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# A Review of Active Management for Distribution Networks: Current Status and Future Development Trends

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# A Review of Active Management for Distribution Networks: Current Status and Future Development Trends

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*Abstract*— **Driven by smart distribution technologies, by the widespread use of distributed generation (DG) sources, and by the injection of new loads such as electric vehicles, distribution networks are evolving from passive to active. The integration of DG including renewable DG changes power flow of distribution network from unidirectional to bi-directional. The adoption of electric vehicles makes the management of distribution networks even more challenging. As such, an active network management has to be fulfilled by taking advantage of the emerging techniques of control, monitoring, protection, and communication to assist distribution network operators in an optimal manner. This paper presents a short review of recent advancements and identifies emerging technologies and future development trends to support active management of distribution networks.**

*Index Terms*— **Active management, distributed generation, distribution network, smart distribution, smart grid.**

## I. Introduction

Smart Grids have been widely hailed as the future infrastructure of electrical power generation for secure and sustainable energy development. Electric power distribution networks (DN) have been a fundamental element and a large part of the power grid infrastructure. They will become even more critical and should be given the priority in developing future smart grids. This is because distribution networks are where most end users, distributed generation (DG) sources and electric vehicles (EVs) are connected. Near 160 million customers in the U.S.A. are served via distribution networks [1]. The increasing penetration level of DG and EVs, the implementation of smart distribution technologies such as advanced metering/monitoring infrastructure (AMI), and the adoption of smart appliances, have changed distribution networks from passive to active. The next-generation of distribution networks should be efficient and optimized system-wide, highly reliable and robust, and capable of effectively managing highly-penetrated EVs, DG sources and other controllable loads. To meet new challenges, next-generation distribution networks need active distribution management (ADM).

Various distribution management technologies, such as distribution automation, AMI, fault location, automated reconfiguration and VAR control, have been studied and some of them have been successfully implemented in today's distribution networks [1] [2] [3]. Different aspects of optimization of distribution network planning have also been investigated, including optimal deployment of capacitor and other VAR compensation devices, section-reclosers, and DG sources [4] [5] [6] [7]. Moreover, advances in new DG technologies, new power electronic converters (PEC) such as solid state transformers capable of regulating real and reactive power flows [8], the expanding use of intelligent appliances and other controllable loads [9], and the application of home and office automation networks [10], all make ADM for next-generation distribution networks possible.

This paper seeks to review recent advancements and identify emerging technologies to support the DN's evolution. Section II gives an overview of framework of ADM. Section III introduces advances of active voltage and energy management. The active protection and fault-location of DN are discussed in Section IV. Section V presents a review over emerging technologies to address these problems and challenges. Discussions on the future development of ADM are given in Section VI. Section VII concludes the review.

## II. Active Management Framework of Distribution Network

In an ADM scheme, the proper coordination of DGs, voltage regulators, shunt capacitors, and other devices in a DN is critical to achieve the highest system security and operation efficiency [11] [12]. Generally, the management framework of the ADM can be categorized into three types; centralized, decentralized, and hybrid hierarchical management (HHM) frameworks.

### *A. Centralized Management Framework*

In the centralized management framework, the voltage, power flow, and equipment status measurements at selected

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locations in the DN are sent to the distribution network central controller (DNCC), as shown in Fig. 1. Similar to the supervisory control and data acquisition (SCADA) of transmission system, the DNCC is able to manage the DN through dispatching active and reactive power from DGs and assigning operation commands to other network elements.

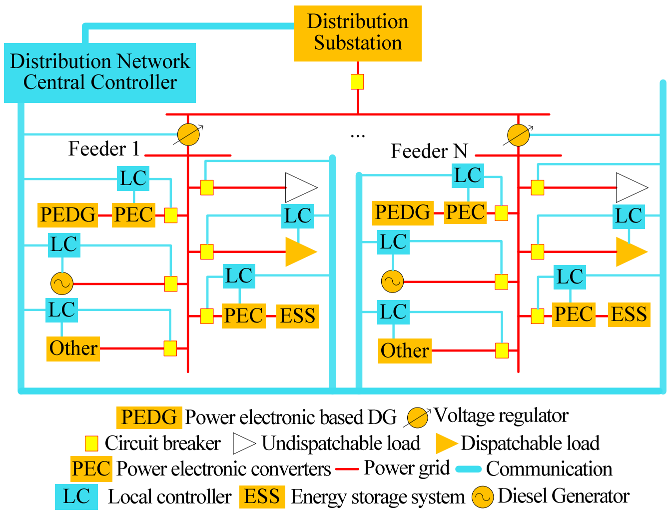


Fig. 1. Illustration of a centralized control framework.

In addition, the DNCC coordinates available devices in the DN to enhance the operation efficiency and keep the voltage and frequency within security range. In [11], a central Distribution Management System Controller was proposed to deliver real-time measurements and network data into a state estimation algorithm to control active devices in the DN. Reference [13] presented an optimal algorithm to coordinate DGs with other devices, such as load ratio control transformer, step voltage regulator, shunt capacitor, shunt reactor, and static VAR compensator to adjust voltage of each node with necessary communication supports. In [14], to efficiently exchange information, a remote terminal unit (RTU) is placed at each DG and each switched capacitor in the system; and then by reading and analyzing the information provided by the RTUs, a central voltage controller adjusts the settings of the voltage regulators on different feeders to coordinately regulate the voltage within the acceptable range. A statistical state estimation method was utilized in [15] to estimate the voltage at each node, and correspondingly set the target voltage of relays and the DGs' output to maintain the voltage profile.

However, as stated in [16], the centralized control is against the "distributed" nature of DN, in which the electrical devices are usually dispersed. Though the centralized control strategy is the most straightforward way to achieve the management and optimization of the overall network, it certainly has several drawbacks: (1) A failure of the central controller may cause the crash of the whole system; (2) the amount of data and communication traffic may quickly exceed the level that can be handled; (3) high investment in communication and data processing; (4) onerous testing is required for even just a few modifications on the control algorithm; and (4) the shutdown of the whole system for maintenance.

*B. Decentralized Management Framework*

To follow the distributed nature of DN, an opposite way to centralized ADM is to develop a decentralized control system. As shown in Fig. 2, the devices in decentralized methods can be autonomous. The control decisions of local controllers could be made according to only the local information or coordination with neighboring devices [17] [18]. For example, by using the local voltage and frequency information, the real and reactive power of DGs and energy storages could be adjusted through $f/P$ and $V/Q$ droop controllers [19] [20] [21].

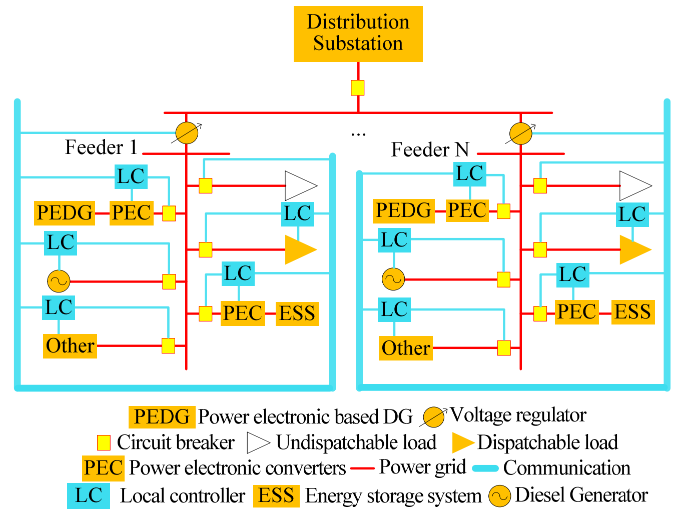


Fig. 2. Illustration of a decentralized control framework.

By coordinating DGs and conventional voltage regulation devices, the voltage could be regulated within the security range in a local/distributed way. In [22], cooperated with line drop compensator, on-load tap changers (OLTC) were controlled to avoid local voltage problems in a medium voltage feeder with DGs installed. It concluded that the parameters and structure of a feeder and DG's connection point jointly affect the effectiveness of the proposed methods. In [23], a large and meshed network is firstly divided into many sub-networks based on the $\varepsilon$-decomposition of the sensitivity matrix; and then the devices in the same sub-network coordinate together to adjust the local voltage within the limitation.

In addition, a popular approach for distributed control scheme is agent based management (ABM), which has been widely studied for the power flow, protection, restoration and voltage regulation in transmission network [24], and has drawn the attentions of its applications in DN management [25]. The definition of an agent in ABM, adapted from [26], is an entity of software and/or hardware embedded in the DN and is able to change the network, be affected by a set of tendencies, and interact with other agents. A system containing two or more coordinated agents is named as multi-agent system (MAS). The management of various devices in the ABM received extensive studies. In [27], the ability of the agents to monitor the local voltage sensitivities was enhanced to facilitate the injection of plug-and-play DGs into the DN. Reference [28] focused on the operation of microgrid in DN through the ABM. In the three-layer ABM, every DG or controllable load determines the best behaviors by themselves. As for the intermittency of DGs, a persistent method was used by assuming that the average energy production for the next short period will be consistent with the current one. However, as it was stated in [29], in an ABM system, agents consider their own benefits more than the global optimization. Therefore, the solution provided by MAS may be sub-optimal.

An interesting paper [30] compared the centralized and decentralized control frameworks from the aspects of total allowed injection capacity and losses. It arrives at a conclusion that the two methods show similar influence on maximizing the DGs' penetration capacity without causing voltage rise issues. However, the two strategies both cause a significant increase of power losses, which is about five times higher than the constant power factor control method.

### C. Hybrid Hierarchical Management Framework

HHM is a more practical framework to manage large distribution networks. It combines centralized and decentralized control and has a multi-layer structure, as shown in Fig. 3.

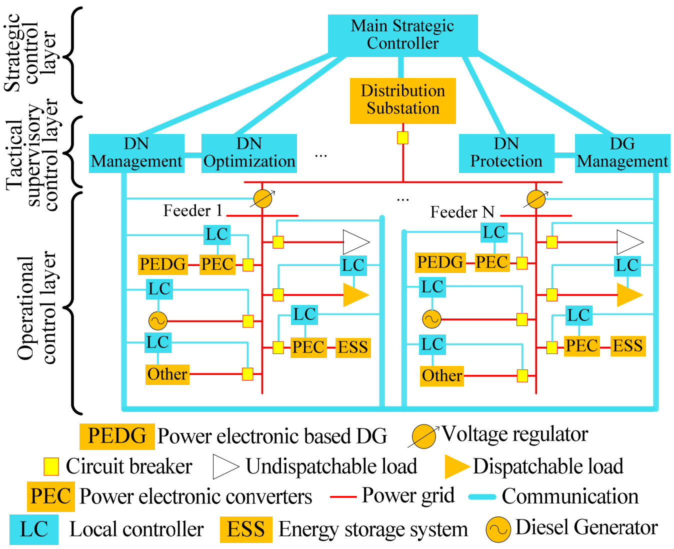


Fig. 3. Illustration of a hybrid hierarchical control framework.

The HHM usually consists of several supervisory control layers [31] [32] [33]. In the top strategy layer, the controller carries out the functions of display, monitoring, operation and management by collecting the information of lower layers and market information. Based on the strategic orders, controllers in the lower tactical supervisory control layer perform different predefined functions to generate optimal settings for the local controllers in the lowest operational control layer. Analogous to a global manufacture standard, ISA-95, a general hierarchical control structure of microgrid was proposed in [34]. In the proposed scheme, the four layers from the top down are tertiary control layer, the secondary control layer, the primary control layer, and the inner control layer. The method could be extended to a cluster that has multiple microgrids and finally control the overall distribution network.

## III. Voltage and Energy Management Methods of Active Distribution Network

Within a given management framework, it is still challenging to develop practical strategies for power and energy management. On the energy-supply side, how to economically integrate DG sources and how to control these sources to regulate system voltage need more research. On the customer side, one challenging issue is how to solve the voltage and power issues caused by the proliferation of new loads such as EVs.

### A. Optimization of DGs in Distribution Network

To economically integrate DGs in DN, the optimal location and sizing of DGs should be determined [35] [36] [37] [38]. In [39], the optimal allocation and sizing of DG and ESS were calculated by a genetic algorithm, and the results showed that using DGs and ESS was able to economically improve the energy-not-supplied index of the DN. Reference [40] presented analytical approaches for optimal placement of DGs based on the network parameters, such as bus admittance matrix, generation information and load distribution of the system. In [41], a modified particle swarm optimization algorithm with both of the technical and economic constraints was proposed to determine the optimal location of DGs and ESS in DN.

In addition, there are numerous objectives in optimization problems of DG-dispatching in DN [42]. A common objective is to mitigate the power congestion and to defer the system upgrade [43] [44]. Energy losses minimization is another common objective in DN to optimally dispatch DGs [40] [45] [46]. Some researchers consider the enhancement of reliability of power supply as another objective [47] [48]. Multi-objective optimization has also been extensively explored. In [49], a multi-objective mixed integer programming algorithm was proposed to optimize three objectives together by economically dispatching DGs in DN.

### B. Active Voltage Management through DGs

Traditionally distribution network operators (DNOs) manage DGs in a unit power factor control mode; however, it ignores the fact that some DGs may be capable of providing reactive power support as well. With increasing needs for the reactive power support, it is very likely that, in the future, DGs will be required to provide such support. The studies to utilize DGs to actively compensate reactive power and regulate voltage in DN could be categorized into dynamic control [50] [51] [52] [53] [54] [55] and steady-state dispatching [27] [56] [57] [58].

The study on dynamic Volt/VAR control of DGs focuses on the design of the power inverter controllers of electronic-interfaced DGs. In [51] and [52], V/Q droop controllers were used to dynamically adjusting the reactive power generation of DGs to regulate the local voltage. Reference [53] introduced the control of the back-to-back voltage source converter of a wind turbine generator. The authors designed the three-stage controllers, rotor-side converter controller, DC-link controller, and grid-side converter controller. In addition, the real and reactive power operating limits were integrated into the design of the controllers. Based on these controllers, the reactive power is actively controlled for voltage regulation without violating the power limits. The authors of [54] proposed an algorithm to control the voltage by automatically adjusting the parameters of the controllers according to the system dynamics. With respect to the limit of reactive power generation of DGs, the work [55] realized that $|Q_{max}| \leq 0.45P_{rated}$ (where $Q_{max}$ and $P_{rated}$ are the reactive power generation capacity and the rated real power output of DGs, respectively) was reasonable because it required no significant extra cost of inverters.

The steady-state analysis mainly commits to formulate the voltage support by DGs as a reactive power dispatching problem. In [27], with fast communications among DGs and voltage regulators, an agent based method was introduced to facilitate a model-free control procedure to dispatch reactive power generation of DGs in an optimal manner. In [56], the reactive power of DG was regarded as a controllable variable and was coordinately dispatched with the OLTC and shunt capacitors. The results showed that the location and the capability of reactive power generation of DGs and other factors determined the performance of the voltage regulation.

Overvoltage is a common and important issue for DN with high penetration of DG. For the worst scenario that the installed devices are unable to keep voltage below the upper limit, a straight forward method was proposed by reducing DGs' power production [59], [60]. Based on the dynamic Thevenin equivalent, a real-time prediction algorithm was proposed in [61] to calculate the active power limit as a reference of the power. However, for a feeder with multiple DGs, how to fairly curtail power of DG belongs to different owners deserves more studies because unfair curtailment may cause conflict of interest between DG owners and DNOs. The simplest method is to equally curtail the power output of DGs once the voltage issue happens [59].

In addition, the study in [62] showed that the allowable penetration level of DGs could be increased if DGs were used as voltage regulators. In the above paper, three different power factor modes of distributed generators were compared which are unitary, capacitive and inductive power factor modes. It concluded that the voltage control mode for the DG helped maximize the allowable penetration of distributed synchronous generation in DN.

### *C. Active Management of Plug-In Electric Vehicles*

Transportation electrification is viewed as one of the most viable ways to reduce CO2 emissions and oil dependency. It was projected that the cumulative sales of plug-in electric vehicles (PEVs) will reach 16 million by 2030 [63]. The increasing number of PEVs will post new challenges to the existing power grid, as they will become a large load to the power grid when they are being charged. In [64], the impact of the PEVs on the Belgium DNs with the consideration of the traffic and driving patterns was studied. After the simulation studies for different scenarios on a 34-node test feeder, it concluded that the large injection of PEVs can cause a significant amount of power losses and voltage deviations. At the same time, the analysis of the paper also showed that the voltage issue and energy deficiency could be mitigated if the charging of PEVs was actively managed. Therefore, the impacts of PEVs on DN must be measured and controlled to maintain the DN's stability. An active management of PEVs was proposed in [65] and [66]. PEVs and other loads in a DN were modeled by a method of finite state machine with variables, and then a safety controller was proposed to locally manage the dis-/charging of PEVs and other controllable loads on a node. With the coordination of controllers at all nodes, the peak power needed is shifted and the safety of the feeder transformer is guaranteed.

Besides exerting great stress on DNs, the PEVs' injection also provides an opportunity to assist the ADM [67] via vehicle to grid (V2G). With the ability of V2G, PEVs are capable of exchanging energy and control information with DNOs to improve the voltage stability and energy security of the grid. In addition, PEVs could be used to balance the intermittent outputs from renewable sources via V2G techniques [68].

### *D. Demand Side Management*

Demand side management (DSM) allows customers to take an active role in the ADM [69] [70]. By taking advantage of the bidirectional information and communication techniques, the customers are encouraged to shift their power consumption toward off-peak periods to reduce the maximum and/or total power needed, therefore reinforcing the energy security and reliability and maximizing the efficiency. When electricity demands are high, reducing peak usage and temporarily employing DGs are a solution that draws more and more attention [71].

Load demand modeling is important for the development of the DSM. A state-queueing model to study the price response of thermostatically controlled appliances (TCA) was proposed in [72]. The model successfully simulates the dynamic response of the TCA type of load along with the price changes. In [73], the residential loads, with customized priority and convenience settings, were categorized into controllable and critical groups for the DSM strategy. With the proposed model, a load shaping tool was designed to not only manage the total demand under the limitation of transformers, but guarantee customers' comfort to a great extent.

The DSM has the potential to improve the investment efficiency in DN. It could be helpful in increasing the penetration level of DGs in the DN by managing the demand-supply balance [74]. The increased DGs help reduce the peak load of both cables and transformers and relieve congestion in substations. As a result, the upgrade of network could be deferred. As for how to overcome the intermittency of some DGs (i.e. photovoltaic resources, wind power generation) by DSM, a model predictive controller was proposed to predict the power consumption in a DN with high wind penetration in [75]. Integrated with the weather forecast and dynamic pricing information, the proposed algorithm could successfully realize a predictive demand dispatch in a real test platform.

## IV. Protection and Fault Location of Distribution Network

In the DN with a large penetration of DGs, the traditional protection and fault-location methods may not work properly since most of them are based on unidirectional power/current flow along radial feeders. Therefore, active methodologies have to be developed to guarantee the security of DN.

### *A. Active Distribution Network Protection*

There are tremendous challenges that protection engineers have to deal with regarding the integration of DGs: Fuse and switchgear coordination, feeding faults after utility protection opens, interrupting ratings of devices, sympathetic tripping, protection relay desensitizing, recloser coordination, and islanding [76]. For instance, when a DG tries to maintain the voltage stability under a fault condition, the reduction of the current seen by relays may induce the relay desensitizing [77]. In addition, both the direction and magnitude of the fault current seen by protection relays can be changed because of the injection of DGs [78]. To deal with the uncertainty of the fault current, an adaptive protection strategy was proposed in [79]. By only collecting the local information of the operating status and the faulted section, the trip characteristics of the relays are timely updated. And the use of microprocessor-based directional overcurrent relays, whose tripping characteristics could be chosen accordingly, brings the adaptive protection into effect [79].

Moreover, islanding is a noteworthy emerging challenge as the penetration of DGs increases. It is a situation that a DN or a portion of the DN has been isolated from the main power grid, but continually supplied by the DGs within it [80]. Such a situation may threaten the safety of line workers, cause distorted voltage and frequency, and lead to unwanted out-of-phase reclosing of the DGs [81] [82]. To detect the islanding, a remote (centralized) strategy will have to rely on communication [83] and advanced monitoring system, such as SCADA [84]. Decentralized strategies try to locally detect islanding by either passively measuring varying parameters such as voltage, frequency and harmonic distortion [85], by actively introducing perturbation to induce a significant change [86], or by hybrid methods to integrate both passive and active strategies [87].

### *B. Active Fault Location in Distribution Network*

There has been increased research effort on fault location for distribution network with DGs [1] [88] [89] [90] [91] [92]. In [89], a general method was given to locate faults for distribution networks with DGs. The method uses synchronized voltage and current measurements at the interconnection points of DG units and is able to adapt to variations in the topology of the system. The authors of [90] proposed a fault location method based on a binary hybrid algorithm of particle swarm optimization and differential evolution, which targeted for solving "premature convergence" issues. It is a two-population evolution scheme with information exchange mechanism and is able to adaptively accommodate the changes caused by multiple fault sections in DN with multiple DGs. In [91], a multiagent management strategy was proposed to enhance the security of DN. By compromising the rule-based expert systems, the proposed intelligent agent could quickly locate and isolate the fault with assistance of the power line communication. A distribution fault anticipation technique, based on large database records of electrical waveforms of failing apparatus, was discussed in [92]. The technique was proposed for failures detection by monitoring sensitive signals. It can be extended to include a larger database with equipment parameters and system constraints [1].

## V. Emerging Technologies

In this section, the emerging technologies that enable the novel management methods and strategies aforementioned are reviewed.

### *A. Advanced Power Electronics*

PECs are interfaces of the energy conversion for DGs and are the basic platform for DNOs to actively manage the DGs [93] [94]. With proper control strategies, PECs facilitate and regulate the power flow in DN, regulate the voltage where DGs are connected, compensate reactive power if needed, provide certain protection to the distributed generators, and help DGs rapidly and smoothly share load when the system islands [95] [96].

In addition, assisted or even redesigned using power electronic techniques, some conventional devices are endowed with novel functions and applications. One example is new solid-state transformers (SST). By using semiconductor-based devices, they are much more flexible in handling high power levels with very fast switching [8] [97]. An SST is able to (1) change the voltage and frequency of the power it produces; (2) has both AC and DC inlet/outlet; (3) directly take in power from wind and PV and (4) connect to the grid through proper power conversion. Another example is the solid-state fault current limiter (SSCL) [98]. Because the increased penetration of DG sources in DN in turn can cause the fault current exceed the ratings of existing power devices, the SSCL was proposed to limit the fault current and reduce oscillations by using series connected capacitors to act as large turn-off snubbers [99]. In the future, the built-in processors and communications will enable SST and SSCL to be key parts in the actively managed DN [100] [101].

Furthermore, the applications of flexible alternating current technologies in DN (DNFACT) enhance the controllability of the ADM. The devices of this kind include Distribution Static Compensator, Dynamic Voltage Restorer, and Solid State Transfer Switch. Reported in [102], DNFACTs were installed close to the load side for improving the system stability and the power supply quality.

Lower cost is always the highest priority in designing and developing PECs. It is critical to have cost effective PECs to integrate and manage various kinds of distributed generation sources and storage units in DNs. To achieve the goal, the effort has to be made at both the levels of hardware (topologies and components) and software (control and management). On the one hand, as reviewed in the previous sections, more features/functions such as reactive power support may be required from future PECs, which may increase their cost. Hence, the power converter manufactures need to come out with new ways to reduce the cost. Modular design that has been explored and used in the past [103] [104] [105] is a possible way. On the other hand, new control methods should be proposed to achieve the same control objectives without adding too much burden on the power electronic hardware side. For instance, a real power management strategy for PVs is welcome if it can achieve the same voltage management goal since it will not increase the converter power ratings while the reactive power support features may.

### *B. Communication and Information Technology*

Communication and information technology (CIT) provide data and information connectivity among active devices in the DN, including DGs, protection devices and loads. It enables distant control for DNs on a continuously increasing scale, and is viewed as one of the deciding factors for the successful realization of the ADM. In a CIT-based project of Distributed Intelligence in Critical Infrastructures for Sustainable Power (CRISP) [106], it has shown the CIT's important functions in protection, control and management, and network reconfiguration. Two important techniques to realize CIT in ADM are an advanced metering infrastructure (AMI) and phasor measurement units (PMU).

#### *1) Advanced metering infrastructure*

An AMI bridges smart meters, customers, energy resources, and various energy management systems. The various uses of metering data provided by AMIs were deeply explored in [107]. To provide advanced functionalities, the requirements for the AMI are to provide sufficient data to cover the network, to utilize powerful engine to store and analyze the data, and to employ accurate links among customer, transformers and substations. Based on these key elements, the AMI is able to monitor the performance of transformers, cables and circuits. In addition, by discovering outage disturbances, the AMI is capable of predicting pending failures in the DN.

#### *2) Application of phasor measurement units*

With respect to the applications of PMUs in DNs, two constraints have to be carefully considered: The total vector error of frequency between different buses is very small [108]; and specific synchrophasor estimation algorithms are needed to tolerate high level harmonic distortions in the DN [109]. A specially designed PMU and a novel algorithm to deal with the aforementioned two constraints are proposed in [109]. More importantly, due to the extremely large number of components in DNs, a distribution PMU technology should also be economically feasible. In addition, PMUs support the state estimation of DN. In [110], a method of designing the measurement infrastructure to maintain a desired accuracy of state estimation with trade-offs among the number of PMUs and the number of other measurement devices was proposed. The optimal placement of PMUs was determined by an optimization algorithm based on the generic algorithm [110]. Furthermore, PMUs help achieve a better protection of DN. In [111], PMUs were used to measure the phase error between the utility grid and DGs to detect loss of mains.

#### *3) IEC Standards*

Two important standards regarding the CIT in power systems are International Electrotechnical Commission (IEC) 61400-25 and IEC-61850 [112]. Their extensions to support the injection of wind energy in ADM were introduced in [112]. Depending on the actual CIT-based network management systems, DGs are smoothly integrated via an optimization algorithm for cost minimization and constraints management [112].

### *C. Smart Appliances*

The study and application of smart appliances (SA) have been extensively explored from smart thermostats to a series of home appliances which include but not limited to smart refrigerators/freezers, clothes washers/dryers, room air conditioners, and dishwashers [10] [113] [114]. By shifting the operation from on-peak hours to off-peak hours, SA is an effective tool for demand side management. In addition, by curtailing the operation temporarily in response to requests, the SA behaves as spinning reserves which is costly in the grid. Furthermore, the demand and the supply from undispatched renewable energy resources (RES) could be well leveled by the SA thereby increasing the penetration of RES. In [113], the benefits of implementing SA were evaluated in terms of peak load shifting and spinning reserves. The calculation based on the price information from real wholesale markets indicates that the annual benefits by using SA are far more than the cost.

### *D. Energy Storage System*

The applications of ESS in ADM potentially benefit the DN, [115] [116] by:

- deferring system upgrade by peak load shaving;
- avoiding widespread outages together with demand response;
- mitigating the intermittency of some renewable energy sources while performing load and frequency regulation ;
- increasing penetration level of DGs in the DN;
- increasing the effective distribution capacity by using the storage devices that have extremely rapidly dis/charge rate; and
- enhancing system reliability.

Among various types of ESS, the battery energy storage system (BESS) takes a large part in smoothing the intermittency of RES in DN. However, the BESS sometimes is unable to act fast enough to follow high-frequency fluctuations. On the other hand, handling a large burst of current, such as in the scenarios of motor startup and rapid increase in solar generation, degrades battery plates and even shortens the life expectancy of BESS. An alternative way is to combine ultracapacitor and BESS in a hybrid energy storage system [117]. This hybrid solution was originally used to quickly capture the braking energy in hybrid EVs [118], and was further introduced to smooth the intermittency of PV generation [119]. By implementing a high-pass filter, the high-frequency fluctuation and low-frequency continuous parts are separated. The battery can supply/absorb continuous energy, and the ultracapacitor is used to smooth the sudden change of load demand or energy generation.

In addition, along with the increasing of PEVs and resident-owned RES in DN, how to enhance the reliability in response to contingencies at the consumer-end is a new challenge. A solution is to install distributed small energy storage units in the residential community, which is referred to community energy storage (CES) [120]. Because the CES units are close to residents, they are able to serve as backup power, mitigate flickers, and integrate local PEVs and RES. Moreover, the clustered CES units perform as bulk energy storage at the substation to level supply and demand, improve the power quality, and even provide ancillary services.

## VI. Discussions on Future Development

The advancement of electricity distribution has been evolving very dynamically in various aspects including the areas reviewed in the previous sections. In this section, the discussion is focused on the future development in the following selected areas: Energy storage, customer participation, and the concept of virtual microgrid for active management of distribution network.

### *A. Community Energy Storage Using Retired EV Batteries*

A surge of retired EV batteries will soon be seen as more and more EVs hit the road. The treatment of old EV batteries is another important aspect for the whole EV development cycle. It needs to be investigated right now to provide a chance for repurposing them to support distribution grid. Old EV batteries that are not suitable for vehicle applications can still have substantial amount (up to 75%) of capacity left [121]. One million of retired 15 kWh/40kW EV batteries with an average of 50% remaining power and energy capability can provide 7,500 MWh energy capacity and 20,000 MW power capacity, a huge waste if not utilized in their secondary applications, such as energy storage for grid support [121] [122] [123]. Sandia National Laboratories released a report on the technical and economic feasibility of such approaches several years ago [121]. Recently, several EV manufacturers have announced their plans on using old EV batteries for stationary energy storage. For instance, General Motors, teamed with ABB, is developing 50 kWh of energy storage systems by using retired Chevy Volt batteries for CES applications [122]. However, management of used EV batteries is far more difficult than their primary EV usage. First, they must be re-characterized for the remaining capacity, internal impedance, and voltage/SOC curves. Secondly, different battery modules, in terms of their size, chemistry, voltage/current rating, capacity, etc., must be integrated. More research is also needed on new PECs and novel characterization and management of energy storage systems consisting of heterogeneous, retired EV batteries.

### *B. Customer Participation*

Customer participation is critical to many ADM technologies such as demand side management, smart appliance adoption and all other customer based approaches. Various incentives from federal and state governments to utilities have been made available to customers to encourage them to participate in a more active way for electricity distribution and management [124]. Though customer behaviors are affected by many factors, technologies can make them more aware and become more responsible for sustainable energy development and usage. Smart phone applications, for example, can provide an effective feedback path for customers, particularly young generations, to make information-aware decisions.

A smart phone application, called Home Emissions Read-Out (HERO), has been created by researchers at Wayne State University to provide consumers with real-time information about local air emissions resulting from their energy choices [125] [126]. HERO can help users make environmentally-informed decisions about the best time to use their electricity to reduce emissions due to electricity generation and usage. The similar idea can be extended to other demand side management programs. According to a FERC report [127], the residential class represents the "most untapped potential for demand response".

Meanwhile, it is also important to guarantee customers fair participation and shared responsibility. For example, it is desired to give different renewable sources (owned by different owners) the equal opportunity to deliver their powers and to fairly distribute the responsibility when the renewable output powers need to be regulated. Similarly, EV owners want their EVs to be charged and to participate in possible V2G applications in a fairly defined way. This unique characteristic of fairness of power management in distribution networks has been realized by researchers recently. New methods such as cooperative and consensus control schemes have been proposed for fair power generation and sharing in distribution networks [128] [129] [130].

### *C. Concept of Virtual Microgrid*

Though microgrids have been intensively explored and widely reviewed as a promising platform to integrate the intermittent renewable sources and electric drive vehicles to the grid [131] [132] [133] [134] [135] [136], the extension of the concept to distribution network management largely remains as an unexplored area. Currently, most microgrids are operated as an attachment or extension to the existing grid and do not cover the major part of distribution networks. The potential of leveraging and expanding microgrid concept and technologies in ADM should be carefully investigated and deserves more research effort in future.

A concept of virtual microgrid (VMG) for ADM has been proposed in [137]. As shown in Fig. 4, in this concept, a distribution network will be virtually or physically partitioned into VMGs based on the physical feeder topologies, protection zones, or other partition and reconfiguration methods. A VMG, a portion of the distribution network, is controlled and managed just like any real microgrids. The whole distribution system will then have a hierarchical structure of at least two different levels/layers: the distribution grid level, the VMG level, and possibly sub-VMG levels. At the VMG level, each VMG controller will manage the components and network within its own scope and communicate information with and receive orders from the upper level controller, i.e. the grid controller. The grid controller will treat each VMG as a single control entity to achieve a system-wide power and energy management system for the whole distribution network.

However, there are many challenging issues that need to be addressed before the VMG concept can be used for managing real distribution networks. For example, how to form a virtual microgrid (or how to partition original distribution networks into VMGs) is one of the critical tasks. Moreover, VMG modeling and new management and control scheme based on the VMG concept should be interesting research topics in future.

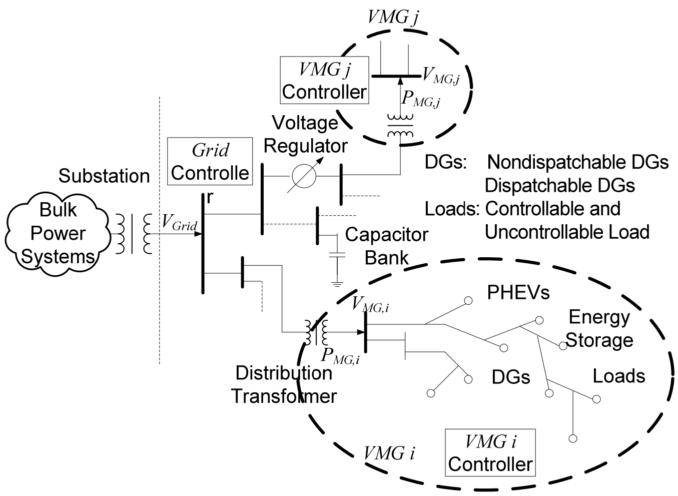


Fig. 4. A distribution network consisting of VMGs.

## VII. Conclusion

This paper provides a review of the recent development in technologies and methods for the active distribution management. Different management frameworks, active voltage and energy management methods, and active protection and fault location techniques for ADM were reviewed. In addition, some specific new strategies of the active management, such as optimization of DGs in DN, demand side management, and agent-based management were also reviewed. Emerging distribution technologies, such as advanced power electronics, communication and information technology, smart appliances, and energy storage systems have been illustrated. Finally, the future trends of energy storage, customer participation, and the concept of virtual microgrid for active management of distribution network were discussed.

Distribution networks are a core part of power systems. It has become one of the frontier areas of smart grid research and implementation activities. Distribution network management is such a dynamic area which deserves more investment and research efforts.

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