and cyber attacks, and other technical conditions involving voltage and frequency stability.

2) **Fault tolerance**: There are other issues identified in [83] concerning TE control such as increasing the speed of financial transactions and guaranteeing resiliency to failures.

3) **Communication**: There are questions to be resolved regarding the best communication technologies to be deployed in TE systems. Since the entire TE-based SG networks will comprise communicating nodes, issues of latency, data rate, and reliability of communication technologies and channels must be considered in the design process. Concepts such as cognitive radio can be leveraged to address some of these challenges [84], [85].

4) **Computing resources**: The role of fog computing comes to the fore in the context of TE systems. In particular, the need for distributed computing systems to be situated ubiquitously throughout SG and MG networks calls for greater research efforts in developing and testing fog computing architectures and systems.

5) **Secured transaction**: A number of studies are ongoing with regards to the feasibility of deploying blockchain technologies and smart contracts in TE systems. These solutions are particularly interesting towards solving many security and reneging problems that may arise in the wake of peer-to-peer interactions in TE-based networks. Other methods can be explored to improve the security and privacy status of TE systems.

6) **Evaluation metrics**: A robust array of evaluation metrics are yet to be implemented in many simulation software platforms. For example, the PNNL has noted that a number of suitable metrics may be formulated and tested in future software releases, such as the number of iterations consumed by many TE-based iterative algorithms, the communication delay, communication drops, load forecast error (particularly in predictive-based TE controllers).

7) **Distributed systems**: Most research efforts are focused on hierarchical architecture of TE control schemes, however, much is left to be studied concerning distributed systems, such as how distributed dispatch and control systems of responsive assets will affect grid stability in islanding conditions, as well as convergence issues between independent and transacting parties.

8) **Validation test-beds**: Validation of TE control schemes, particularly either under real-life conditions or within emulation test-beds is of utmost importance to the success of TE systems. Presently, many assumptions are being made in the modelling phase of TE systems, which may in turn pose significant problems under real-life deployment conditions.

9) **Cyber security issues**: There have been a number of recent cyberattacks on power grids, for example, the Ukrainian power grid was successfully attacked in 2015 [86]. This attack and many others have raised several concerns about the vulnerability of smart grid systems, thus warranting the need for more robust and effective solutions. In this regard, a number of solutions have been proposed, such as the notable remedial action scheme based on thyristor controlled series capacitors (TCSCs) introduced in [87]. Here, authors proposed a three-level framework, which includes the optimal location of TCSCs in the first phase, injection of false data into the system in the second phase, and the use of remedial action in the third phase. Their study concluded that the RAS-based TCSC solution can successfully alleviate targeted congestions caused by cyberattacks. In a different article, the case of cyberattacks against phasor measurement units (PMU) during an event was analysed [88]. The authors developed an optimization-based attack identification method and demonstrated that the method was robust to cases of inaccuracies under pseudo-measurement and line impedance conditions. A notable study was conducted based on a hardware-in-the-loop (HIL) test bed developed to study and analyse cyberattacks and their impacts on MGs [89]. The authors concluded that the simulated MG would lose its resilience to cyberattacks assuming the actual components in the loop where considered in the study and they would retain their resilience if the physical components were not considered. Such an observation further emphasizes the need for more extensive studies regarding the effects and modelling of cyberattacks in SG systems. There are yet many other recent solutions proposed to mitigate cyberattacks in SG systems, such as in [90]–[94], however, with the relative recent introduction of TE systems, there is need for improved solutions particularly along transactive lines. Further studies and innovative developments along multi-level TE control mechanisms will be required towards obtaining a more holistic picture of the benefits and characteristics of transactive approaches.

IX. CONCLUSION

This article has provided a general discussion of transactive energy (TE) with specific focus on TE control strategies, architectures, as well as on the state-of-the-art simulators available for the design, evaluation, and analyses of TE systems. The concept of TE control strategies and controllers was reviewed via a hierarchical structure comprising four broad levels wherein TE strategies/controllers can be deployed. Such a structure includes the lowest level (being level 1) situated at the residential/complex building environment, followed upwards by the microgrid level (level 2), distribution (level 3), and transmission system operator (level 4) control levels. These hierarchical levels present a more organized and centralized approach for deploying and managing TE systems across an entire SG network. Nevertheless, we have noted that distributed architectures are gaining greater attention from the industry and academia, thus increasing the potential for valuable research outputs in this regard. We have also discussed different types of TE architectures such as the centralized, decentralized, distributed, and hierarchical architecture. We highlighted the different characteristics of each architecture based upon how an MG would typically interact with a main grid. Essentially, we have noted that the centralized architecture sends control information only from a single management point. However, in a decentralized architecture, control information may originate from an MGCC. It was also noted that distributed architectures are simply extensions of decentralized models, with the difference being the capability for all participating parties in a distributed architecture to communicate and transact in a peer-to-peer manner. The choice of any architecture depends on the specific goal(s) and design demands

of a grid project. A few notable state-of-the-art simulators available for studying TE systems were also discussed. These simulators were discussed and notable research works for TE purposes were mentioned. While each of these simulators may be limited across different specific characteristics of interests, nevertheless, we have noted that the Transactive Energy Simulation Platform (TESP) software suffices as a notable stride in the development of robust TE simulation packages. It is a combination of different simulators, thus emphasizing its robustness as compared to other simulators in the market. Finally, we concluded this article with a number of specific future research areas where effort may be required towards guaranteeing the effective and efficient deployment of TE systems in SG networks.

APPENDIX
THE FOLLOWING ABBREVIATIONS WERE USED IN THIS ARTICLE

Abbreviation	Meaning
ACL	Air Conditioning Load
API	Application Programming Interface
BTO	Building Technologies Building
CPF	Continuation Power Flow
DOE	Department of Energy
DER	Distributed Energy Resources
DLMP	Distribution Locational Marginal Price
DLT	Distributed Ledger Technology
DSO	Distribution System Operator
eIOT	Energy Internet of Things
EMS	Energy Management System
EMT	Electromagnetic Transients
EST	Educational Simulation Tool
EV	Electric Vehicle
FNCS	Framework For Network Co-Simulation
GNE	Graphical Network Editor
GWAC	GridWise Architecture Council
GUI	Graphical User Interface
HELIC	Hierarchical Engine for Large-scale Infrastructure Co-simulation
HVAC	Heating, Ventilation Air Conditioning
HEMS	Home Energy Management Systems
ITD	Integrated Transmission and Distribution
IoT	Internet of Things
MAS	Multi-agent System
MCP	Market Clearing Price
MG	Microgrids
MGCC	Micro Grid Central Controller
MPC	Model Predictive Control
NREL	National Renewable Energy Laboratory
NS	Network Simulator
OPF	Optimal Power Flow
PF	Power Factor
PID	Proportional Integral Derivative
PNNL	Pacific Northwest National Laboratory
PSAT	Power System Analysis Toolbox
PST	Power System Toolbox
RIAPS	Resilient Information Architecture Platform for Smart Systems
SCADA	Supervisory Control and Data Acquisition
S-DTEM	Secure Distributed Transactive Energy Management
SG	Smart Grid
SPS	SimPower System
SSA	Small Signal Stability Analysis
TCL	Thermostatically Controller Loads
TDS	Time Domain Simulation
TE	Transactive Energy
TEC	Transactive Energy Controller
TES	Transactive Energy System
TESP	Transactive Energy Simulation Platform
TSO	Transmission System Operator
VST	Voltage Stability Toolbox
VPP	Virtual Power Plant

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ADEIZA J. ONUMANYI (Member, IEEE) received the B.Eng. degree in electrical and electronics engineering from Abubakar Tafawa Balewa University, Bauchi, Nigeria, in 2005, and the M.Eng. and Ph.D. degrees in communication engineering from the Federal University of Technology (FUT) Minna, Nigeria, in 2010 and 2014, respectively. He lectured and conducted research at the Department of Telecommunication Engineering, FUT Minna, from 2010 to 2021, during which he served as a Postdoctoral Fellow at the University of Pretoria, South Africa, from 2018 to 2019. He is currently conducting his research at the Council for Scientific and Industrial Research (CSIR), Pretoria. He has won several grants at FUT Minna. He has participated in different technical workshops. He has published several research articles in different peer-reviewed journals and IEEE flagship conferences. His research interests include spectrum sensing in cognitive radio, wireless sensor networks, smart grid, transactive energy, radar systems, image processing, and low powered wireless area networks. He has served on several organizing committees for different conferences, including IEEE conferences. He reviewed several articles for high impact journals.

SHERRIN J. ISAAC (Member, IEEE) was born in Ethiopia, in 1967. He received the B.Eng. degree in electronics and telecommunications and the M.Eng. degree in electrical degree from the University of Zambia, Lusaka, Zambia, in 1988 and 1994, respectively, and the M.B.A. degree from the University of Pretoria, Pretoria, South Africa, in 2006. In 1989, he joined the University of Zambia as a Project Engineer. Since 1998, he has been with the Council for Scientific and Industrial Research (CSIR), Pretoria, where he is currently a Research Group Leader in advanced Internet of Things. He is also a Professional Engineer in South Africa. His current research interests include cyber-physical systems for smart infrastructure with respect to the Internet of Things, security, distributed embedded artificial intelligence, and real-time control, operations, and maintenance.

CAREL P. KRUGER received the dual B.Eng. degrees (Hons.) from the University of Pretoria, in 2012 and 2015. In 2012, he joined the Council for Scientific and Industrial Research (CSIR), South Africa. He is currently a Senior Research and a Development Engineer at the Advanced Internet of Things Research Group (AIOT), CSIR, and specializes in embedded hardware and software development and systems engineering for Internet of Things (IOT) applications. His research interests include wireless sensor networks, cyber-physical systems, and smart grid control algorithms.

ADNAN M. ABU-MAHFOUZ (Senior Member, IEEE) received the M.Eng. and Ph.D. degrees in computer engineering from the University of Pretoria. He is currently the Centre Manager of the Emerging Digital Technologies for 4IR (EDT4IR) Research Centre, Council for Scientific and Industrial Research (CSIR), an Extraordinary Professor at the University of Pretoria and Tshwane University of Technology, and a Visiting Professor at the University of Johannesburg. He is also the founder of the smart networks collaboration initiative that aims to develop efficient and secure networks for the future smart systems, such as smart cities, smart grid, and smart water grid. He has participated in the formulation of many large and multi-disciplinary research and development successful proposals (as a principal investigator or main author/contributor). His research interests include wireless sensor and actuator networks, low power wide area networks, software-defined wireless sensor networks, cognitive radio, network security, network management, and sensor/actuator node development. He is a member of many IEEE Technical Communities. He is also an Associate Editor of IEEE ACCESS, IEEE INTERNET OF THINGS JOURNAL, and IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS.

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