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State of the Art in Research on Microgrids: A Review

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ABSTRACT The significant benefits associated with microgrids have led to vast efforts to expand their penetration in electric power systems. Although their deployment is rapidly growing, there are still many challenges to efficiently design, control, and operate microgrids when connected to the grid, and also when in islanded mode, where extensive research activities are underway to tackle these issues. It is necessary to have an across-the-board view of the microgrid integration in power systems. This paper presents a review of issues concerning microgrids and provides an account of research in areas related to microgrids, including distributed generation, microgrid value propositions, applications of power electronics, economic issues, microgrid operation and control, microgrid clusters, and protection and communications issues.

INDEX TERMS Microgrids, distributed generation, economics, operation and control, protection, communications.

NOMENCLATURE

DER	Distributed energy resource.
DG	Distributed generation unit.
DR	Demand response.
DSM	Demand side management.
EMS	Energy management system.
ESS	Energy storage system.
GA	Genetic algorithm.
MAS	Multi-agent system.
MILP	Mixed integer linear programming.
OPF	Optimal power flow.
PCC	Point of common coupling.
PHEV	Plug-in hybrid electric vehicle.
PSO	Particle swarm optimization.
PV	Photovoltaic.
STATCOM	Static synchronous compensator.
T&D	Transmission and Distribution.
UPS	Uninterruptible power supply.
VSC	Voltage source converter.

I. INTRODUCTION TO MICROGRIDS

The MICROGRID, as defined by the U.S. Department of Energy, is ‘‘a group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes’’ [1]. Based on this definition, DER installations could be considered as a microgrid if comprised of three distinct characteristics: they must have electrical boundaries that are clearly defined, there must exist a master controller to control and operate DERs and loads as a single controllable entity, and the installed generation capacity must exceed the peak critical load thus it could be disconnected from the utility grid, i.e., the islanded mode, and seamlessly supply local critical loads. These characteristics further present microgrids as small-scale power systems with the ability of self-supply and islanding which could generate, distribute, and regulate the flow of electricity to local customers. Microgrids are more than just backup generation. Backup generation units have existed for quite some time to provide a temporary supply of electricity to local loads when the supply of electricity from the utility grid is interrupted. Microgrids, however, provide a wider range of benefits and are significantly more flexible than backup generation.

The concept of microgrids dates back to 1882 when Thomas Edison built his first power plant. Edison's company installed 50 DC microgrids in four years. At that time centrally controlled and operated utility grids were not yet formed. With the utility grid subsequently utilizing large centralized power plants which benefited from the economies of scale, and significantly increasing transmission connections for reliability purposes, the electric grid turned into a monopolistic utility by connecting isolated microgrids, and these microgrids faded away. There is a new wave in recent years, however, to deploy microgrids which is driven in part by the need for higher reliability and power quality, advancements in power electronics and DER technologies, and a more engaging generation of electricity consumers [2].

The main microgrid components include loads, DERs, master controller, smart switches, protective devices, as well as communication, control and automation systems. Microgrid loads are commonly categorized into two types: fixed and flexible (also known as adjustable or responsive). Fixed loads cannot be altered and must be satisfied under normal operating conditions while flexible loads are responsive to controlling signals. Flexible loads could be curtailed (i.e., curtailable loads) or deferred (i.e., shiftable loads) in response to economic incentives or islanding requirements. DERs consist of distributed generation units (DG) and distributed energy storage systems (ESS) which could be installed at electric utility facilities and/or electricity consumers' premises. Microgrid DGs are either dispatchable or nondispatchable. Dispatchable units can be controlled by the microgrid master controller and are subject to technical constraints depending on the type of unit, such as capacity limits, ramping limits, minimum on/off time limits, and fuel and emission limits. Nondispatchable units, on the contrary, cannot be controlled by the microgrid master controller since the input source is uncontrollable. Nondispatchable units are mainly renewable DGs, typically solar and wind, which produce a volatile and intermittent output power. The intermittency indicates that the generation is not always available and the volatility indicates that the generation is fluctuating in different time scales. These characteristics negatively impact the nondispatchable unit generation and increase the forecast error, therefore these units are commonly reinforced with ESS. The primary application of ESS is to coordinate with DGs to guarantee the microgrid generation adequacy. They can also be used for energy arbitrage, where the stored energy at low price hours is generated back to the microgrid when the market price is high. The ESS also plays a major role in microgrid islanding applications. Smart switches and protective devices manage the connection between DERs and loads in the microgrid by connecting/disconnecting line flows. When there is a fault in part of the microgrid, smart switches and protective devices disconnect the problem area and reroute the power, preventing the fault from propagating in the microgrid. The switch at the point of common coupling (PCC) performs microgrid islanding by disconnecting the microgrid from the utility grid. The microgrid scheduling in interconnected and islanded modes is performed by the microgrid master controller based on economic and security considerations. The master controller determines the microgrid interaction with the utility grid, the decision to switch between interconnected and islanded modes, and optimal operation of local resources. Communications, control, and automation systems are also used to implement these control actions and to ensure constant, effective, and reliable interaction among microgrid components.

Microgrids offer significant benefits for the customers and the utility grid as a whole: improved reliability by introducing self-healing at the local distribution network; higher power quality by managing local loads; reduction in carbon emission by the diversification of energy sources; economic operation by reducing transmission and distribution (T&D) costs; utilization of less costly renewable DGs; and offering energy efficiency by responding to real-time market prices. The islanding capability is the most salient feature of a microgrid, which is enabled by using switches at the PCC, and allows the microgrid to be disconnected from the utility grid in case of upstream disturbances or voltage fluctuations. During utility grid disturbances, the microgrid is transferred from the grid-connected to the islanded mode and a reliable and uninterrupted supply of consumer loads is offered by local DERs. The islanded microgrid would be resynchronized with the utility grid once the disturbance is removed [3], [4].

The installed microgrid capacity is estimated to grow from the 1.1 GW in 2012 to 4.7 GW in 2017 with an estimated market opportunity of $17.3 billion [5]. Considering the growing interest in microgrid deployment, the research on microgrids has significantly increased over the past few years. This paper presents a review on different aspects of microgrid research, ranging from DER technologies to microgrid communications, with the primary objective of providing insight on current trends and directions in microgrid research and further identifying areas in need of further investigation.

The rest of the paper is organized as follows: Section II focuses on microgrid DERs and reviews a variety of issues associated with renewable DGs as well as ESS deployment in microgrids. Section III discusses microgrid applications to support grid performance, with a focus on improving grid reliability, resiliency, and power quality. Section IV reviews the application of power electronics in microgrids as the integration of DERs necessitates a broader application of power electronics. Section V focuses on microgrid economics and provides a detailed review of current literature on related issues such as microgrid scheduling, demand side management (DSM), market pricing, and optimal planning. Section VI focuses on microgrid operation, control, and islanding, covering the existing literature on microgrid control methodologies and architectures as well as control of tie-line power, power electronic converters, uninterruptible power supply (UPS) systems and resynchronization of microgrids. Section VII reviews microgrid clusters in which two or more electrically coupled microgrids are controlled and operated in a coordinated fashion. Section VIII reviews microgrid protection, which includes the modeling of faults in microgrids, protection of power-electronically coupled microgrids, and protection schemes based on microprocessors and communications, protection of DC microgrids, and fault current limiters. Section IX discusses the issues related to microgrid communications necessary to achieve microgrid efficient protection and control, while Section X concludes the paper. To make the discussions consistent in the paper, a single representation of concepts/definitions has been used that can appear in different forms in different papers. For example, the utility grid is used instead of different variations of the larger grid to which the microgrid is connected, covering the main grid, macrogrid, and main power system.

II. DISTRIBUTED ENERGY RESOURCE TECHNOLOGIES FOR MICROGRIDS

DERs are small-scale energy resources which could be placed at utility facilities or at customers' premises to provide a local supply of electricity. DERs could potentially result in a significant change in traditional methods of energy generation, in which electricity is generated in large-scale centralized power plants and is transmitted over long distances by high voltage transmission lines to reach load areas. DER technology can further provide power to remote locations where required T&D facilities are not available or are costly to build. Moreover, DERs offer a low construction and deployment time compared to large generators and T&D facilities. A comprehensive review on DERs and current practices in microgrids as well as the interaction problems arising from the integration of various DERs in a microgrid can be found in [6] and [7], respectively. As discussed in detail in [8], DERs include a variety of technologies. Two common and widely-used DERs, which are considered in this section, are renewable DGs and ESSs. There has been an increasing emphasis on the utilization of renewable DGs, such as wind and solar energy resources, in recent years. The main drivers for this trend include the clean and sustainable nature of such resources compared to the polluting and limited fossil fuels that have traditionally been used to generate power. State and governmental mandates, that push for a broader integration of renewable energies and enforce the environmental agenda to mitigate greenhouse gasses generated by the exhaustion of fossil fuels and combat climate change, are also among factors resulting in increased renewable energy proliferation. Renewable DGs are commonly dependent on meteorological factors. This makes these resources highly unpredictable and creates vast volatilities in their power generation. This variability is one of the challenges that needs to be overcome in order to allow for broad integration of renewable energy. Sunlight is the origin of most of renewable DGs either directly, such as solar energy, or indirectly, such as wind, hydroelectric, and biomass energies. Sunlight is directly converted to solar energy using solar panels. Wind and hydroelectric power are the result of differential heating of the earth's surface. Biomass energy is the sunlight energy stored in plants. There are also some other types of energy not driven by the sun such as geothermal energy, whose origin is the internal heat in the Earth, and the energy of the oceans' waves, which comes from tides and winds. Renewable DGs offer several benefits including sustainability, being emission free, and benefiting from an almost ubiquitous primary source of energy [9], [10]. As detailed in [11], there are numerous policies and regulations applied by various states within the U.S. to support investments on renewable DGs, such as renewable portfolio standards, public benefit funds for renewable energy, output-based environmental regulations, interconnection standards, net metering, feed-in tariffs, property assessed clean energy, and financial incentives. Based on renewable portfolio standards, all electric providers should provide a specific amount of electric power using renewable DGs. Public benefit funds are obtained by levying small taxes on electricity rates. Output-based environmental regulations ordain emission limits in order to encourage electric producers to increase efficiency and control air pollution. Interconnection standards are technical requirements which should be met by electricity providers that want to connect renewable DGs to the grid. These standards determine how electric utilities in a state would treat renewable DGs. Net metering rules are used to compensate the power generation for prosumers; if the local power generated by a customer is more than its load, the excess power would be sold to the utility grid, and on the other hand, if the generated power is not sufficient to supply loads, they would use electricity from the utility grid. This procedure requires accurate metering of the electricity demanded by consumers. Feed-in tariff is a policy for encouraging renewable energy development which requires electric utilities to make long-term payments for the power fed by renewable energy developers into the grid. The payments may comprise both the electricity sales and payments for renewable energy certificates. Feed-in tariff policies can be cost-efficient to allow a rapid development of renewable DGs, thus, would be beneficial for electricity consumers, renewable energy developers, and the whole society. Implementing feed-in tariffs has been a successful experience to meet economic development and renewable energy targets around the world. Based on the property assessed clean energy policy, the cost of renewable energy installations or increasing energy efficiency is refunded to residential properties instead of individual borrowers. As a result, property owners would be encouraged to invest in renewable energy improvements. Other financial incentives including grants, loans, rebates, and tax credits are offered in some states within the U.S. to encourage the development of renewable energy.

The application of renewable DGs in microgrids is one of the extensively studied topics in the literature. A microgrid that utilizes controllable prime movers, such as gas engines, to compensate fluctuating demand and output of renewable energy is presented in [12]. In [13], a building integrated photovoltaic (PV) for urban areas is proposed that can run in isolation from the utility grid while being connected to the grid at all times. In [14], a simulation framework utilizing sequential Monte Carlo simulations is developed to investigate the performance of autonomous microgrids that have the ability to interconnect to achieve adequate load service and shows the sensitivity of a small microgrid assembly to large amounts of wind generation, which can have a significant negative impact on its reliability. The paper concludes that to mitigate the effects of the high variability in the power output of the wind turbines, much greater amounts of storage, aggregate wind generation, or both are needed. In [15], the challenges facing the operation of intermittent power sources, such as wind power, in capacity-limited microgrids are discussed. A wind plant pitch angle controller and a rotor speed controller are introduced for wind power plant active power adjustment to help with frequency regulation. The use of static synchronous compensator (STATCOM) is further discussed for stabilizing the microgrid voltage during short circuit faults. In [16], the planning of micro hydro power plants and micro wind power turbines into mountainous regions with weak natural energy is discussed. The discussions indicate that regions with relatively weak natural energy may be developed by applying the microgrid with possible compensation between micro-sources. The study in [17] examines the feasibility of applying a micro hydro power generation system in a microgrid as part of the various regional energy programs underway in Africa. It also points to R&D advancements in various technologies focused on energy sustainability and suggests that micro hydro power generation systems integrated even at microgrid powered levels have potential to provide an efficiency of service to rural communities and can serve as primary building blocks for future system expansion.

Solar energy applications in microgrids are also studied in several publications, with the primary objective of enhancing solar energy generation by maximum power point tracking. At any level of solar radiation, there is a unique point on the current-voltage characteristic of the solar cells at which they generate maximum power. Maximum power point tracking controls solar cells to generate power at this point. In [18], a fuzzy-logic controller is used for maximum power point tracking of PV systems and implemented by fuzzifying the rules of hill-climbing search methods to reduce its drawbacks. In [19], a survey of perturb and observe techniques is presented which shows that existing techniques suffer from oscillations, complexity, designer dependency, and high computational load. It further presents a modified perturb and observe maximum power point tracking technique and shows that high-performance steady-state operation can be achieved with no oscillations around the maximum power point using the proposed technique. The study in [20] uses neural network to estimate the optimal tilt angle at a given location and thus an estimate of the amount of energy available from the PV in a microgrid. It is demonstrated that the neural network is able to estimate the optimum tilt angle with an accuracy of 3° and the optimized irradiation at the microgrid with negligible error. The study in [21] shows that including a diverse set of renewable energy generation technologies and optimizing the mix of renewable units could potentially reduce energy balance fluctuations in a small-scale microgrid. Due to the volatility of the renewable generation, the microgrid islanded operation cannot rely on such sources. In order to address this concern, a new concept called "provisional microgrid" is outlined in [22], proposing a microgrid without islanding capability. This would add flexibility to utilize nondispatchable units and would facilitate the integration within the utility grid.

The variable nature of renewable DGs in microgrids necessitates the presence of an energy source to compensate for their fluctuations. The islanding events in microgrids and the need for a power supply to ensure seamless transfer to the islanded mode also makes the case for integration of energy storage systems (ESS) in microgrids. ESS enhances flexibility in power generation, delivery, and consumption. It provides utility grids with several benefits and large cost savings. Large-scale ESS increases the efficiency of utility grids which means reduced operation cost and emissions and increased power reliability. Conventional large-scale power plants are not able to respond to load fluctuations in real-time which results in a poor voltage and power quality. Considering the increasing penetration of renewable DGs, the application of ESS has significantly increased. The reason is that renewable DGs are intermittent; for example, wind farms and solar PVs generate power when the wind is blowing and the sun is shining. Accordingly, the employment of ESS allows the utility grid to store energy when it is more than the amount required to meet the demand, and supply loads in peak hours. Therefore, this technology lets variable generation resources to continue their power generation even in the absence of wind and sunlight, which means providing electric utilities with a continuous and reliable power. Storing energy from various resources to economically serve shifting loads based on electricity prices and serve non-shiftable loads during peak hours is one of the several applications of ESS. The employment of ESS would improve power quality via frequency regulation, benefit electric producers by allowing them to generate power when it is most efficient and least expensive, provide critical loads with a continuous source of power, and help the society during emergencies such as electricity interruptions because of storms, equipment failures, or malicious attacks. According to [23], benefits could be in the form of either avoided costs or additional revenue received by the operator. Benefits from avoided costs include the costs of alternatives to the ESS which are avoided. Based on this concept, if an ESS is used such that there is no need for generation equipment, the benefit of this ESS would be the avoided cost of generation. For the ESS owner, benefits from additional revenue would be associated with the revenue from selling energy and other services. For an electricity end-user employing ESS for reducing electricity bill, the benefits would be lower costs of energy [24], [25]. In [26], an algorithm is proposed to manage the devices in real-time in order to mitigate pulsed loads effects on the system performance in microgrids involving ESS. The study in [27] presents a control strategy for the PV source integrated in a microgrid allowing it to operate at maximum power point at all times except for times that the frequency needs to be stabilized.

In [28], microgrids are classified based on their value proposition into three types: reliability, energy arbitrage, and power quality. The paper explains that because the energy source of inverter-based microgrids responds slowly, ESS is only necessary for this type of microgrids with a mostly critical load designed to have a power quality higher than the utility grid, and is optional for other types of microgrids. The study in [29] focuses on empirically characterizing Vanadium Redox batteries efficiency, as a viable ESS technology for portable microgrids, based on known climatic operating conditions and load requirements. The study in [30] proves that ESSs applied in microgrids can perform the task of active power balancing and voltage regulation at the same time. In the grid-connected mode, ESS may ensure load levelling and reducing the power exchange with the network which makes the system operation more efficient and flexible. ESS may enhance DER penetration and contribute to better quality of energy delivery to customers. The proposed control of ESS ensures successful transition to islanded mode as well. A composite ESS that contains both high energy density storage battery and high power density storage ultracapacitor is proposed in [31] to meet the aforementioned requirements. The proposed power converter configuration and the energy management scheme can actively distribute the power demand among different ESSs. In [32], a new fuzzy logic pitch controller and an ultracapacitor ESS is proposed to smooth the output power of wind turbine and enhance microgrid performance in the islanded mode. The two proposed controllers are compared with the conventional PI pitch controller, which is usually used to control wind generation system when the wind speed exceeds a rated value.

III. MICROGRIDS TO SUPPORT GRID PERFORMANCE

In [33], several value propositions of community microgrids are enumerated which could be simply extended to a majority of types of microgrids. These value propositions include improved reliability and resiliency, emission reduction, reduced costs of recurring system upgrades, enhancing energy efficiency and power quality, and lowered energy costs. However, the microgrid value propositions, which are of utmost importance and appeal for grid operators to support grid performance, are improved reliability, resiliency, and power quality. The study in [34] describes the primary value propositions of microgrids including reliability, energy arbitrage, and power quality. Furthermore, requirements and characteristics are discussed for microgrids designed for each of the value propositions.

A. RELIABILITY

One of the most important benefits of microgrids is to improve consumers' supply reliability. Electric utilities constantly monitor consumers' reliability levels and perform required system upgrades to improve supply availability and to reach or maintain desired performance. Consumer reliability is typically evaluated in terms of system and customer average interruption frequency and/or duration (SAIFI, SAIDI, CAIFI, and CAIDI indices). Outage causes, such as storms, equipment failure, etc., impact reliability levels by increasing the average frequency and duration of interruptions, however, when a community microgrid is deployed, these metrics can be significantly improved. This is due to the intrinsic intelligence (control and automation systems) of microgrids and the utilization of DERs that allow islanded operation from the utility grid. Since the generation in community microgrids is located in close proximity to consumer loads, it is less prone to being affected by T&D grid disturbances and infrastructure issues. Additional flexibility to provide service under these conditions is provided by the ability to adjust loads (e.g., demand response) via building and/or microgrid master controllers. Improved reliability can be translated into economic benefits for consumers and utility due to a reduction in interruptions costs and Energy Not Supplied (ENS). The magnitude of these benefits is dependent upon load criticality, value of lost load, and the availability of other alternatives such as backup generation or automatic load transfer trips. Microgrid studies associated with reliability can be considered from two perspectives of evaluation and improvement.

In the context of microgrid reliability evaluation, studies in [35]–[39] consider reliability assessment of islanded microgrids with renewable DGs. The Monte Carlo simulation is used in [40] for reliability calculations. A novel method is presented in [36] for assessing the reliability of microgrids, considering the probabilistic behavior of solar and wind power. The study period is divided into different timeframes, and for each timeframe, the timeframe capacity factor is considered for each renewable DG. To assess the microgrid reliability, the loss of load expectation and expected energy not supplied are calculated which result in a reduction in the required data and running time for reliability assessment. These two virtues suit the model well for optimization-based planning problems. The main advantage of the proposed model is that it does not depend on detailed data that is hard to obtain, and does not deal with convergence, error limit, or runtime issues that exist in simulation-based methods, such as in Monte Carlo simulation. In [35], simulation model and technical discussions are presented on unit commitment and economic dispatch of DERs showing that a microgrid with DERs offers much better SAIFI, SAIDI, and Average Service Availability Index performances compared to a microgrid and a system without DERs due to its ability of seamless transfer to islanded mode when the utility grid fails. In [40], a computational methodology is presented that can be used for quantifying the reliability and operational performance of low voltage distribution systems with DGs that operate as microgrids. It is based on a sequential Monte Carlo simulation which simulates all features of the DGs that can be connected to a microgrid in order to achieve an acceptable level of power supply to the microgrid consumers. It is shown that the microgrid adequacy is critically dependent on the reliability performance of the system supply source while a sufficiently large generation capacity of DGs can improve the system reliability indices in emergency conditions when additional power generation is required to supply the load demand. The relative indices being calculated clearly indicate that this operating procedure may significantly improve the microgrid reliability performance. In [39], a procedure of supply reliability evaluation for microgrids is presented which includes renewable energy sources such as wind power and solar PVs. The study in [38] presents a model for the assessment of the reliability of combined heat and power-based DER capacity of a 6-bus meshed microgrid. Probabilistic methods such as loss-of-load probability, loss-of-energy probability, and frequency-and-duration are used in the context of tracking electric demand profiles. Worth of reserve capacity and demand for reserve with these fast-start DERs is evaluated from capacity outage probability distribution and demand curve. The study in [37] uses Markov process to model generation to load ratio when analyzing the impact of renewable energy sources on the islanded microgrid reliability.

In [39], [41], and [42], metrics are proposed for the reliability assessment of islanded microgrids. In [41], a series of new metrics is proposed which is able to evaluate the effect of outages in a distribution system and the islanding process. In the first step, the reliability of the distribution system is assessed while microgrids are equivalently considered as loads connected at their PCC. In the second step, a Monte Carlo simulation is used to assess the reliability of microgrid containing renewable DGs, while the rest of the distribution system is substituted by an equivalent conventional generator model. In [42], a probabilistic technique is proposed to evaluate the success of islanded microgrids, taking into consideration the special features and operational characteristics of both dispatchable and wind DGs in islanded microgrids. Discussions demonstrate that voltage and reactive power constraints have considerable effects on the microgrid successful operation. New adequacy and reliability indices are proposed to account for the effect of voltage and reactive power constraints. In [43], a new modeling approach is presented to provide the hourly generation models for each type of renewable DGs. It also presents an approach to develop an hourly load model, by taking into account both power correlation and hardware availability. The model uses that information to present a method to analytically evaluate loss of load probability. In [44], the sustainability and reliability of microgrids are assessed in the Northwestern European electricity market considering thermodynamic exergy-based and reliability indices when evaluating the role of microgrids in regional utility grids. Performed studies suggest that a power network, in which fossil-fueled microgrids and a price on CO2 emissions are included, has the highest composite sustainability index. In [45], a new method for reliability evaluation of active distribution systems with multiple microgrids is proposed. Multi-state models, to better represent various types of DGs and virtual power plants, and model microgrids with intermittent sources are considered. The non-sequential Monte Carlo simulation method is then adopted to evaluate the reliability of active distribution systems considering different operation modes under single or multiple contingencies. Used techniques enhance the state evaluation process and improve the Monte Carlo simulation speed. In [46], stochastic linear programming is introduced to obtain optimal operating schedules for a given microgrid under local economic and environmental conditions. The paper indicates that using a stochastic approach can both increase the reliability of microgrid operations and improve its economic performance, which also illustrates the advantages of using integrated modeling approaches. In [47], the application of high reliability distribution system in the economic operation of a microgrid is studied and it is demonstrated that the implementation of high reliability distribution systems and automatic switches can reduce the expected frequency, the duration of interruptions, and the expected energy not supplied in microgrids. Studies are performed in a working microgrid in the campus of the Illinois Institute of Technology in Chicago. In [48], an analytical technique is presented that evaluates the reliability of customers in a microgrid using a recursive algorithm in order to compose a connection matrix of DGs.

In the context of microgrid reliability improvement, reliability improvement methods have been proposed through coupled microgrids [49], adding renewable DGs [50], autonomous customer-driven microgrids [51], efficient operation of DGs [52], and vehicle-to-grid integration [53]. In [54], a dispatching strategy is presented based on the criterion of limiting the risk in operation. The study in [55] suggests improvements in reliability of micro hydro power plant and micro wind power turbine by considering the feasible cooperation between the system grid and power sources of micro hydro power plant and micro wind power turbine. In [56], the value of autonomous microgrid is increased by factoring operations management into microgrid management and cross-microgrid management, leading to improved reliability. In this work, the topology of microgrids is described, including nesting, union, and intersection topologies. The proposed scheme is called the Structured Energy. Structured Energy, using microgrids as the basic components, allows a long-term planning to deal with scarcity and surplus. In [50], ‘‘the feeder addition problem’’ is defined to determine potential locations for adding interties between feeders in a legacy radial distribution system and make it partially meshed to improve the reliability in the islanded mode of operation. A heuristic technique, called the sequential feeder method, and a multi-objective GA are used in this model. In [51], the role of autonomous, customer-driven microgrids in hardening utility grids is described by providing significant reliability and security benefits. The study in [52] applies heuristic optimization techniques, such as Harmony Search Algorithm, PSO, and GA, for operational efficiency and minimum interruption costs, with a focus on using DGs in a microgrid. It shows that the efficient operation of DGs can improve reliability indices due to the reduction in interruption frequency and duration. In [53], simulation results of vehicle-to-grid operations in a microgrid are presented for evaluation of the grid reliability. The paper further proposes a charging and discharging control method based on the current load and battery status to relieve power load during peak hours and smooth out the load profile. The results are significant in that vehicle-to-grid operations contribute to local energy reliability during emergency as well as cost savings in electricity bills and fuels for generators by reducing peak load. In [54], a new operating paradigm is proposed, called risk-limiting dispatch, that uses real-time information about supply and demand obtained from the smart grid, taking into account the stochastic nature of renewable sources and DR. The operational decision making of the proposed approach is based on the criterion of limiting the risk in operation, rather than the conventional worst case dispatch.

B. RESILIENCY

Resiliency improvement is observed as a complimentary value proposition of microgrids. Resiliency refers to the capability of power systems to withstand low-probability high-impact events by minimizing possible power outages and quickly returning to normal operating state [57]. These events typically include extreme weather events and natural disasters, such as hurricanes, tornados, earthquakes, snow storms, floods, cyber-security attacks, malicious attacks, etc. Recurring and seemingly increasing intense seasonal storms, which many utilities are facing every year, could also be included among these events. Recent hurricanes in the United States and the potential significant social disruptions have spawned a great deal of discussion in the power and energy industry about the value and application of microgrids. If the power system is impacted by these events and critical components, e.g., generating facilities and/or T&D infrastructures, are severely damaged, service may be disrupted for days or even weeks. The impact of these events on consumers could be minimized by the development of community microgrids which allow the local supply of loads even when the supply of power from the utility grid is not available.

In [58], a vulnerability index is presented in terms of loss of load, which is used together with reliability and economy as objectives in microgrid planning optimization to ensure its resilient operation in the islanded mode. The problem is solved using MAS technology and PSO. In [59], a composite sustainability-resiliency index is calculated using fuzzy logic to be used in a multi-objective microgrid operation optimization model in order to account for the capacity of the power network system to self-recover to a new normal state after experiencing an unanticipated catastrophic event. In [60], a tool is presented to model a flywheel energy storage, capable of providing resilient power to critical loads. In [61], a microgrid availability calculation method is proposed to be used during natural disasters based on Markov state space models. The method uses minimal cutset approximations for calculations. In [62], control actions to be conducted for multi-microgrid service restoration and subsequent operation in islanded mode are proposed. The study in [60] proposes a decentralized multi-agent control method for distributed microgrids, allowing microgrid agents to successfully transition from normal operations to an emergency condition and back again when conditions have resolved. The study in [63] proposes phase droop control and a central power management controller for a microgrid in a region exposed to hurricanes as control means to stabilize the system when it is subject to disturbances. The study in [64] presents the development of advanced microgrid load management functionalities, including exploitation of responsive loads, which are able to manage microgrid ESS. They are proposed as complementary resources to microgrid primary frequency regulation and to run the microgrid online. In [65], a hardware-in-the-loop reconfigurable system design is proposed to facilitate the realization of fault prevention, detection, and mitigation at various levels with various degrees of collaboration; they include local actuation, supported by devices with embedded intelligence, resilient and robust local collaboration at both local and system levels, and distributed state estimation, as well as system-level adaptation, supported by control-theoretic security solutions. The study in [66] discusses utility system vulnerabilities to multiple failures and the potential for such failures under natural and/or manmade threat models of the residential communities. The study in [57] proposes a resiliency-oriented microgrid scheduling considering uncertainties in load, generation, and the utility grid supply interruption time and duration. The problem is decomposed into normal and resilient operation problems. The unit commitment, ESS, and adjustable loads schedules are revised, and loads are curtailed, if necessary, to ensure feasible resilient operation.

C. POWER QUALITY

Consumers' needs for higher power quality have significantly increased during past decades due to the growing application of voltage sensitive loads, including a large number and variety of electronic loads and LEDs. Utilities are always seeking efficient ways of improving power quality issues by addressing prevailing concerns stemmed from harmonics and voltage. Microgrids provide a quick and efficient answer for addressing power quality needs by enabling local control of frequency, voltage, load, and the rapid response from ESS.

Power quality compensators to be used in microgrids have been proposed in [32] and [67]–[73]. In [67], an autonomous-control method for a DC microgrid is described. The proposed control method, intended for suppression of circulating current, detects only the DC grid voltage. Each unit can be controlled autonomously without communicating with others. This method brings high reliability, high-flexibility and maintenance-free operation to the system. In [68], a power flow and power quality control for a single-phase high-frequency AC microgrid is presented using single-phase p-q theory-based active filters. It finds an approximate sinusoidal form of the current from the intermediate supply bus, which is further in phase with the fundamental source voltage. It would result in a sinusoidal load voltage which is crucial for voltage sensitive loads within the microgrid. In [69], a group of grid-interfacing system topologies is proposed with the purpose of interfacing local DG/microgrid to the utility grid, or interconnecting microgrids by adapting the conventional series-parallel structure to enhance the voltage quality. With the reconfigurable functionalities, the proposed systems have been compared with conventional series–parallel systems and shunt-connected systems, showing flexible applicability. In [70], a grid-interfacing power quality compensator is proposed to be used with individual DGs in a microgrid, and is implemented using shunt and series inverters with both inverters optimally controlled to enhance the power quality and the quality of currents flowing between the microgrid and the utility grid. The practicality and the effectiveness of the proposed compensator are verified by simulation and experimental results. In [71], a flexible AC distribution system device is presented for microgrid applications to improve the power quality and reliability of the overall power distribution system that the microgrid is connected to. The control design employs a new model predictive control algorithm which results in faster computational time for large utilities by separately optimizing the steady-state and the transient control problems. Extended Kalman filters are also employed for frequency tracking and to extract the harmonic spectra of the grid voltage and load currents in the microgrid. In [72], a three-phase four-wire grid-interfacing power quality compensator is presented for microgrid applications to be used with each individual DG in the microgrid. The compensator consists of two four-phase-leg inverters (a shunt and a series), and is optimally controlled to achieve an enhancement of both the quality of power within the microgrid and the quality of currents flowing between the microgrid and the utility grid. In [73], frequency/sequence selective filters are proposed for adding power quality conditioning capability into voltage-source inverter based DERs in a microgrid containing both complex bandpass and bandstop sections, which are designed on three-phase space-vector quantities. Simulation and experimental results are presented to validate these filtering concepts. The proposed schemes are observed to improve filtering signals in three-phase, three-wire power systems, especially when there is a narrow gap between the desired and undesired frequencies.

The study in [74] states that utilizing DERs is a way of enhancing power quality in the distribution system. In [75]–[77], multiple methods are proposed for harmonic filtering and mitigation. In [75], a new cooperative harmonic filtering strategy is proposed for the interface converters of DGs. It consists of droop control method based on the reactive volt-ampere consumption of harmonics of each interface converter. In this method, the overall harmonic filtering workload can be evenly shared without communications. In [76], a harmonic compensation method is proposed for a DC microgrid connected with doubly-fed induction generators. In [77], it is shown how the grid of an existing holiday park can be changed into an autonomous microgrid by implementing an additional control system as well as additional ESSs and power electronics to maintain the balance between load and generated power, and to guarantee the quality of supply on an acceptable level. The paper is especially focused on the existing harmonic problem coming from the interaction between grid components and installed solar inverters. Discussions are supported via a power quality test laboratory. The study in [78] proposes a harmonic compensation scheme for power electronics-interfaced DGs, improving steady-state power control accuracy in a microgrid with frequency deviations.

In [79], enhanced control strategies based on frequency droop are proposed for DGs to improve synchronization and real power sharing, hence minimizing transient oscillations in the microgrid. In [80], an enhanced droop control method is proposed through adaptive virtual impedance adjustment to address inaccurate power sharing problems in autonomous islanded microgrids. In [81], a profile-based control approach is presented to accommodate pulsed-power loads in microgrids based on identifying the optimal charging profile. It is shown to be highly effective in reducing the power disturbances of pulsed-power loads. In [82], a DC microgrid was applied to residential houses with a cogeneration system such as gas engine or fuel cell. DGs are capable of stably supplying loads with high quality power against sudden load variations, voltage sags of the utility grid, and short circuits of the load. In [83], a system for a residential complex is presented as an instance of the DC microgrid where each house has a cogeneration system such as gas engine and fuel cell. The output electric power is shared among houses, where the total power can be controlled by changing the running number of cogeneration systems. Supercapacitors are chosen as main ESS systems in this model. Results show that the proposed system could supply high-quality power under a variety of conditions such as voltage sag in the utility grid, as well as disconnection and reconnection procedures.

IV. APPLICATION OF POWER ELECTRONICS IN MICROGRIDS

Many of DERs are not suitable to be directly connected to the microgrid network. Hence, power electronic interfaces are required to enhance/enable their integration [6]. Examples are PV cells and ESS which generate DC power, or wind turbines that need improvements in generated power quality and frequency. Although power electronic devices would enhance integration and controllability of these resources, they would also bring new challenges regarding control and protection. In an islanded microgrid, rotating generators can serve the role of a voltage source and manage the grid frequency, but in their absence the power electronic converters are needed to behave as voltage sources. In the grid-connected mode, the converters function as current sources feeding the microgrid. This section provides a review on the current applications of power electronics in microgrids.

A single-stage single-phase high-step-up zero voltage switching boost converter with voltage multiplier cell is proposed in [84] to satisfy the strict efficiency and power density requirements in the fuel-cell microgrids. The integration of the solid-state transformer with zonal DC microgrids is discussed in [85]. By utilizing the DC and AC links of solid-state transformers, both networks can access the distribution system, which renders the coordinate management of the power and guarantees a high power supply reliability. A power delivery strategy relying on integrating DER in AC distribution networks through a multi-terminal voltage source converter (VSC)-based DC system is proposed in [86]. A topology is designed that integrates both AC and DC networks and is unified for different voltage and power levels. It allows full power controllability, yet has a compact monolithic and scalable structure. In [87], a voltage unbalance and harmonics compensation strategy for the VSCs in islanded microgrids is presented where the virtual impedance loop is modified to improve the compensation effect. The impedance model of the VSC is built to explain the compensation ability of the proposed strategy. The study in [88] simplifies the differential algebraic system of decentralized multi-inverter microgrid active power/voltage frequency and reactive power/voltage magnitude droop control to study the stability of the microgrid for different droop control gains based on varying assumptions, while in [89] a pseudo-droop control structure integrated within a microgrid through distributed power generation modules is presented which is capable to function in off-grid islanded, genset-connected, and grid-connected modes of operation. The PV inverter ceases to convert power until the line-frequency limits are restored to the normal range, as the DC level is within the specified set point limits. The PV inverter control is enhanced with the implementation of frequency-detection function, which continuously monitors the microgrid line frequency and reduces its power if a specific pattern is detected while the hybrid converter varies the line frequency determined by the desired battery-charging profile. In [90], a feasibility study is introduced using the evolutionary design to optimize control parameters for an islanded microgrid with a large number of inverters, and it is demonstrated to provide improved transient response when compared to a manual design.

In addition to enabling an efficient connection, power electronics devices are capable of providing additional benefits for microgrids. Power electronic interfaces can improve the power quality of customers by improving harmonics and providing extremely fast switching times for sensitive loads. Power electronics can also provide benefits to the connected utility grid by providing reactive power control and voltage regulation at the distributed energy system connection point. A useful feature of a power electronic interface is the ability to reduce or eliminate fault current contributions from distributed energy system, thereby allowing negligible impacts on protection coordination. Finally, power electronic interfaces provide flexibility in operations with various other DERs, and can potentially reduce overall interconnection costs through standardization and modularity [91]. This issue is discussed in [92] in which a power-electronic interface, including an ESS module and an inverter for coupling DERs within a microgrid is introduced. The control of power electronics-interfaced DG systems are further discussed in [93]–[96]. In [93], a decentralized control architecture for the autonomous operation of a microgrid with power electronic interfaces based on a multi-agent system (MAS) is presented in which all agents are hierarchically equal and there is no central agent. In [94], an operation range control strategy based on frequency-voltage droop is proposed and shown to be able to control voltage by decoupling the real and reactive power control and improving the microgrid stability. In [95], the control and protection of power electronics-interfaced DG systems in a customer-driven microgrid are discussed considering microgrid configurations and features, DG interfacing converter topologies and control, power flow control in grid-connected operation, islanding detection, autonomous islanding operation with load shedding and load demand sharing among DGs, and system/DG protection. The study in [96] presents experimental results from the operation of a prototype microgrid which comprises a PV generator, battery ESS, local load, and a controlled interconnection to the low voltage grid with fast acting power electronics interfaces. It provides a technical description of the system components and the control concept implementation, along with extensive measurement results demonstrating its capability to operate in the desired way.

V. MICROGRID ECONOMICS

The proximity of generation to load in microgrids provides significant benefits in terms of reduced losses and T&D payments. These benefits need to be assessed and demonstrated in order that microgrids could remain competitive with the large-scale generation. Various papers have discussed microgrid scheduling, planning, its interactions with the electricity market, and demand management. However, there are still several areas regarding economic aspects of microgrid operation and planning in need of research. This section reviews available studies on microgrid economics.

A. ECONOMIC EVALUATION

Microgrids can potentially benefit from a less expensive generation stemmed from local renewable DGs with the ability of generating power in high market price hours and also in times of congestion in the utility grid. Moreover, reduced energy purchases from the utility grid would be translated into reduced T&D charges, hence ensuring economic benefits for the microgrid. Microgrids are also able to sell their excess power back to the utility grid and be paid, or credited, under the net metering policy. The lowered energy costs impact each individual consumer within the microgrid. However, the microgrid local generation not only lowers energy costs for local consumers, but also could potentially benefit the entire system by reducing the T&D networks congestion levels and enabling a better economic dispatch of available energy resources in the utility grid. In addition, microgrid deployment enables the application of load management strategies by local consumers, hence further increases economic benefits.

Economic merits of microgrids are extensively discussed in the literature [41], [97]–[104]. The study in [97] compares different DERs connected to a practical microgrid using real valued cultural algorithm suggesting that solar and biomass gasification (a form of sustainable energy) units are more economical than fuel cell and solar. The study in [98] shows that using microgrids to meet the end-user demand when electricity prices are high would reduce their costs and pay back the investment cost. It also demonstrates the reduction of losses with increased microgrid penetration in the low voltage network. In [99], it is argued that microgrids can efficiently serve not only rural communities but also large urban centers, and function as drivers for efficient municipal town planning systems, resource management, and growth catalysts. In [100], it is suggested that although establishing microgrids might require a high initial cost, a proper operation will result in a significant income for the society. The study in [101] shows that a well-weighted mixture of comparably more expensive dynamic DER and less costly static reactive power sources in a microgrid can provide a cost-effective reactive power and voltage support to the grid. The study in [102] presents a minimum incremental cost assessment of upgrading a microgrid by adding a wide-area UPS facility to loads and micro-sources in a distributed virtual power plant, concluding that further developments are needed to bring down the cost of power electronics investment, thus justifying microgrid widespread utilization. The study in [105] discusses the evaluation of microgrids' economic performance and presents results from a software developed for this purpose. In [103], economic performances of industrial PV microgrids in China are analyzed by comprehensively considering three indices of the levelized energy cost, emission reduction benefits, and payback period. Real microgrid output data and optimal simulation results based on a proposed optimal model are used. The study shows that the optimized countercurrent PV microgrid and batteries can bring the most economic and emission reduction benefits to consumers and the system. In [104], four microgrid benefits are surveyed including the reduced peak loading, reliability improvement, emission reduction, and the provision of certain power quality services. The paper further suggests a quantification methodology for each one and shows how the proposed benefits can support a microgrid business case. In [41], a series of new metrics for the reliability and economic assessment of microgrids in the distribution system is proposed including reliability parameters for microgrids in the islanded mode. Indices indicate DG and load characteristics, microgrid economics, and consumer based reliability. A two-step Monte Carlo simulation method is used to assess the reliability and economics of a microgrid with intermittent DGs as well as the reliability of distribution system with microgrids. In [106], it is shown that the application of used plugin electric vehicle battery packs as ESS to provide frequency regulation in building microgrid is economically viable. The proposed formulation incorporates ESS, DSM and power exchanges with the grid.

B. MICROGRID SCHEDULING

Microgrid scheduling problem aims at minimizing the operation costs of local DERs, as well as the power exchange with the utility grid, to supply forecasted microgrid loads in a certain period of time (typically one day). The microgrid scheduling problem is subject to a variety of operational constraints such as energy balance, load management, and DER limitations. An optimal model predictive control-based strategy for the multi-objective optimization problem is proposed in [107] with the goals of minimizing fuel costs and changes in power output of diesel generators, minimizing costs associated with low battery life of ESS, and maximizing the ability to maintain real-time power balance during operations. In [108], two new cost-prioritized droop schemes are developed to reduce the microgrid total generation cost. They operate by tuning the dispatch priorities of DGs and curve shapes of their resulting active power versus frequency plots. In [109], a knowledge based system controller is used to schedule a wind-diesel-ESS isolated microgrid an hour ahead so that the diesel generator power is reduced and fuel cost is minimized. The study in [110] presents a scheduling model for a residential microgrid considering temperature dependent thermal load in the model facilitating a combined heat and power control.

The microgrid scheduling problem can be investigated from two major perspectives: scheduling architecture and methodology. In the context of the scheduling architecture, the existing Energy Management System (EMS) architectures for microgrids are reviewed in [111] and [112], where centralized and distributed models are identified as common microgrid scheduling schemes. The scheduling problem can be solved centrally in a central computing unit, able to access generation and load information and dispatching generation according to total load demand and individual generator's cost curve [113]–[120]. In [113], a centralized control system that coordinates parallel operations of different DG inverters within a microgrid is proposed, employing a model predictive control algorithm that optimizes the steady-state and transient control problems separately. The large number of control devices requires higher capacity of communication network and higher computational capability, which would act as a barrier for employing the microgrid centralized control. The study in [114] proposes a control software aiming to provide advice to power system operators regarding scheduling of resources in an islanded system. In [115], a scheduling approach for a hydrogen storage system is presented. In [116], the microgrid scheduling problem is solved by differential evolution approach. In [118], a scheduling scheme is proposed for a microgrid, including advanced PV generators with embedded ESS and gas microturbines. The scheduling is performed in two parts: a central energy management and a local power management at the customer side. The study in [120] proposes a scheduling model for microgrids considering uncertain islanding. The problem is decomposed into normal and islanded problems and islanding cuts are used to revise the schedules to ensure feasible operation.

In the distributed model, however, each component is considered as an agent with the ability of discrete decision making, and the optimal schedule is obtained using iterative data transfers among agents [121]–[128]. In [126], consensus theorem is used in a decentralized multi-agent platform. In [127], the dual decomposition method is utilized to decompose the original problem into smaller subproblems solved by controllers of DGs, dispatchable loads, DES, and renewable energy sources. Each control scheme offers its own benefits and drawbacks, but the centralized model is commonly more desirable as it ensures a secure microgrid operation and is more suitable for the application of optimization techniques. The main drawbacks of the centralized scheme are reduced flexibility in adding new components and relatively extensive computational requirements [111]. The study in [128] presents a nonlinear droop scheme for power sharing in a microgrid with different types of DGs aiming at reducing total microgrid generation cost. The study in [125] presents a model to simulate closed loop price signal control optimal power flow (OPF) by a microgrid central controller. The central operator only influences the decision taken by each unit via price signals. Dispatch decision is decentralized to each controllable unit increasing system capability to cope with a large number of generating units. A range of case studies show the approach's ability to handle small and large scale disturbances both within and outside the microgrid. Optimization is used by an advanced Primal Dual Interior Point Method based on Nonlinear Programming.

Available software to solve the microgrid scheduling problem include WebOPT [129] and HOMER [130]. WebOPT is a mixed integer linear programming (MILP) optimization program for planning purposes developed using General Algebraic Modeling System. HOMER software is used for simulation, optimization and sensitivity analysis of microgrids. In [131], a simulation platform is presented for the modeling and study of microgrids using MathWorks Simulink modeling software, providing a library of tools for designing and simulating the behavior of a microgrid on time scales from seconds to days which includes a collection of power system and power electronics components that may be arbitrarily configured.

In the context of the scheduling methodology, a variety of approaches are proposed to solve the microgrid scheduling problem, including deterministic, heuristic, and stochastic methods. Deterministic methods include advanced primal dual interior point method based on nonlinear programming [125], sequential quadratic programming [132], MILP [35], [77], [133]–[139], subgradient search [140], reduced gradient search [141], quadratic programing and linear programing [127], [142], and interior point method [143]. The MILP is a modification of standard integer programming that treats the objective and constraint functions as continuous, and some variables as integers. In dynamic programming, the problem is decomposed into a series of smaller problems, and an optimal solution is developed to the original problem step-by-step. The optimal solution is recursively developed from the subproblems. Its fundamental form examines every possible state in every interval and rejects infeasible ones. Dynamic programming methods typically suffer from the curse of dimensionality. Lagrangian relaxation decomposes the problem into a master problem and a number of manageable subproblems which would be solved separately. The subproblems are linked by Lagrangian multipliers that are added to the master problem to yield a dual problem. The dual problem has lower dimensions than the primal problem and is easier to solve. The difference between the two functions yields the duality gap for which the primal function is an upper bound. This gap provides a measure of the optimality of the solution. It is more flexible for handling different types of operating constraints in a power system and has higher computational efficiency compared to other methods. It can be easily extended to incorporate various constraints. Its main drawback is the inability to guarantee the solution feasibility and convergence [144]. In [145] a non-linear mixed integer programming problem is decomposed into integer and continuous variable optimizations and the continuous problem is solved using successive dynamic programming. In [138] models of an energy supply chain network are proposed in an MILP framework based on small-scale micro-generation through combined heat and power systems aiming at minimizing operation and trade costs under full energy demand satisfaction. In [146], the microgrid economic scheduling is posed as an MILP model. No complex heuristics or decompositions are used leading to significant improvements in scheduled quality and in computational burden. Unit commitment, economic dispatch, ESS, sale and purchase of energy to/from the utility grid, as well as curtailment schedule are considered. The study in [139] presents an optimal dispatching strategy of microgrid-based ESS which also includes wind generator, PV system, fuel cell, micro turbine, and diesel generator. Results show that a battery switch station can bring more profit and reserve for the microgrid than other types of ESS.

Heuristic methods are flexible, and allow for the consideration of practical operating constraints, obtain feasible solutions if there are any, and have modest computational requirements, but cannot guarantee the optimal solutions or furnish an estimate of the magnitude of their optimality which is rather significant in large-scale utility grids [144]. Heuristic methods used for the microgrid scheduling include simulated annealing [117], gravitational search algorithm [147], mesh adaptive direct search [132], linear programming along with heuristics depending on the fuzzy ARTMAP neural network [121], harmony search algorithm, bio-inspired optimizations, including genetic algorithm (GA), particle swarm optimization (PSO) [52], [148], direct search [149] and modified direct search [150], adaptive modified particle swarm optimization (with a better performance than GA and PSO) [151], matrix real-coded genetic algorithm [152], non-dominated sorting genetic algorithm [153], differential evolution [154], artificial immune system and vaccine-enhanced artificial immune system [148], neural networks [155], two-layered scheduling algorithm based on a GA outer layer and an inner mix linear/quadratic programming model [156], improved multi-objective teaching–learning-based optimization [157], and fast evolutionary algorithm [158]. PSO is the most common heuristic method in solving the microgrid scheduling problem. It can be applied to global optimization problems with nonconvex or nonsmooth objective functions. PSO is easy in its concept and implementation by having only a few parameters to adjust. It can solve problems with high-quality solutions within relatively shorter calculation times and more stable convergence characteristics than other stochastic methods [159]. Simple GA implementations using the standard crossover and mutation operators can locate near-optimal solutions, but usually do not converge to the optimal solution. Using the varying quality function technique and adding problem-specific operators can result in satisfactory solutions [160]. Differential evolution can handle optimization problems with nonsmooth/nonconvex objective functions. It has a simple structure and a good convergence property, and requires a few robust control parameters, but takes a relatively longer computation time to achieve the final solution [161]. In [152], an EMS is proposed to optimally coordinate the power production of DG sources and ESS to minimize the operational costs of microgrids. A matrix real-coded GA optimization module is used to achieve a practical method for load management. In [153], a multi-objective optimization model is presented to minimize the power generation cost and to maximize the useful life of lead-acid batteries via the nondominated sorting GA. Results show that the proposed method can optimize the system operations under different scenarios and help users obtain the optimal operation schemes. The study in [154] shows how different optimal output sets of DER-mix, operating within their respective capacity limits, could economically share an electrical tracking demand among micro-turbines and diesel generators of various sizes. It satisfies different heat demands, on the basis of multi-objective optimization, compromising between fuel cost and emission. Optimization is done using differential evolution technique under real power demand equality constraint, heat balance inequality constraint, and DER capacity limits constraint. In [158], improved fast evolutionary algorithm is applied to determine the economic load sharing scenario in a typical microgrid by minimizing the cost incurred for operation, maintenance, and emissions. Results reveal that the developed technique is easy to implement, has converged within an acceptable execution time, and yields highly optimal solution for combined economic and emission dispatch with the minimum operation and emission costs. The study in [162] proposes an operation optimization model based on the multi-cross learning-based chaotic differential evolution algorithm, which has a higher exploration capability compared to PSO and gravitational search.

Stochastic methods are primarily used to handle prevailing uncertainties in the microgrid scheduling process. In [46], a stochastic programming method is adopted to address the scheduling of a reconfigurable lithium ferrophosphate battery to improve the reliability and economic performance of the microgrid. In [163], chance-constrained programming is utilized to consider the random wind power, PV power, as well as thermal and electric load in the optimal schedules of a combined heat and power system. The study in [164] presents a scheduling of autonomous generators, renewable resources, ESS devices, and schedulable loads in a microgrid for buildings. The problem is formulated as stochastic optimization and solved by a scenario tree method. It is shown that for this problem even in the presence of uncertainties, the deterministic model based on forecasts of demand and renewable generation offers an efficient equivalence to the stochastic model. The study in [25] formulates the same stochastic optimization problem considering uncertainties in demand profiles and solar radiation, and solves it using a scenario tree method. It attempts to find the optimal ESS capacities and operating plan in a building energy system. It is found that thermal ESS units and water tanks are effective in saving the energy cost in all scenarios, but the electrical battery may not be economical to use due to its high investment cost and short lifetime. It is found that it would be sufficient in many cases to obtain the best combination of ESS devices with the forecasted demand and solar radiation, without using stochastic formation.

In addition to deterministic, heuristic, and stochastic methods, hybrid methods, which benefit from a combination of two or more methods, are proposed and used in the microgrid scheduling. A hybrid of evolutionary programming and hill climbing techniques is used in [165]. In [166], a bi-level prediction strategy for short-term load forecast of microgrids is presented. The upper level uses the enhanced differential evolution optimizing the adjustable parameters of the feature selection method with the forecast engine in the lower level. The hybrid forecast engine is composed of the neural network and evolutionary algorithm.

There are some decisive factors in microgrid scheduling, including market price, emission consideration, and power flow in microgrids. In the context of electricity price, there are two common types of pricing: flat rates and time-based rates. Under flat rate pricing, customers pay a fixed charge per KWh of electricity consumed independent of the time of usage, thus flat rates are unvarying. Flat rates are often assigned to residential customers, and are the only option in the absence of meters that can record time-differentiated usage (except block rates). A range of time-based rates are currently offered directly to retail customers, including time-of-use pricing (TOU), real-time pricing (RTP), and critical peak pricing (CPP). In TOU, a rate with different unit prices is defined for electricity usage during different blocks of time, typically for a day. TOU rates reflect the average cost of generating and delivering power during those time periods. TOU rates often vary as a function of time of day (e.g., peak vs. off-peak period) and season, and are typically pre-determined for a period of several months or years.

TOU rates are in widespread use for large commercial and industrial customers. TOU rates require meters that register cumulative usage during the designated time blocks. In RTP, the electricity price typically fluctuates hourly reflecting changes in the wholesale price of electricity. Forecasted RTP prices are typically made available to customers on a day-ahead or hour-ahead basis. CPP rates include a pre-specified high rate for usage designated by the utility in a critical peak period, and may be triggered by system contingencies or high prices paid by the utility for procuring power from wholesale electricity markets. CPP rates are not yet common, but have been tested in pilots for large and small customers in several states [167], [168]. In [169] the problem of energy imbalance management in a microgrid is studied from the market perspective. The paper proposes a pricing scheme that provides robustness against intermittent power inputs. It is shown that the parameters can be obtained by solving a linear matrix inequality problem, which is efficiently solvable due to its convexity. The underlying idea is to use fuzzy systems together with a linear matrix inequality approach to assure the robustness of market dynamics. The proposed design outperforms the existing area control error pricing scheme by managing the imbalanced energy more quickly, and also being robust against system disturbances. In [170], a nonlinear optimal model of cogeneration microgrid is presented to deal with the economic operation of available power resources which formulates a 24-hour work schedule. Test results indicate that the peak-valley energy price would increase the system operation costs, while using battery and peak load shifting can effectively reduce operation costs. In [171], an economic investment model is presented for microgrid operators to optimize their profits in a competing market formed by the utility company, subject to environmental policies. The microgrid operators play a Nash game in the market. The analyses show that the utility company has the flexibility to adjust the Nash Equilibrium of lower level microgrid optimization problems by changing the electricity price and energy arbitrage market demand.

Emission consideration is another important issue that has been noticed in several proposed microgrid scheduling problems. In [135], emissions are minimized within the optimization framework. In [133], the operation plan of a microgrid under three objectives including minimization of the annual cost, CO_2 emission, and primary energy consumption are studied. In [135], a weighted average of energy costs and CO_2 emissions in zero-net-energy commercial buildings is minimized. In [143], atmospheric pollutants, such as sulfur oxides (SO_2), carbon dioxides (CO_2), and nitrogen oxides (NO_x) caused by fossil-fueled thermal units, are considered as the environmental cost in the scheduling optimization problem. In [172], an optimization model for the optimal energy management of microgrids in commercial buildings is presented to increase the efficiency of energy utilization, minimize operational costs, and reduce environmental impacts of energy utilization. It was shown that by using the developed multi-objective optimization approach, total daily energy costs and green-house gas emissions of these microgrids can be significantly reduced as compared to nonintegrated baseline solutions.

Although the microgrid size is much smaller than the utility grid and also the congestion in the microgrid network is less probable, the issue of power flow in microgrids has been discussed in some publications with the primary objective of preventing voltage volatilities and ensuring the microgrid reliable operation. The study in [173] proposes an OPF solution that considers the entire system: the ESS device limits, voltages limits, currents limits, and power limits. The power network may be arbitrarily complex, and the proposed solver obtains an optimal solution. The method combines a power flow solver with a dynamic programming recursive search, achieving a numerically efficient solution. This combination is robust and numerically efficient and reveals the optimal stored energy versus time for each ESS device. The study in [174] presents a Newton Raphson equation for the solution of power flow analysis in microgrid, comprising 2n current injection equations and m active power equations for a system with n buses including one slack bus and m generator buses. The reactive power mismatch of the generator bus is introduced as a new state variable, which leads to a simple procedure for converting bus model between the generator bus and the load bus. In the conversion process, the submatrix Y^* is retained, and only few rows and columns are added or deleted. The proposed method is also applied to other occasions where the polar coordinates are adopted. The study in [175] considers the OPF for microgrids, with the objective of minimizing either power distribution losses or the cost of power drawn from the substation and supplied by DGs leading to voltage regulation. A semi-definite programming (SDP) relaxation technique is advocated to obtain a convex problem solvable in polynomial-time complexity. Numerical tests demonstrate the ability of the proposed method to obtain an optimal solution of the original nonconvex OPF. To ensure scalability with respect to the number of nodes, robustness to isolated communication outages, and data privacy and integrity, the proposed SDP is solved in a distributed fashion by resorting to the alternating direction method of multipliers. The resulting algorithm entails iterative message-passing among groups of consumers and guarantees faster convergence compared to competing alternatives. Another approach is proposed in [176] to use an equivalence for converters in an AC-to-DC network to replace the DC microgrids with AC microgrids, solve the OPF problem of the equivalent AC network using semi-definite programming, and then use it to determine the solution of the original OPF problem.

C. DEMAND SIDE MANAGEMENT

An electricity grid would be stable when the electricity demand and supply are in balance in real time. Traditionally, the power generation would increase in response to an increase in load. The concept of demand side management (DSM) includes energy efficiency and demand response (DR), thus working from the other side of the equation. DSM programs encourage consumers to modify their pattern of electricity usage, and pay them to reduce consumption instead of planning for generating more power [177], [178]. DSM would be an indispensable component of microgrids for either direct load controlling or real-time pricing. DSM is defined by the U.S. Department of Energy as "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [167]. Energy prices are subject to constant fluctuations, based on the time and location of consumption/generation, as a result of the power system restructuring and establishing the electricity market. Fluctuating energy prices stimulate DSM in microgrids to shift loads away from high price hours, benefit from low price hours, lower their electricity demand, and further improve microgrid economics. DSM has several economic, environmental, and reliability benefits. It reduces costs, alleviates electrical system emergencies, reduces the number of blackouts, increases system reliability, and defers high investments in generation, transmission and distribution network capacity [172]. DSM programs in order to promote more efficient management of loads include: 1) promoting the use of energy-efficient products and equipment such as more efficient lighting technologies, 2) encouraging customers to shift non-critical usage of electricity from peak hours to evening and early morning hours, 3) promoting the construction of high efficiency buildings, and 4) promoting energy awareness and education [179]. Therefore, by deploying DSM, consumers could be considered as virtual power plants since they help stabilize the utility grid by planning and monitoring their activities, and are paid for lowering, shifting, or modifying their usage [177]. The success of DSM fundamentally depends on the ratio of controllable loads to the total load in the utility grid. It is expected that the advent of new types of electric equipment such as plug-in hybrid electric vehicles (PHEV) increases the ratio of controllable loads over the next years. Additionally, the ESS in PHEVs would allow them to store the electricity and use it at peak hours. Therefore, PHEVs would make DSM a beneficial tool for balancing power supply and demand too [114]. In [180], a microgrid scheduling method is proposed that considers demand side bidding and DR. Consumer behavior is modeled by price elasticity matrices considering different scenarios and levels of consumer rationality. These price elasticity matrices are utilized to calculate the levels of DR for different consumer types and used in the bidding mechanism for the double sided microgrid market. The study in [181] presents an intelligent metering/trading/billing system and its implementation for DSM in smart grids that enables customers to shift their air conditioning loads in cooperation with the microgrid controller. Customers can adjust their demands and participate in Direct Load Control. In [182], a market-based mechanism is developed for building a smart microgrid operator to control different loads, offer regulation service reserves, and meet the associated obligation of fast response to commands issued by the wholesale market independent system operator. The primary objective is to maximize the sum of the smart microgrid operator and independent system operator welfare associated with internal and external arrivals. The study shows that the static prices become optimal as the capacity of the buildings to support loads increases. In [183], the concept of priority index is introduced for customers participating in a multi-agent based DR system considering the size and number of times of participation. It is simulated on a system with two microgrids, showing that intelligent EMS is successful in reducing the peak demand depending on the amount of load participation in the DR during peak hours. Also the customers with high priority index can obtain power supply at lower costs. In [184], the possibility of reducing the load variance in a household microgrid by regulating the charging patterns of family PHEVs is investigated. The study shows that by regulating the charging profiles of the PHEVs, the variance of the load demand can be dramatically reduced. In [185], an EMS is proposed based on a rolling horizon strategy for a renewable-based microgrid. For each decision step, an MILP optimization based on forecasting models is solved. The EMS provides online set points for each generation unit and signals for consumers based on a DSM mechanism. The results of the EMS show the economic benefit of the proposed unit commitment with a rolling horizon in comparison with a standard unit commitment. The study in [186] presents a strategy to integrate DSM for residential loads and economic dispatch for renewables in a microgrid. In this strategy, user preferences and generation capacity are considered as constraints of the optimization problem, and the objective function is created from the cost of generation for each generating unit in each hour. Then, the optimal solution for the problem is obtained using a GA. Results of this study reveal that the integrated methodology would be up to 15% more economical than independent DSM and economic dispatch models. The study in [187] presents Automated DSM control techniques for microgrid operation. Two control strategies are proposed, using Matlab Simulink. The first strategy considers the capacity of power generation as the reference to prevent abnormal increase of load. The second strategy considers the total maximum allowable transmission loss as the reference to make a decision on connecting additional loads.

D. MICROGRID PLANNING

As discussed previously, microgrids offer unprecedented economic and reliability benefits to electricity customers and the utility grid as a whole. Microgrid benefits, however, must be scrutinized and compared with the microgrid investment cost to ensure a complete return on investment and further justify microgrid deployments [188]. An accurate assessment of microgrid economic benefits is a challenging task due to significant uncertain data involved in the assessment. Moreover, some of the assessment results, such as reliability improvements, are difficult to comprehend for customers when represented in terms other than dollar amounts. Thus, efficient planning models are required for ensuring the economic viability of microgrid deployments and further justifying investments.

In [103], the size of ESS in a microgrid is optimized considering the initial investment cost of components, operation and maintenance cost, equipment replacement cost, electricity purchase cost, and emission reduction benefits to obtain the lowest average annual investment cost and the ability of peak load shifting. The problem is solved by a PSO method. In [189], technologies are optimally selected and sized for a college microgrid using two software packages of HOMER and WebOpt. In [190], multi-criteria decision aid techniques are used to select a desirable multi-microgrid deployment strategy. In [191], a microgrid design model is proposed, which includes PVs, fuel cell and battery bank in the grid-connected mode and in the presence of other DGs under pool and hybrid electricity market models to maximize the net present value of the system. In [192], the importance of frequency and voltage regulation considerations in the microgrid planning due to significant impacts of the battery internal resistance on these regulations is discussed. In [193], an existing planning method is applied to a distribution network with microgrids. The results show that the integration of microgrids with optimal backups will lead to lower overall distribution network costs. In [194], the sizing of an ESS in a microgrid is formulated as an MILP, considering unit commitment problem with spinning reserve. Time series and feed-forward neural network techniques are used for forecasting the wind speed and solar radiations, respectively, along with the associated forecasting errors. It is shown that an optimal size exists for ESS and differs for grid-connected and islanded microgrids. In [195], an analytical hierarchy process based approach of data envelopment analysis is proposed for finding the preferential ranking of various configuration plans for a typical medium-voltage rural distribution system, such as single source DG, hybrid DG, or a microgrid. Studies in [196] and [197] show that how uncertainties in energy and fuel prices affect the microgrid planning. In [198], a method to size the ESS needed to meet a certain level of reliability in a microgrid is presented. Methods to size DGs in a microgrid to satisfy certain reliability criteria are presented using MILP in [199] and simulated annealing in [200]. In [201], it is shown that using non-flat PV reduces the loss of load probability compared to flat modules. The reliability considerations, as part of the planning optimization, can be found in [58], [79], and [202]–[204]. The study in [202] considers the acceptable annual reliability level in the generation and transmission planning and utilizes the microgrid as a means to improve the system reliability. It is formulated as MILP and simulated by Monte Carlo. In [205], uncertainties are considered in the microgrid planning. The problem is decomposed into the investment master problem and the operation subproblem, and the robust optimization is employed to find a solution in the absence of knowledge about the uncertain data distribution. In [58], a vulnerability index in terms of the loss of load is considered in the planning optimizations solved by PSO. In [203], power-quality and reliability constraints are considered in DER planning in the microgrid and solved by PSO. In [206] and [207], emission penalties are considered in the microgrid planning problem. Emission optimization in [206] results in an increased percentage of integration of renewable resources as emission penalties rise. The study in [207] shows that although the power generated by DGs may not necessarily be more emission efficient than the power imported from the utility grid, using thermal waste can improve the emissions. HOMER [206] is used in the analysis. In [208], generation units are designed and reliability indices of System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Customer Average Interruption Duration Index (CAIDI) are evaluated for a microgrid. In [79], bus voltage limitations are considered as constraints to be kept within the standard range in the microgrid planning problem. In [209], a method is proposed to size microgrids and is solved by GA while optimizing a host of objectives including life-cycle cost, renewable energy source penetration, and airborne pollutant emissions.

VI. MICROGRID OPERATION, CONTROL, AND ISLANDING

Microgrids operate in two modes of grid-connected and islanded. In the grid connected mode, microgrids trade power with the utility grid. In the islanded mode, however, the microgrid operates autonomously without connection to the utility grid. Because of characteristics of the microgrid such as two-way power transfer, presence of DGs, DSM, and considerable presence of power electronics, control of the microgrid in each operation mode as well as the switching between the modes are of the challenges that need to be solved to use microgrids efficiently and realize their features.

A. MICROGRID POWER MANAGEMENT AND CONTROL

It is common to use a hierarchical control structure to control microgrids. The hierarchical structure typically consists of three broad layers: Primary control that stabilizes frequency and voltage using droop controllers, Secondary control that compensates the steady state deviations in voltage and frequency caused by the primary control, and Tertiary control that takes into account economic considerations and determines power flow between the microgrid and utility grid to achieve the optimal operation [210]–[212].

In addition to the control structure, control methods are very important. Some renewable DGs such as wind and solar PV have fluctuations, and don't generate constant power. As a result, the microgrid control would be a complex and difficult process. The study in [213] states that there are two main control methods for microgrids: master-slave control and peer-to-peer control. The former associates with a voltage-frequency (V-f) control while other DGs associate with P-Q control, to control the active and reactive power to be reached to the planned ones. Peer-to-peer control associates with frequency-active power (f-P) and voltage-reactive power (V-Q) controls. Both controls (master-slave and peer-to-peer) have their own advantages and disadvantages. The study in [211] reviews hierarchical control strategies and discusses the coordination among different hierarchies. In [214], an overview about microgrid structures and control techniques at different hierarchical levels is carried out. In [215], the utilization of potential function concept in the secondary and tertiary control of a microgrid is proposed. This approach is generalized in [216] where power flow and resource voltage/power constraints are considered, and potential functions provide secondary control set points to design the trajectory of the system subsequent to disturbances in order to meet explicit local and system-wide constraints. The study in [217] proposes a hierarchical control where the secondary level sends proper control signals to the primary level to control selective compensation of sensitive load bus voltage fundamental negative sequence, as well as positive and negative sequences of main harmonics. In [218], a distributed hierarchical intelligent EMS is proposed that forecasts the generation using neural network, optimizes operating costs, and improves the overall system operation. In [219], a fixed power–voltage–current hierarchical cascaded control structure is proposed with robust internal model voltage controller that yields the robust transition between grid-connected and islanded modes either in load (constant real and reactive powers) or generator (constant real power and voltage) operational modes making it more flexible and robust to islanding detection delays. In [220], a central secondary controller is introduced to manage the compensation of voltage unbalance at PCC in an islanded microgrid by sending proper control signals to DGs local controllers. The study in [221] discusses the microgrid control hierarchy to achieve the desired functions and objectives using a university campus microgrid as a testbed. The study in [222] presents a robust hierarchical control system of DG converters for the robust microgrid operation and seamless transfer between grid-connected and islanded modes, providing high disturbance rejection performance against voltage disturbances and power angle swings, respectively. In [223], a three-level hierarchical hybrid control system is presented, where the intelligent reconfiguration strategies of the operational mode are established via a distributed system modeling language called Petri nets and the information fusion technique. In [212], a three-level hierarchical control is proposed that can be used for AC or DC interconnection with an AC or DC distribution system. In [224], a hierarchical control scheme is presented using a MAS for the black start operation of microgrids with power electronic interfaces. The study in [225] further presents a hierarchical active power management strategy for a medium-voltage islanded microgrid that includes the power management of the fuel cell/super-capacitor hybrid system, current sharing among the components, voltage control of the AC-side, and power sharing among DGs. The study in [136] proposes a novel double-layer coordinated control approach for the microgrid energy management, consisting of two layers: the schedule layer and the dispatch layer. The study in [226] presents a hierarchical control structure for DC microgrids aiming at their resilient and economic operation.

1) CONTROL ARCHITECTURE

Two common control architectures for microgrids are centralized and distributed. Standardized procedures and easy implementations are among advantages of the centralized approach. The study in [112] presents a microgrid central controller with two major functions for distribution systems: having a communication channel with the distribution system operator and the electricity market, and exchanging information with the microgrid local controllers and processing them. In the centralized control scheme, the central controller makes decisions about the dispatch of all DGs and ESSs according to the objective function and constraints. In [111], a centralized EMS architecture is proposed for implementation on isolated microgrids in the islanded mode of operation. In [227], a control method is proposed for a set of inverters separated by communication links that separates the control tasks in the frequency domain. Power sharing and voltage regulation are controlled centrally, and commands are distributed through a low-bandwidth communication link. High bandwidth controllers are distributed to each local inverter. The disturbance rejection level achieved by this method is equal to that of a single inverter with a single full bandwidth controller.

In microgrids where each DG has its own controller and pursues distinct objectives, distributed control provides premium applicability. The number of transmitted messages between different individual components and the microgrid controller increases as the size of the microgrid increases, necessitating a larger communication bandwidth. Decentralized control can reduce the number of messages and also simplify the optimization with special constraints by reducing it into subproblems and solving them locally [228]. In [88], a differential algebraic system of the microgrid decentralized active power/frequency and reactive power/voltage magnitude droop control is developed and simplified to determine stable boundaries of the microgrid for different droop control gains. In [229], an analytical justification for using a distributed voltage-control scheme is presented to stabilize the grid-voltage under a wide-range of operating conditions, and a novel DC microgrid solution, geared at maximizing efficiency and reducing the system installation cost, is described. In [230], it is shown that the full exploitation of energy resources is possible without central controllers, by taking advantage of the local measurement, communication, and control capability. In particular, it is shown that the microgrid operation can be optimized by applying token ring control and grid mapping techniques, which only require communication capability between neighbor nodes via power lines. In [231], a decentralized power control method in a single-phase flexible AC microgrid is proposed to enable the microgrid inverter to operate seamlessly in both grid-connected and islanded modes of operation.

In [232], a decentralized control strategy is developed using frequency variations to control power generation and loads within the microgrid. Power electronics transformers enable active power flow to the grid. In [233], a decentralized power sharing algorithm is used based on the droop control in a hybrid microgrid which consists of inertial and converter-interfaced DGs. One DG functions to compensate the non-linear (i.e., unbalanced and harmonic) load of the microgrid and to improve the power quality while other DGs share the power. The proposed control scheme can seamlessly change its mode of operation depending on the power demand of the nonlinear load. The extension of the nonlinear load to a low-voltage residential distribution network shows the possibility of supplying single-phase residential loads with PVs. The study in [234] investigates the stability enhancement of decentralized inverter control in microgrids by setting up a wireless network to acquire the information of total real and reactive power generation of all DGs. The paper also proposes a power sharing based control strategy, which introduces additional terms to the traditional droop control strategy to capture the differences between the desired and actual real and reactive power generation. The study in [235] proposes decentralized regulators for DGs in meshed islanded microgrids that only depend on the transmission lines connected to them; therefore, if a DG is plugged in or out, only the DGs connected to it need to retune their controller. The study in [236] provides a comprehensive account of the application of game theory in distributed control of microgrids including cooperative energy exchange and use of non-cooperative games for modeling the interactions between loads and DERs in microgrids. The study in [237] proposes a mode-adaptive decentralized control strategy for DC microgrids to improve the classical droop control. It utilizes the DC voltage to facilitate flexible mode definition, seamless mode transition, and reliable power sharing.

a: MULTI-AGENT SYSTEMS

One of the approaches to implement distributed control is using MAS. In this approach, each of the controllable elements in the microgrid such as inverters, loads, and DGs have agents associated to them, where the communication and coordination of the agents is governed by the multi-agent theory. MAS includes the microgrid cluster management agent, microgrid control agent, and local agent. The loosely coupled agents forming the MAS are physically or logically dispersed, and have some distinct characteristics: 1) their data is distributed, 2) they have an asynchronous or simultaneous process of computation, 3) they lack information and capability of problem solving, and 4) they interact and cooperate with each other, hence their problem solving capability would be improved [238]. In [224], a MAS architecture is used in a hierarchical control scheme in a microgrid with power electronic interfaces. Five types of agents are proposed in this architecture, including grid agent, central agent, generation agent, load agent, and breaker agent. With this architecture, the MAS is able to coordinate DGs and loads to maintain steady state operation of the microgrid in both grid-connected and islanded modes; it can also perform a black start if a seamless transition to the islanded mode fails or if a black start becomes necessary for any other reason. In [239], an Internet Protocol and a MAS technology-based microgrid monitoring and control system are proposed and implemented. When the utility grid experiences failure/outage, MAS architecture would isolate the microgrid from the utility grid in order to ensure the microgrid safe and stable operation and enable the utility grid operation in grid-connected mode after the fault is cleared. In [223], a hierarchical hybrid control system is presented, composed of an upper level energy management agent, several middle level coordinated control agents, and many lower level unit control agents to maintain and restore the frequency and voltage of a microgrid. The study in [240] describes the general architecture of a secondary control of a microgrid based on MAS architecture. Maintaining the microgrid frequency and power exchange with the utility grid close to predefined values is achieved by optimally dispatching generation and consumption resources and ability to operate in both grid-connected and islanded modes. In the islanded mode, the control system maintains the frequency of the microgrid close to the reference level. The study in [124] describes a microgrid management system which is developed using agent based technologies. Its application to the effective management of generation and ESS devices connected to a low-voltage network is further presented. In [241], a MAS architecture for real-time operation of a residential microgrid with an RTDS is proposed. The MAS architecture is developed in an open source IEEE FIPA compliant platform, and a two-stage operational strategy is implemented on the MAS architecture. In [242], the participation of the microgrid controlled by the MAS architecture in the energy market is studied. Every DER and controllable load decides through the auction algorithm what is best for it, taking into account the overall benefit. In [243], an energy coordination control strategy is presented based on the MAS architecture under the islanded mode to efficiently dispatch power between generators and loads in the microgrid within a non-cooperative environment. Considering DGs' interests, each agent with its own mechanism for decision making interacts and collaborates to achieve the overall goal of the system. In [123], an application of MAS architecture is presented for DER management in microgrids, by representing each element in the microgrid as an autonomous intelligent agent, and presenting the multi agent modeling of a microgrid. The study in [244] compares the centralized and decentralized MAS architecture microgrid power management and control. A method is further presented for facilitating the fundamental self-organizing and cooperative behavior amongst the microgrid agents. In [245], a MAS architecture is designed to provide control to a microgrid and smooth its transition from grid-connected to an islanded mode during upstream outages. In [246], the decentralized agent-based control for microgrids using the agent cooperation through negotiation and the resulting MAS architecture self-ordering power management objectives is presented. The MAS architecture guides microgrid asset operation based on the market price, resources available to the microgrid, and additional environmental and efficiency objectives. The study in [247] proposes a MAS architecture for optimizing the DR by updating the grid generation resources and controlling the customer load. It can switch the customer load and control the charging of PHEVs depending on their battery state of charge to reduce the cost and avoid overloads during peak hours.

b: COOPERATIVE CONTROL

When a microgrid becomes islanded from the utility grid, the primary control keeps the voltage and frequency stable. However, the voltage and frequency can still divert from their nominal values. In order to retrieve the voltage and frequency to nominal values, a secondary control mechanism should be employed. This secondary control could be the distributed cooperative control. ''Cooperative'' means that all participants cooperate with each other and act as a single group to reach the common goals [248]. In [249], a two-layered cooperative control strategy of micro-sources and ESSs within a microgrid during islanded operation is presented. The ESS handles the frequency and the voltage as a primary control. Consequently, the secondary control in the microgrid management system returns the current power output of the ESS into zero. In [250], a fully distributed scheme of the secondary voltage and frequency control is proposed based on the distributed cooperative control of MAS, and is implemented through a communication network with one-way communication links. In [248], the input–output feedback linearization is used to convert the fully distributed secondary cooperative voltage control of microgrids, based on the control of MAS, to a linear second-order tracker synchronization problem. The control parameters can be tuned to obtain a desired response speed. In [251], the collaboration of microgrids with the aim of load management is studied, and it is shown that this objective could be achieved by a collaboration between microgrids using a communication infrastructure and defining a set of purchase prices. A natural consequence of this collaboration is to smooth the power generation within the grid. It is shown that power sharing in the grid-connected mode results in lower prices than that in the islanded operation. This is due to the fact that low demand microgrids benefit from selling power to the grid. On the other hand, high demand microgrids reduce their production cost by purchasing power from the grid.

2) VOLTAGE AND FREQUENCY CONTROL

Synchronous generators exhibit a self-stabilizing feature due to their high rotational inertia [252]. Most of generation units integrated in the microgrid are not of the synchronous generator type and thus somehow need to mimic the droop characteristic existing in those generators. In [253], bifurcation theory is used in scheduling the drooping characteristics of frequency (and voltage) regulation in isolated microgrids to provide insight on how the choice of the droop coefficients affects both the stability of the microgrid and the reserve requirements. In [254], the implementation of conventional frequency-voltage droops into the batteries grid-side inverters is proposed, thus downscaling the conventional grid control concept to the low-voltage grid and further avoiding expensive control systems that require communication and extra cabling. In [255], the conventional droop control for microgrid converters is modified based on a feed-forward current control that allows the converter to work in several modes, either grid-connected or islanded mode, permitting the inverter to work as a grid supporting source or ancillary services provider. The study in [256] investigates the voltage and frequency control of islanded microgrid after intentional and unintentional switching events and shows the voltage-active power and frequency-reactive power dependency in a weak low-voltage network. It further shows that in order to maintain the frequency balance in islanded microgrids, there is a need for a reference sine wave generator inside the ESS which imitates the utility grid phase voltages, and provides the input for the phase locked loop of the ESS unit during islanding. In [257] two control methods are proposed to ensure acceptable power sharing in a weak system condition and a highly resistive network for rural distribution networks: first, without any communication between the DGs, where the feedback quantities and the gain matrices are transformed with a transformation matrix based on the line resistance-reactance ratio; and second, with a minimum communication-based output feedback controller. The converter output voltage angle reference is modified based on the active and reactive power flow in the line connected at PCC. The web-based communication of the power flow quantities is more economical and makes the proper power sharing solution possible. In [231], a power droop control is proposed with a derivative controller in the islanded mode. Transitions between the operation modes are evaluated to be smooth. In [89], a pseudo-droop control structure in a microgrid is presented that uses the microgrid line-frequency variation as the agent of communication for energy control among DGs. In [258], an EMS is presented for an islanded droop-controlled microgrid, which adjusts DG outputs to minimize the fuel consumption and also ensures the stable operation. Optimized generator outputs are implemented in real-time by the EMS, through adjustments to droop characteristics within prevailing constraints. In [259], real and reactive power management strategies of power electronics-interfaced DGs are proposed in the context of a multiple-DG microgrid. Three reactive power management strategies are identified and investigated based on the 1) voltage-droop characteristic, 2) voltage regulation, and 3) load reactive power compensation. The real power of each DG is controlled based on a frequency-droop characteristic and a complimentary frequency restoration strategy. A small-signal dynamic model for a multiple-DG microgrid is developed and its Eigen structure is used to examine the microgrid stability, design and optimize control parameters, investigate the impact of power management strategy on the microgrid dynamics after islanding, and evaluate interactions between the DG and the network. Results show that the reactive power management systems based on the voltage-droop characteristic and voltage-regulation can cause overcompensation and require limits on reactive power controllers. Control parameters, including gains of real and reactive power controllers, effectively change the damping ratio of the DG-network oscillatory modes of the microgrid, and relative location and electrical proximity of DG affect the interaction modes of the DG. In [260], a control parameter-tuning method is presented using the PSO algorithm and gain-scheduling method to maintain the required control performance and power quality of multiple microgrid generators for both grid-connected and islanded modes. The study in [261] presents a dynamic model of flywheel ESS to mitigate problems introduced by wind generation into microgrids and control the power exchange between the device and the utility grid which has three modes: voltage control, frequency control, and active power stabilization. Case studies show an acceptable performance of the proposed control techniques along with a high effectiveness to smooth the active power fluctuations of wind generation. In [262], a voltage and frequency control is applied to doubly-fed induction generator which improves the dynamic behavior of a microgrid composed of a doubly-fed induction generator and a synchronous generator. Simulation results show that the proposed control approach for DGs in the microgrid increases the dynamic performance, reduces frequency changes, and improves the bus voltage regulation during the islanded operation. The study in [263] proposes an adaptive droop control for ESSs in a microgrid so that the ESS with a higher state of charge delivers more power. In [264], output power of DGs is adjusted in an islanded droop-controlled microgrid to minimize the fuel consumption and also ensure stable operation. Three key elements make up the proposed EMS: droop stability analysis, droop selection, and generator dispatch optimization. The analysis may make it feasible to implement more sophisticated DG droop settings in islanded microgrids. In [265], small-signal models of droop based generation control schemes are developed for DG inverters, which are comprised of active power-frequency and reactive power-voltage controllers, enabling decentralized operation with load sharing in a microgrid. The study in [266] presents an angle droop control loop for a microgrid with interfaced DG converter that enhances load sharing.

There are many studies on the context of microgrid voltage control. When connected to the utility grid, the microgrid voltage will be dictated by the utility grid as it acts as an infinite bus. In the islanded mode, however, voltage control becomes an important and challenging task that requires careful attention. In [267], a state-space model of the microgrid with voltage control is simplified to enable stability analysis using the eigenvalue and participation factor analysis. Simulation results show that loads with higher power factors, longer distribution feeders, smaller VSC filter impedance, and smaller control loop gains improve robustness of the system, but make it slower. In [268], a set of controllers is proposed containing inner current and voltage loops for regulating the grid-interfacing inverter, and outer real and reactive power loops for controlling the flow of power within the microgrid. Particular focus is on the proper power sharing between DGs when a utility fault occurs and the microgrid islands. The proposed controller also incorporates algorithms for synchronizing the microgrid and the utility grid once the fault is cleared and the microgrid is on the verge of transiting from the islanded to the grid-connected mode. The study in [269] proposes the voltage control for a distribution feeder connected with multiple PV systems, and presents field tests conducted in Japan. In [270], an H_∞ controller is presented for the voltage-source-inverter voltage control in a microgrid with a power-factor correction capacitor-bank for resonance damping. The study in [271] proposes a control and operation strategy for a DC microgrid consisting of nondeterministic wind generation, ESS, variable load, and AC grid connection which uses DC voltages as control input to switch between different operating conditions. The strategy has three modes: DC voltage control and power balancing by using the AC grid-connected converter under normal power and load variation; coordinated DC voltage control and power balancing by using the grid-connected converter and ESS during the AC grid fault and grid-connected converter power limit; and islanded operation and strategy for proper load shedding. In [272], a control strategy in a VSC fed microgrid is proposed where multiple voltage-power droop/frequency-reactive power boost controllers jointly regulate the microgrid voltage by drooping the voltage reference of each controller against its real power output. This allows multiple VSCs to operate in parallel in a microgrid and work in both modes of operation. In [273], the application of L-index, a novel voltage stability index, is proposed to microgrids providing an online mechanism for computing and rating the status of the interconnected system into the utility-supplied, microgrid start-up, as well as grid-connected and islanded modes for improved operation. In [274], the voltage control on a DC microgrid is studied using a voltage droop based power sharing and coordination strategy among the slack terminals for power smoothing during grid-connected condition and normal operation during islanding condition. The study in [275] proposes a coordinated control of DGs and distribution static compensator (DSTATCOM) in a microgrid in which the power flow and the voltage at different locations of the feeders are communicated to the DSTATCOM to modulate the reactive compensation. The single-phase DSTATCOM compensates for the reactive power deficiency in the phase while DGs supply "maximum available active power." During reactive power limit of the DG, the "maximum available active power" is fixed to a value lower than the maximum active power to increase reactive power injection capability of DGs. A primary control loop based on the local measurement in the DSTATCOM always ensures a part of reactive compensation in case of the communication failure. In [276], the voltage-reactive power dot droop control method is proposed with Formula restoration mechanism to improve the reactive power sharing among distributed resources interface converters in the microgrid environment. The converter's output voltage, resulting from integrating formula, will keep varying until the desired reactive power output sharing is accomplished which allows the proposed method to overcome the effect of different line impedances of each converter. In [277], a droop control principle for islanded low-voltage microgrids strategy is proposed that modifies the set value of the microgrid voltage at the inverter AC side as a function of the DC-link voltage to balance the microgrid. The study in [278] shows that the voltage-based droop control is possible in both grid-connected and islanded modes. In the islanded microgrid, proper power sharing and voltage control are obtained. An optimized integration and capturing of the renewable energy is achieved by using constant-power bands. In the grid-connected mode, the control strategy does not need to be changed. Without the need for communication, the renewables take part in the voltage control by using soft curtailment in case of extreme voltages. In [279], a reactive power control method is proposed which can regulate the voltage at one or a group of the target buses in a microgrid while ensuring maximum power point tracking, employing a sliding mode control scheme, and directly controlling the active and reactive powers of a doubly-fed induction generator wind system. This control method doesn't involve any synchronous coordinated transformation, and further doesn't restrict the voltage swings experienced at different buses compared to the unity power factor method. The method eliminates the need for decoupled proportional-integral loops. Additionally, the control performance is not degraded by errors in system parameters. In [280], an autonomous control strategy based on DC voltage variation for a DC microgrid with variable sources and loads is proposed. It is divided into three levels according to DC voltage variation. Within the three levels, slack terminals are assigned to each level to balance the power flow. At least one slack terminal must be operational at each time to ensure the stable and normal operation. A control strategy has been proposed and examined during various static and transitional operations, such as grid connection, load step, islanding, load shedding, generation curtailing, and AC reconnection. The study in [281] defines the voltage droop coefficient as a function of respective VSC active and reactive power outputs for the parallel operation of VSCs in an islanded multi-bus microgrid which leads to a reduction in the reactive power sharing dependence on real power control and system parameters. In [229], an analytical justification for using a distributed voltage-control scheme is proposed. In this scheme, the microgrid voltage droops in response to low-supply/high-demand is introduced to stabilize the grid-voltage under a wide range of operating conditions. The paper further describes a novel DC microgrid solution that is geared at maximizing efficiency and reducing the system installation cost. In [282], a power management scheme is presented for DC microgrids to optimize energy utilization, which consists of four operation modes in which the DC bus voltage level is employed as an information carrier to represent different operation modes.

Frequency control, or active power-frequency droop, is another important area of research in microgrids. Most of DERs installed in the microgrid generate DC or variable-frequency power that unlike synchronous generators cannot be relied on for the frequency regulation in the islanded operation. The high penetration of power-electronically interfaced DGs leads to a low inertia in microgrids. Therefore, proper measures need to be implemented to control frequency in the microgrid [235]. The study in [283] proposes a DR-based frequency control strategy for an islanded microgrid using the adaptive hill climbing method. Both the frequency and voltage profiles are regulated at the same time, and the transient part of the frequency profile is improved under sudden load disturbances. In [284], a dynamic control method for an electrolyzer system (that electrolyzes water to produce Hydrogen) in a microgrid is proposed, which secures a real power balance and enhances the operational capability to handle frequency fluctuations in multiple renewable energy hybrid microgrids. The proposed control and monitoring system can both improve the frequency fluctuations caused by random power fluctuations on the generation and load sides, and relax tie-line power flow fluctuations caused by frequency variations in the interconnected microgrids. In [285] a coordinated controller of the electrolyzer and micro-turbine is proposed with better robustness and stabilizing effects than that of the electrolyzer controller. It is based on a PSO-based fixed-structure H_∞ loop shaping. The controller absorbs power fluctuations caused when the intermittent power generations from the wind power and PV are integrated into the system, and enhances the frequency control effect of micro-turbine in the microgrid. In [286] coordinated and uncoordinated approaches are proposed for aggregators to provide primary frequency regulation reserves. The study shows that it is more beneficial to implement the coordinated approach, with the possibility of having different amounts of committed reserves in different hours, than the uncoordinated approach in which only a fixed amount of reserve is assigned to all hours and, therefore, the settings of controllers are changed much less frequently. In [287] the boost convertor attached to the PV panel in a microgrid is used to regulate the frequency of the microgrid despite changes in the load. In [288] it is shown that in the presence of feeder flow control, when several DGs are connected to a single feeder with series connections, the system frequency changes significantly, and some of the DGs are excessively loaded during the transition between grid-connected and islanded operations. The paper proposes methods to determine the droop constants that produce stable and appropriate power sharing. The study in [253] employs bifurcation theory to schedule the drooping characteristics used for frequency and voltage regulation in isolated microgrids and offers a procedure to determine the best direction to vary the coefficient with respect to the microgrid stability. It further analyzes the advantages of using Dobson's margin sensitivity formula to evaluate the priorities and limits in primary reserve scheduling. In [289] a coordinated control method is presented for output power fluctuation leveling of PV plants so as not to harmfully influence the utility grid at times with large frequency deviations. The study in [290] shows that in an autonomous microgrid that only contains VSC-interfaced DGs, the frequency variation with the frequency droop controller is significantly higher than that with the angle droop controller that is derived from DC load flow. In [291], a comprehensive central DR algorithm is proposed based on the communication between the utility control center and responsive loads providing frequency (and consequently voltage) regulation as well as minimizing the amount of manipulated responsive loads in the absence/presence of wind power generation. The study in [292] uses the frequency droop control with the additional disturbance as the link to compensate reactive, imbalance, and harmonic power sharing errors. Real power sharing variations are generated and used to adjust the DG virtual impedances at fundamental positive sequence, fundamental negative sequence, and harmonic frequencies. This approach would compensate the impact of unknown feeder impedances and improve power sharing at the steady state. The study in [293] proposes a control strategy using under-frequency load shedding to restore frequency stability of islanded microgrids.

3) ADAPTIVE CONTROL

Adaptive control is used to control the systems with varying or uncertain parameters. As microgrid operating modes can unexpectedly change as a result of disturbances in the utility grid, adaptive control schemes are proposed. In [294], an adaptive control strategy is proposed to augment the existing controllers and enhance their performance while monitoring the response of a controlled device and temporarily modulating its control set point to achieve close tracking of the set point in the presence of disturbances. It presents a detailed analytical derivation for the case that the overall behavior of the system (the devices and the controller) is approximated using a second-order transfer function. It is used to confirm the viability of this strategy and its ability in designing a response with limited over- or undershoot. In [295], an adaptive control method is presented for a DC microgrid to coordinate the operation of converters, DERs, and switches used in a DC microgrid. In [296], an adaptive control is presented for frequency regulation by using a combination of a classical PI controller and a PSO-fuzzy system.

4) CONTROL OF TIE-LINE POWER FLOW

When the microgrid power exchange with the utility grid is scheduled, it is necessary to create a control mechanism so that the actual power flow matches the scheduled values. The control of the power flow between the microgrid and the utility grid has been the main discussion in [297]–[300]. In [298], a power flow control scheme is proposed between the utility grid and the microgrid using back-to-back converters that isolate frequency between the two systems. In this case, voltage or frequency fluctuations in the utility side have no impact on voltage or power in the microgrid side. Only locally measured data are used by DGs where no communication is needed for load sharing. In [299], the use of an improved superconducting magnetic ESS controller for the stabilization and control of the power flow of wind-hybrid microgrids is proposed. In this sense, the design and implementation of a novel high-performance power conditioning system scheme of the superconducting magnetic ESS is described. In [300], the use of a superconducting magnetic ESS in combination with a DSTATCOM as an effective ESS is proposed for stabilization and control of the tie-line power flow of microgrids incorporating the wind generation. The study in [297] addresses controlling the power transfer through the PCC by introducing the concept of a smart transformer at the PCC. This method controls the active power exchange between the microgrid and the utility grid, depending on the state of both systems and other information communicated to the smart transformer. The control is compatible with the voltage-based droop control of DGs in the microgrid.

B. MICROGRID MODELING, ANALYSIS, AND TESTING

In [301] a small-signal state-space model of a microgrid is presented which includes inverter low frequency dynamics, high frequency dynamics, network dynamics, and load dynamics. The model analysis shows that the dominant low-frequency modes are highly sensitive to the network configuration and the parameters of the power sharing controller of micro sources. The high frequency modes are largely sensitive to inverter inner loop controllers, network dynamics, and load dynamics. In [302], an advanced web-based framework is proposed based on the service-oriented architectures for integrated microgrid modeling, monitoring, and control which is platform, language, and vendor independent, and thus represents an ideal candidate for an effective integration in existing EMSs and distribution management systems. Different challenges and approaches in microgrid testing are discussed in [303]. The study in [304] establishes the simulation models for simulating the dynamic performance of a microgrid feeding the electrical loads in a sailing boat, that consists of two solid-oxide fuel cells, a diesel-engine generator, a battery ESS, a wind turbine generator, a sea-water aqua electrolyzer, an AC-to-DC converter, and a DC-to-AC inverter. The study in [305] applies the concept of real time analysis in a smart grid by developing a test-bed smart microgrid in power system laboratories with a high level of reliability.

C. CONTROL OF POWER ELECTRONIC CONVERTERS

In [306] a control scheme is proposed for controlling the interlinking converter to keep the hybrid microgrid in autonomous operation with active power proportionally shared among its DERs. Power sharing depends only on DER ratings and not the placements within the microgrid. In [307], a control strategy is proposed for a single-phase series-connected inverter with the microgrid to interface AC loads not only to regulate the load voltage under voltage disturbances, but also to control the load power drawn from the microgrid. In [308], an approach for the control of a microgrid with VSC-interfaced DER is proposed to operate in grid-connected and islanded modes, as well as to provide a smooth transition between the two modes. In [309], a dynamic electro-thermal model is proposed that can be simulated with the power electronic circuit simulator and is used to estimate the transient junction temperature of the semiconductor devices. In this approach, the resulting junction temperature is used to facilitate the power sharing between parallel-connected converters. The use of power-cycling method based on the junction temperature improves the overall system efficiency and reliability. In [310], a new control scheme for parallel-connected inverters is presented, taking into account the effect of the line consisting of two single-phase inverters connected in parallel based on instantaneous average current-sharing control that requires interconnections among inverters for information sharing. In [311], a power control and sharing strategy is proposed for power electronics-interfaced DGs in a low-voltage multi-bus microgrid containing a virtual inductor at the interfacing inverter output as well as an accurate power control and sharing algorithm with consideration of both impedance voltage drop effect and DG local load effect. It can accurately control the DG real and reactive output powers in both grid-connected and islanded modes without physical communications among DGs. In [312], a novel extended-phase-shift control of isolated bidirectional full-bridge DC-to-DC converter is proposed for power distribution in microgrids. Compared with the traditional phase-shift control, extended-phase-shift control, it reduces current stress and improves the system efficiency. By establishing mathematical models of transmission power, backflow power, and current stress, the paper comparatively analyzes control performances of the traditional phase-shift and extended-phase-shift control. In [313], a hybrid control architecture is proposed to balance the power shared among the multiple interfacing inverters and optimize the system-operating efficiency. The inverters are divided into blocks according to their geographical location. To control the power sharing of inverter blocks located in a wide range, a modified droop-control method with virtual resistor scheme is applied. The study in [314] proposes a complete modeling and control system for a bidirectional, single-phase, multifunctional pulse width modulation converter for residential power level distributed renewable energy and grid-connected microgrid applications. A simple control structure is used to cover all of the required operating modes, including islanded and grid-connected modes. A new single-phase locked loop and active islanding detection algorithm are also proposed for system-level operation in order to meet IEEE standard 1547. The resulting control structure is very simple, and presents robust, low transient responses even for extreme load steps between no-load and heavy-load conditions. The transition between modes was also seamlessly achieved, as predicted, due to the common inner current-loop that all operating modes have. In [315], a new formulation of direct power control is proposed that allows to analyze the shortcomings of this kind of algorithms, mainly regarding the power limits in which table-based algorithms are valid. In [316], a hybrid AC/DC microgrid is proposed to reduce the processes of multiple DC-AC-DC or AC-DC-AC conversions in an individual AC or DC microgrid. The models and coordination control schemes are proposed for all converters to maintain a stable system operation under various load and resource conditions. In [317], controller design and optimization methods are proposed to stably coordinate multiple inverter-interfaced DGs and to robustly control individual interface inverters against voltage and frequency disturbances. Droop-control concepts are used as system-level multiple DG coordination controllers, and control theory is applied to device-level inverter controllers. Optimal control parameters are obtained by PSO. The study in [318] investigates the inverter-based microgrid control employing conventional control techniques such as the root locus and the frequency domain analysis. In [319], a multi-loop controller is proposed with voltage differential feedback, and with output voltage decoupling and output current decoupling by only using the output voltage feedback. The output voltage differential feedback loop actively damps the output LC filter resonance and thus increases the system stability margin. The study in [320] presents a hybrid off-grid power system consisting of two PV Arrays, two dispatchable DG sets, two charge controllers, two bidirectional inverters, as well as two battery banks, and outlines different topologies for optimum energy extraction from solar panels, minimization of generator fuel consumption, and assurance of higher reliability through redundancy. Controller Area Network messages are used as the communication interfaces between key components and also as the interface with the data monitoring system. In [282], control methods for modular PV converters, battery converter and grid-connected DC/AC converter are developed. The power balance of the DC microgrid under the extreme condition (the islanded mode with full-charged batteries) is guaranteed by the proposed control method for modular PV converters. In [321], a dynamic modeling and control strategy is presented for a sustainable microgrid primarily powered by wind and solar energy using a current-source-interface multiple-input DC-to-DC converter to integrate the renewable energy sources to the main DC bus. The study in [322] proposes harmonic current filtering and resonance damping methods for inverter-interfaced DGs in an islanded microgrid using the concept of variable harmonic impedance. In [323], a control strategy is proposed for electronically coupled DERs in a microgrid to improve the performance under network faults and transient disturbances. The control of UPS–based microgrids is another topic of investigation in a handful of papers. In [324], the control strategy for a microgrid consisting of several line-interactive UPS systems, which are connected in parallel, is proposed. The control technique consists of an inner voltage feedback loop that regulates the output voltage and an outer active and reactive power sharing loop based on the droop method to deter communications and further avoid critical communications upgrades among UPS units. The study in [325] integrates battery and its bidirectional DC-to-DC converter in the UPS system. The DC link controller loop is designed to set the active power demand during battery charging mode, which allows for a smooth transition between battery charging and discharging modes.

D. MICROGRID ISLANDING

The salient feature of a microgrid is its ability to be islanded from the utility grid by upstream switches at the PCC. Islanding could be introduced for economic as well as reliability purposes. During utility grid disturbances, microgrid is transferred from the grid-connected to the islanded mode, and a reliable and uninterrupted supply of consumer loads is offered by local DERs. The microgrid master controller would offer the optimal operation by maintaining the frequency and voltages within permissible ranges. The islanded microgrid would be resynchronized with the utility grid once the disturbance is removed [259], [326], [327]. Considering its importance, many studies are focused on the microgrid islanding. In [328], a control strategy is proposed to detect islanding and ensure DG synchronization at the time of reconnecting and load shedding when needed. It includes two interface controls: one for grid-connected operation and the other for intentional-islanding operation. The study in [329] describes and evaluates the feasibility of control strategies to be adopted for the operation of a microgrid when it becomes isolated and concludes that a fast elimination of a fault in the medium-voltage network is required. Additionally, single master operation and multi master operation are simulated and shown to be effective in order to ensure the microgrid stability, and that the management of ESS devices is absolutely essential to implement successful control strategies. In [330], the process of planned islanding and necessary steps that need to be taken in order to lead to successful projects is presented. Some of the current experiences from Canadian utilities in this area are investigated and the additional requirements, in terms of equipment and system studies, needed for the operation of an islanding project, are discussed. In [331], various islanding scenarios of a 13.8-kV microgrid are studied including a synchronous generator and a power electronics-interfaced DG. It is shown that an appropriate control strategy for the power electronics-interfaced DG can ensure stability (through active power control) of the microgrid and maintain voltage quality (through reactive power control) at designated buses, even during islanding transients. When switching between islanded and grid-connected modes, significant changes in voltage and frequency values may occur; therefore, microgrid stability becomes an important issue to be considered. Stability issues may also occur due to unpredicted variations in the generation of nondispatchable DGs. Microgrid stability studies are divided into two groups of small-signal and transient. The microgrid stability problem is investigated in [332]–[335]. In [332], an in-depth simulation study on the stable operation of microgrids during faults is presented where it is shown that only motor loads introduce instability to a microgrid not impedance loads. In [333], the impact of the DG interface control on microgrid transient stability is analyzed and shown that the critical clearing time of a microgrid is highly dependent on the microgrid control strategy, DG interface control, and load type. In [334], the stability of low-voltage DC microgrids is analyzed where sources are controlled using a droop-based decentralized controller. The model provides an upper bound on droop constants which is useful during the design and the planning of DC microgrids. The study in [335] identifies fluctuations in loads intermittent energy resources as small disturbance and proposes a small signal stability study method based on Singular Entropy and Matrix Pencil. In [336], different control and protection schemes needed to ensure islanded operation of a distribution system, and further enable it to operate as a microgrid, are analyzed. In [337], an intelligent load management algorithm in the islanded mode is proposed. It detects the conditions in which an insufficiently supplied load exists and systematically removes loads from the system so the islanding can be maintained and operating limits can be satisfied.

Once the fault is alleviated, the microgrid will be resynchronized with the utility grid. Resynchronization refers to reconnecting the islanded microgrid to the utility grid while ensuring that the microgrid voltage and frequency are synchronized with that of the utility grid [338]. If not ensured, serious damages due to current surges may happen to the microgrid components during the switching process. The study in [339] discusses applications of microgrids in distribution system restoration, and provides a control framework to recover from power outage. In [340], an active synchronizing control scheme is proposed that adopts the network-based control of multiple DGs to adjust the frequency and voltage of the microgrid. It is shown that the scheme provides the microgrid with a deterministic and reliable reconnection to the grid. In [341], a grid synchronization method for a multi-converter DG system is proposed, allowing multiple droop-controlled converters to adjust the frequency, phase, and amplitude of their output voltages to prepare for grid connection. The entire synchronization process can be executed with very limited communication requirements. The study in [342] shows that a network of loads and DC-to-AC inverters equipped with power-frequency droop controllers can be considered as a Kuramoto model [343] of phase-coupled oscillators, enabling characterization of the behavior of the network of inverters and loads. A necessary and sufficient condition for the existence of a synchronized, unique, and stable solution is provided. Moreover, a distributed integral controller based on averaging algorithms regulating the system frequency in the presence of a time-varying load and preserving the power sharing properties of the primary droop controller is proposed in this model.

VII. MICROGRIDS CLUSTERS

The significant and widespread deployment of microgrids, which is happening now and is anticipated to grow in the future, necessitates additional studies on the interaction of microgrids as well as cases that microgrid clusters are emerged. Microgrid clusters can be studied from different perspectives. Economic benefits of microgrid clusters are discussed in [190] and [344] in which it is shown that their operation leads to reduction in emissions and end user costs while addressing the load growth. Microgrid clusters enable an efficient energy trading by allowing cooperation. The study in [345] formulates a coalitional game between a number of microgrids to study novel cooperative strategies in microgrid clusters. Simulation results show that the proposed algorithm yields a reduction in terms of the average power losses relative to the non-cooperative case. In [346], an analysis of price competition among interconnected microgrids is presented using the game theory framework, which explicitly computes a Nash Equilibrium and shows its uniqueness.

In [347] a game theoretic approach is proposed to model and analyze the strategic situations arising from the interactions of multiple decision making participants in the microgrid decentralized environment like smart agents, distributed computing, smart sensors, as well as a solid and fast communication infrastructure. The study in [348] addresses the case where two microgrids are isolated from the utility grid but can exchange energy with each other in a peer-to-peer manner aiming to minimize the total cost resulting from energy generation and transfer, while each microgrid satisfies its local power demand. The control of the microgrid clusters is another important issue to be studied. In [349], a microgrid cluster control system is proposed and implemented using MAS for communication and control among a number of adjacent microgrids. The study in [238] presents a novel microgrid cluster with a distributed control oriented hierarchical system and distributed MAS architecture. In [350], the control of microgrid clusters is performed in three levels: local microsource and load controller, microgrid central controller, and distribution management system. The control of this system is done by a central autonomous management controller, which serves as an interface to the distribution management system. In [351], a hierarchical and decentralized scheme is proposed for coordinated voltage support and frequency control, as well as for state estimation of microgrid clusters. Fuzzy state estimation and microgrid cluster state estimation are further proposed in [350] and [352]. In [352], control functionality to manage micro-generation in microgrid clusters is proposed considering active loads and ESS, subject to different constraints. The study in [353] sets up a framework to operate the system of systems composed of a distribution company and several microgrids. A decentralized OPF is used to operate this active network. The study in [354] proposes an OPF algorithm for microgrid clusters. It tries to minimize the operation cost of the cluster, total energy loss, and voltage profile deviation of all system buses. It is solved by sequential quadratic programming technique.

VIII. MICROGRID PROTECTION

The unique characteristics of microgrids necessitate changes to the conventional distribution network protection strategies. Connection of DERs, which are normally power electronics-interfaced, results in bi-directionality of fault current, reduction in fault current capacity, disruption in fault detection, and protection sensitivity. Furthermore, the dynamic topology of the microgrids due to islanding and sectionalizing necessitates the protection to be able to adapt itself to new conditions. Considering this elevated need, several studies have investigated the topic of microgrid protection.

A. FAULT MODELING AND ANALYSIS

The study in [355] explains that the protection of microgrids needs to be included in the generation and be plug-and-play since the overcurrent protection might detect the current magnitude as a fault. The study in [356] discusses the assignment of fault current coefficient. In [357], an arc model is presented to study series faults in low-voltage DC microgrids. In [358], the fault current distribution is studied and a grounding electrode system is developed to ensure the microgrid safety. In [359], fault current level of an islanded microgrid cluster is analyzed and found much higher than a single islanded microgrid. In [360], Dijkstra's algorithm is used to determine the relay hierarchy and then update the new relay settings accordingly. In [361], a protection strategy is proposed through an enabling microprocessor-based relay for protection of low-voltage microgrids. The protection strategy does not require communications nor adaptive protective devices. In [362], a fast fault detection method for microgrids based on DGs equipped with power electronics interfaces is proposed, which provides reliable and fast detection for different types of faults within the microgrid. Analysis and simulation results are presented for different types of faults within the microgrid. The study in [363] presents two overcurrent and overload protection schemes for voltage-controlled DERs in an islanded microgrid. In [364] an anti-false-alarm method to detect one or two open switch faults is proposed to avoid the disadvantages of current open-switch fault diagnosing methods for a doubly fed wind power converter based on the investigation of the characteristics of current signals. The method ensures that the DGs are running after the fault. In [361] an enhanced control strategy for electronically coupled DERs is proposed that enables these resources to ride through network faults irrespective of whether they take place within the microgrid or in the upstream network. The proposed method ensures acceptable power quality for the duration of the faults, which is an important feature for protection against certain classes of faults, as well as for sensitive loads. A supplementary control loop is also proposed that improves the microgrid post-fault recovery.

Studies in [365]–[368] discuss applications of differential protection in microgrids. In [365] a multi-level approach based on power line carrier technology is proposed to provide the most effective form of network protection of a meshed microgrid, while ensuring a high level of reliability and power quality by quickly identifying faulted points in the system, and effectively isolating them. The study shows that the traditional communication-less protection schemes are not applicable in a meshed microgrid where a fault at one location is indistinguishable from another. A protection method based on differential current measurement and comparison is proposed that utilizes the power line as the communication medium. In [366], two main challenges associated with the operation of microgrids are considered as voltage/frequency control and protection. First, a control strategy for inverter based DGs is proposed to control both voltage and frequency during the islanded operation. Second, a protection scheme is proposed to protect both lines and DGs during the islanded operation. Both the control scheme and the protection scheme are coordinated to avoid nuisance tripping of DGs and non-critical loads. The study is performed using a digital computer simulation approach in PSCAD/EMTDC. In [368], a protection scheme is presented using digital relays with a communication network for the microgrid protection. The increased reliability of adding an additional line to form a loop structure is explored. Also a new method for modeling high impedance faults is demonstrated to show how the protection scheme can operate. The protection system relies primarily on differential protection based on sampling the current waveform at 16 samples per cycle or more. A high impedance fault detection model using random duration and time varying resistances is also protection scheme. In [367], a differential energy based fault protection scheme in microgrids is presented using the time-frequency transform technique. Spectral energy content of the fault current signals retrieved at both ends of the feeders is found using time-frequency transform, and differential energy is computed to register the fault patterns. A threshold can be set on the differential energy to issue the tripping signal for different faulty situations in the microgrid in grid-connected and islanded modes, under both radial and loop networks. Results indicate that the proposed scheme can reliably protect the microgrid against shunt faults and high impedance faults, and thus can be extended for large power distribution networks with multiple DGs.

Fault modeling is also very important to identify the need to switch islanded mode. In [369], principles of two dominant islanding detection techniques are combined based on positive feedback as well as the voltage unbalance and total harmonic distortion to obtain a new hybrid islanding detection technique for synchronous DGs. Simulation results show that the proposed hybrid technique is more effective than each of the techniques used, and verify the advantage of the proposed hybrid islanding detection technique, which is the fact that only the DGs in the vicinity of load switching change their frequency set point. This could potentially be a huge advantage over the positive feedback technique. In that technique, several DGs that are connected to the utility grid may together push the voltage and frequency error to be higher, and as a result, the positive feedback technique could destabilize the utility grid. The proposed technique also permits autonomous operation of the microgrid as opposed to the positive feedback technique, which does not permit autonomous operation. Contrary to voltage unbalance and total harmonic distortion method, the proposed technique is able to efficiently discriminate between load switching and islanding.

B. COMMUNICATIONS-BASED PROTECTION

Due to variable microgrid operating conditions and meshed topology of microgrids, it is necessary to use communications to update protection settings [365], [370]. The study in [365] shows that the traditional communication-less protection schemes are not applicable in a meshed microgrid where a fault at one location is indistinguishable from another. The paper proposes a multi-level approach based on the power line carrier technology. In [368], a protection scheme is presented using digital relays with a communication network for the protection of the microgrid relying primarily on differential protection based on sampling the current waveform. It also presents a model for high impedance faults incorporating randomness.

IEC 61850 is an international standard for substation automation and a part of the International Electrotechnical Commission's Technical Committee 57 (TC57) architecture for electric power systems. These standards will result in very significant improvements in both costs and the performance of utility grids. They are based on abstracting definition of the data items and the services or in other words creating data items/objects and services that are independent of any underlying protocols. The abstract definitions then allow mapping of the data objects and services to any other protocol that can meet the data and service requirements [371]. Due to the existence of different levels of fault current in microgrids, new protective schemes need to be developed that can monitor changes in the microgrid and calculate the operating conditions at any given time. Logical nodes available in IEC61850 and IEC61850-7-420 communication standards are used to design such versatile schemes [372]. In [373], it is demonstrated that the utilization of IEC61850-based communication in low voltage microgrid protection is needed to ensure a fast and reliable protection. In [374], an approach is presented for automatically generating an IEC 61850-compliant implementation of intelligent electronic devices suitable for embedded platforms and for protection applications where runtime performance is critical. In [370] and [372], a scheme based on the central protection unit is proposed to monitor the microgrid DGs and relays, and accordingly update them. In [365], the power line is used as the communication medium. In [370], the implementation of communication infrastructure of a novel protection scheme for microgrids with high DG penetration is presented in Matlab Simulink Environment. Microgrid Central Protection Unit is utilized to monitor all components within the microgrid and new operating conditions are calculated for every interrupt call received by the controller. The study in [375] presents an adaptive protection scheme for a university campus microgrid using communication-assisted relays responding to the higher fault currents in the grid-connected mode and lower fault currents in the islanded mode.

C. PROTECTION OF DC MICROGRIDS

In [376] shortcomings of protection approaches for microgrids that are not limited to an area with clear boundaries are addressed, and a flexible framework is proposed for protection scheme design of DC microgrid applications. The proposed protection scheme enables the required levels of fault discrimination to be achieved while minimizing the associated installation costs. In [377], a low-voltage DC microgrid protection system is proposed. The possibility of using commercially-available devices to protect such a system is shown in this study. Problems may arise with high-impedance ground faults which can be difficult to detect. It was shown that during the coordination of protection devices, problems may arise with the converter protection. Therefore, the converter fault current can be used together with the DC-link voltage to solve the problem and ensure a reliable protection system. In [378], a fault protection and location scheme is presented for a ring-bus-based DC microgrid consisting of zone intelligent electronic devices which are capable of detecting fault current in the bus segment and isolating the segment to avoid the system shutdown. In [357], an arc model for studying series faults in low-voltage DC microgrids is presented. It is suitable for electromagnetic transient simulations of series DC arc faults. The advantages of the method for transient simulations are demonstrated via experiments. The study in [379] presents feasibility analysis results of positioning the superconducting fault current limiter and its effects on reducing fault current in a utility grid containing AC and DC microgrids. The strategic and optimal location of superconducting fault current limiter in the utility grid, which could limit fault currents and has no negative effect on DGs, is found to be the connection point of each DG. In [380], a fault detection and isolation scheme is presented for low-voltage DC microgrids to detect the fault in the bus between devices and to isolate the faulted section regardless of fault current amplitude or the power supply's feeding capacity. Therefore the microgrid keeps operating without disabling the entire system. It proposes a loop-type DC microgrid, which has a segment controller between connected components.

D. FAULT CURRENT LIMITATION (FCL)

In [381] the state of the art in fault current limiters (FCL) is summarized, focusing on devices in or near the field test status. Furthermore, solid state FCLs are identified to be appropriate to use in microgrids. In [382], two current-limiting algorithms are proposed for controlling a series inverter connected between the microgrid and the utility grid during utility voltage sags, namely the resistor-inductor feedforward and flux-charge-model feedback algorithms. The study in [383] introduces a unidirectional fault current limiter named UFCL installed between the upstream and downstream networks. It only limits the contribution of the downstream network during a fault in the upstream network. Inversely, during a fault in the downstream network, the UFCL is inactive and allows a full contribution of the upstream network. It is shown that by this strategy, the proposed UFCL can preserve the coordination protection of the upstream overcurrent relays, and also as an added advantage, alleviate deep voltage sags caused by the upstream faults. It is shown that due to the full contribution of the upstream network during fault conditions in the downstream network, power quality of the microgrid will be improved. Furthermore, the coordination between the upstream and downstream overcurrent relays is preserved. In [298], a microgrid protection scheme is proposed that relies on optimally sizing fault current limiters and optimally setting directional overcurrent relays. The problem has been formulated as a constrained nonlinear programming problem and is solved using the GA with the static penalty constraint-handling technique. The study in [379] conducts a feasibility analysis of the positioning of the superconducting FCL, concluding that the strategic and optimal location of superconducting FCL in the utility grid is the connection point of each DG in both AC and DC microgrids.

IX. MICROGRID COMMUNICATIONS

The role of communication systems in the microgrid is to provide a means to exchange data and monitor various elements for control and protection purposes. In a centrally controlled microgrid, the communication network is necessary to communicate control signals to the microgrid components. In a microgrid with the distributed control, the communication network enables each component to talk with other components in the microgrid, decides on its operation, and further reaches predefined objectives [112]. Communications within the microgrid is necessary to enable a rapid fault clearing and increasing efficiency in islanding incidences. Despite its significant role in developing efficient and advanced microgrids, no review on microgrid communications is currently available.

The study in [234] proposes the establishment of a wireless network to acquire the information of total real and reactive power generation of all DGs in order to enhance the microgrid stability. In [384], a microgrid test-bed is proposed to investigate cognitive radio networks in the fifth generation wireless technology. The technique of independent component analysis with robust principal component is applied to smart meter wireless data recovery. In [385], a heterogeneous wireless network architecture has been established to set up a multi-agent coordination between DGs to make decisions in a decentralized economic dispatch. In [126], a communications algorithm is proposed based on the consensus theorem as a solution for economic dispatch of DGs in a decentralized multi-agent platform. The study in [386] asserts that for power sharing improvements amongst DGs in weak system conditions, the web-based low bandwidth communication is more economic and justifiable than costly advanced high bandwidth communications. In [387], an optimization scheme providing online set-points for each DG, operation modes for a water supply system, and signals for consumers based on a DSM mechanism through a SCADA system is proposed. In [388], a secure energy routing mechanism is proposed that detects most internal attacks by using message redundancy during topology discovery. In [389], a semantic overlay network is presented that allows to efficiently route queries related to microgrid control in the overlay network, based on an XML description of the static and dynamic characteristics of the intelligent electronic devices. The dynamic structure of the microgrid, which may change at each instant, requires that connections in the microgrid be monitored and the relay hierarchy be reset. In [390], a reliable overlay topology design scheme is presented that maximizes the usage of renewable energy in the microgrid and applies survivability approaches borrowed from high-speed networks to microgrids. In [391], a DC microgrid with multi-layer control and smart grid communications is proposed, enabling better DC microgrid integration and providing possibility to reduce the negative impact on the utility grid by using the supervision interface. The power balancing control interface provides possibility for advanced energy management with low speed communication. The study in [392] proposes a distributed energy management strategy based on the power line communication in a DC microgrid.

X. CONCLUSION

Microgrid penetration is currently growing across the globe, leading to various challenges and opportunities. This paper attempted to provide a review of the state of the art in research on microgrids, hence paving the way for interested educators, researchers, and developers in gaining insight into this important and timely topic and understand a variety of microgrid-associated issues under investigation by the research community. The review comprised of an introduction to microgrids, their components and associated benefits, and a review of applications in enhancing grid performance, which further followed by studies on microgrids economics, operation, control, protection, and communications.

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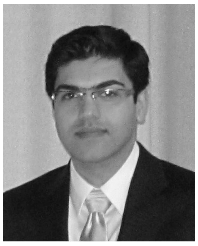

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