A REVIEW ON SMART CONSUMPTION AND DISTRIBUTED POWER GENERATION IN ACTIVE DISTRIBUTION NETWORKS

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ABSTRACT
Active distribution networks (ADNs) are transforming conventional passive grids into intelligent, consumer-interactive energy systems. The rapid integration of renewable energy sources, smart appliances, low-voltage DC (LVDC) distribution, and home energy management systems (HEMS) is enabling fine-grained control over energy consumption at residential, commercial, and industrial levels. Parallel developments in prosumer technologies such as Building-to-Grid (B2G), Vehicle-to-Grid (V2G), and Solar-to-Grid (S2G) are accelerating consumer participation in energy markets. Additionally, distributed power generation using distributed energy resources (DERs), energy storage, and microgrids significantly improves reliability, resilience, and efficiency. This paper provides a comprehensive IEEE-style review of smart consumption strategies, distributed generation, net metering policies, and demand response mechanisms that shape the future of active distribution networks. Emerging trends, challenges, and opportunities for grid–consumer interaction are also discussed.
Keywords— Active distribution networks, LVDC, HEMS, B2G, V2G, Solar-to-Grid, Demand Response, DER, Microgrids.

I. INTRODUCTION

The transformation of the global power sector from centralized, fossil-fuel-dominated generation to increasingly decentralized, renewable-based supply has fundamentally reshaped the operation of distribution networks. Historically, electric grids were designed for unidirectional power transfer, where electricity flowed from large centralized power stations through transmission and distribution lines to passive consumers. However, the last decade has seen an exponential rise in distributed energy resources (DERs), such as rooftop solar photovoltaic (PV) systems, small wind turbines, fuel cells, and battery energy storage systems. This transition toward decarbonization has converted traditional consumers into active "prosumers" who both consume and generate power. The bidirectional power flow caused by these DERs challenges the conventional distribution network's design assumptions related to voltage control, protection coordination, and load management. Consequently, power networks now require advanced monitoring, automation, and control strategies to ensure reliability, stability, and power quality under increasingly dynamic operating conditions.

To address these emerging challenges, modern active distribution networks (ADNs) have evolved as intelligent, flexible, and interactive infrastructures capable of handling variable renewable generation and responsive loads. ADNs integrate various advanced technologies such as smart meters, IoT-enabled sensors, distributed automation, and communication platforms that facilitate real-time monitoring and decision-making. Equally significant is the introduction of load-side innovations such as smart appliances, home energy management systems (HEMS), and low-voltage DC (LVDC)

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distribution in buildings. These technologies enable energy-efficient consumption, enhance load flexibility, and support demand response programs. Smart appliances, for example, operate based on user-defined settings, time-of-use tariffs, renewable generation availability, or direct grid signals. LVDC distribution eliminates unnecessary power conversion stages, improving overall efficiency while aligning with DC-based renewable energy systems and storage technologies. Together, these solutions help balance the intermittent nature of renewable energy sources and contribute to creating a more stable and sustainable distribution network.

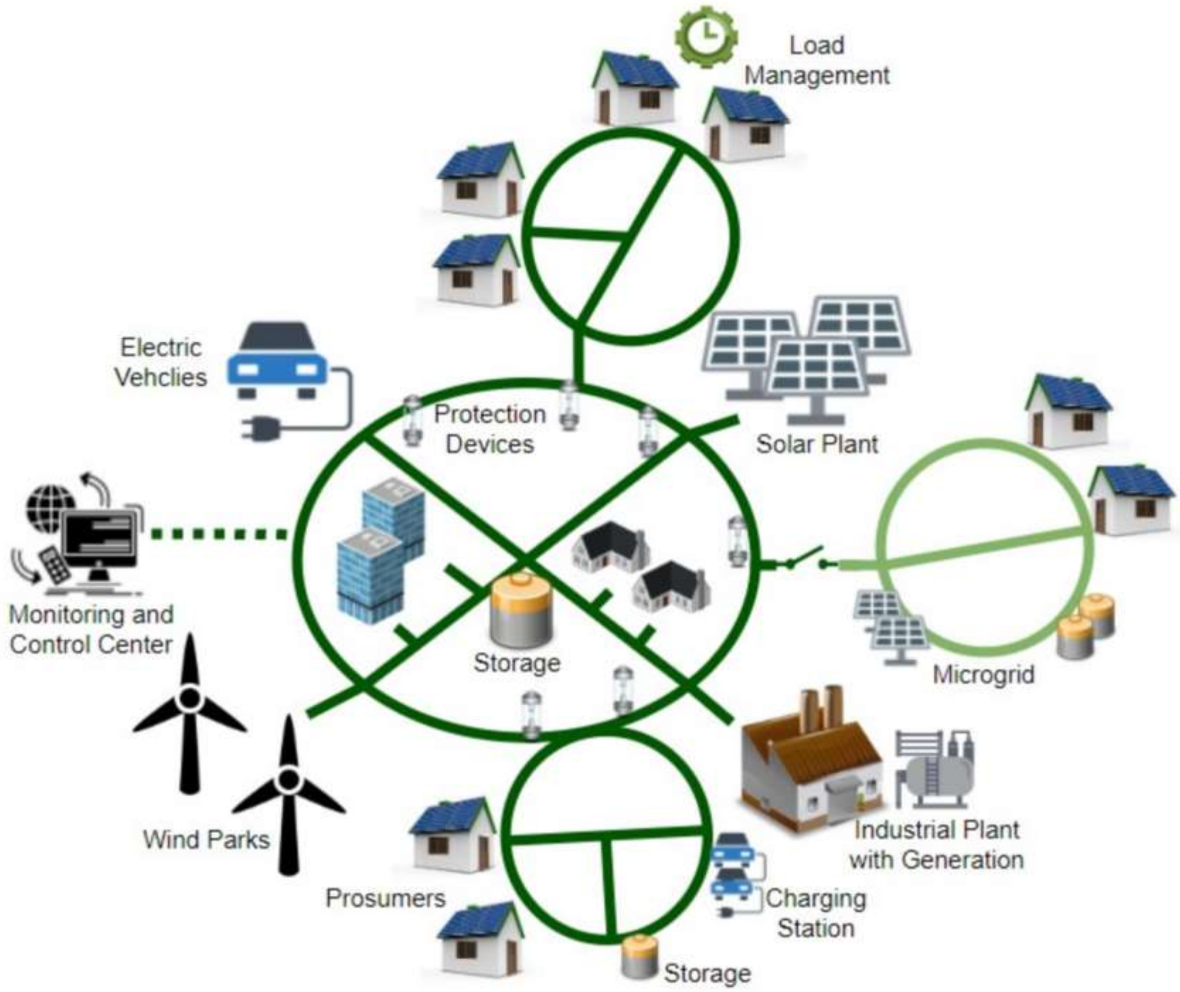

Fig 1.Illustration of an active distribution network

In addition to smart consumption technologies, distributed power generation plays a critical role in enhancing energy resilience and environmental sustainability. Rooftop solar PV, microgrids, electric vehicles (EVs), and battery storage systems enable consumers to actively interact with the grid and support system-level services. Frameworks such as Building-to-Grid (B2G), Vehicle-to-Grid (V2G), and Solar-to-Grid (S2G) further facilitate coordinated energy exchange between end users and utilities. These bidirectional models allow buildings and EVs not only to draw power from the grid but also to supply stored or locally generated energy back to it during peak demand or grid contingencies. Furthermore, the increasing penetration of DERs requires new control strategies for forecasting, scheduling, and real-time power flow optimization. This paper provides a comprehensive review of the enabling technologies behind smart consumption and distributed generation in active distribution networks. It highlights the operational challenges, integration requirements, and potential opportunities associated with these innovations, emphasizing their role in transitioning toward cleaner, more flexible, and consumer-centric electricity systems.

II. LITERATURE REVIEW

Recent literature has extensively addressed the evolution of active distribution networks, particularly focusing on the integration of distributed generation, energy storage systems, and consumer-side intelligence. A large body of studies highlights the importance of HEMS in residential and commercial sectors, demonstrating improvements of 15–30% in energy efficiency through automated load scheduling and optimized power consumption. HEMS platforms leverage advanced metering infrastructure, occupancy patterns, dynamic pricing, and renewable generation forecasts to minimize operating costs while increasing self-consumption of distributed solar energy. Other studies emphasize the role of LVDC distribution systems in buildings, showing that they reduce AC–DC conversion losses and simplify the integration of PV panels, battery storage, EV chargers, and LED lighting—all of which inherently operate on DC. Researchers argue that LVDC networks offer higher overall energy efficiency, improved power quality, and enhanced compatibility with grid-interactive buildings.

The literature also highlights ongoing developments in prosumer-oriented frameworks such as Building-to-Grid (B2G) and Vehicle-to-Grid (V2G) systems. Multiple studies report that EVs, when properly scheduled, can contribute between 20–30% peak shaving in residential communities through controlled charging and discharging. V2G-enabled EVs provide ancillary services including frequency regulation, spinning reserve, and voltage support. Meanwhile, B2G systems integrate photovoltaic panels, storage devices, HVAC systems, and smart loads using coordinated control algorithms to minimize electricity bills and reduce stress on distribution feeders. Solar-to-Grid (S2G) technologies, enhanced through smart inverters and maximum power point tracking (MPPT) mechanisms, are shown to improve grid stability during variable solar generation. These frameworks significantly contribute to enhancing flexibility and controllability in ADNs, enabling both utilities and consumers to benefit from coordinated energy flows.

Despite these advancements, several research gaps persist. Studies consistently point out the lack of standardization in communication protocols and interoperability among smart appliances, meters, and grid controllers. Cybersecurity vulnerabilities remain a pressing concern, particularly in IoT-based HEMS and EV charging systems, which are susceptible to unauthorized access or data manipulation. Additionally, large-scale modeling of consumer behavior remains underexplored, limiting the accuracy of demand response simulations and energy optimization frameworks. Researchers emphasize the need for improved forecasting algorithms, adaptive control methods, and hybrid energy storage optimization strategies to address the uncertainty associated with renewable energy generation. Collectively, these gaps highlight the necessity for future research to focus on robust, secure, and scalable solutions that ensure seamless integration of smart consumption technologies and distributed power generation in active distribution networks.

III. SMART CONSUMPTION IN ACTIVE DISTRIBUTION NETWORKS

Smart consumption plays a pivotal role in the transformation of conventional distribution networks into intelligent and flexible ADNs. Smart appliances form the backbone of consumption-side intelligence, enabling automated, efficient, and grid-responsive behavior. Through communication with HEMS platforms or utility signals, these appliances can adjust their operation based on real-time electricity pricing, demand response commands, user-defined preferences, or availability of renewable energy. For example, smart HVAC systems can pre-cool or pre-heat spaces during off-peak hours, while smart washing machines or dishwashers can delay operation based on dynamic pricing. This interaction significantly reduces peak demand, lowers consumer bills, and increases renewable energy utilization. IoT-enabled appliances also allow remote monitoring and control, providing both convenience and energy savings.

LVDC distribution systems further support smart consumption initiatives. Modern households and commercial buildings contain numerous DC-based loads, including laptops, LED lighting, routers, sensors, and EV chargers. LVDC networks reduce the number of AC–DC conversions required, minimizing energy losses and improving overall system efficiency. They also simplify the integration of rooftop solar PV and battery storage systems, which inherently produce and store energy in DC form. By enabling direct coupling between DC loads and DERs, LVDC systems provide faster response, enhanced power quality, and smoother bidirectional energy exchange. This infrastructure is particularly beneficial for homes and buildings equipped with DC nanogrids, where PV, ESS, and EV chargers operate in a coordinated manner to balance supply and demand while interacting with the main grid.

Smart consumption also encompasses prosumer-driven energy models such as net metering, B2G, V2G, and S2G. Net metering policies enable consumers to export excess solar energy, reducing electricity bills and supporting grid balancing. B2G systems expand this capability by allowing buildings to participate in demand response programs, provide grid support, and optimize internal energy use through coordinated control of PV, ESS, HVAC, and smart appliances. Similarly, V2G-enabled EVs serve as mobile storage units capable of discharging energy during peak demand or emergencies, providing valuable ancillary services. Solar-to-Grid systems leverage smart inverters to inject solar energy while maintaining voltage and frequency stability. Together, these technologies significantly improve the flexibility, resilience, and sustainability of active distribution networks by empowering consumers to become active contributors to grid stability and energy efficiency.

IV. DISTRIBUTED POWER GENERATION & POWER SUPPLIES

Distributed power generation has emerged as a cornerstone of modern active distribution networks due to its ability to reduce dependency on centralized power plants and enhance overall system resilience. Distributed Energy Resources (DERs) such as rooftop photovoltaic (PV) systems, small wind turbines, micro-turbines, biomass generators, and fuel cells contribute significantly to decentralizing energy production. Rooftop PV in particular has experienced exponential growth due to falling installation costs and favorable policy mechanisms, enabling households to generate clean electricity near consumption points. Similarly, small wind turbines and micro-turbines enhance generation diversity by providing localized energy supply even where solar conditions are not optimal. Biomass-based generators and fuel cells serve as reliable, low-emission alternatives suitable for continuous operation, supporting both residential and commercial loads. Collectively, these DERs mitigate transmission losses, improve voltage stability at the distribution level, and increase the resilience of local grids by enabling multiple generation nodes across the network.

The integration of renewable energy sources introduces inherent intermittency into distribution systems, primarily due to fluctuating solar irradiance and variable wind speeds. These variations cause unpredictable changes in power output that must be compensated for in real time to maintain grid balance. To address these challenges, active distribution networks rely heavily on fast-response technologies such as Energy Storage Systems (ESS) and flexible loads. ESS technologies like lithium-ion batteries, ultra-capacitors, flywheels, and hydrogen storage systems play a critical role in maintaining supply-demand equilibrium. They smooth renewable power fluctuations, provide voltage and frequency support, and supply backup power during short-term outages. ESS-driven peak shaving reduces stress on transformers and distribution feeders, extending system lifespan and improving power quality. In parallel, flexible loads such as smart appliances, electric vehicles, and HVAC systems participate in real-time demand response to absorb surplus renewable energy or reduce consumption during peak periods. This integrated approach enables high penetration of renewable resources without compromising system stability.

Demand response (DR) further strengthens the role of distributed generation by enabling consumers to actively adjust their electricity usage based on grid signals. DR mechanisms flatten load curves, reduce peak demand charges, and minimize the need to operate expensive peaker plants. Price-based DR strategies encourage users to shift consumption away from high-tariff periods, while incentivebased DR programs reward customers for reducing load during critical grid events. Microgrids elevate these capabilities by combining DERs, ESS, loads, and control systems into self-sustaining, flexible energy ecosystems. Operating either in grid-connected mode or islanded mode, microgrids enhance reliability, resilience, and renewable integration, especially in remote communities, campuses, and industrial clusters. Their hierarchical control architecture—comprising primary, secondary, and tertiary layers—enables coordinated power flow, stable operation, and optimal economic dispatch. Through microgrid deployment, distributed generation evolves from simple local supply to a sophisticated grid-supporting resource that enhances autonomy, efficiency, and sustainability across active distribution networks.

V. SYSTEM ARCHITECTURE FOR ACTIVE DISTRIBUTION NETWORKS

A modern active distribution network is built upon an integrated architecture that unites sensing, communication, distributed generation, and advanced control technologies. Smart meters and sensors deployed throughout the grid offer real-time monitoring of voltage, current, energy consumption, and power quality parameters. This granular visibility allows utilities to dynamically detect faults, predict load variations, and manage distributed assets with greater efficiency. Distributed Energy Resources (DERs), including solar PV, wind units, micro-turbines, and storage systems, are embedded at various nodes within the distribution network, creating a multi-source power supply environment. Distributed storage enhances reliability by providing instantaneous support during fluctuations and enabling time-shifted consumption of renewable energy. Home Energy Management Systems (HEMS) and Advanced Metering Infrastructure (AMI) extend these capabilities to residential and commercial consumers, enabling coordinated control of smart appliances, EV chargers, and local renewable systems.

The backbone of ADN operation lies in its advanced power electronic interfaces, which include bidirectional AC/DC and DC/DC converters that allow flexible energy exchange between DC-based renewables, storage devices, electric vehicles, and the AC distribution grid. Smart inverters equipped with grid-forming or grid-following capabilities actively contribute to voltage regulation, reactive power compensation, and frequency stability. These power interfaces ensure seamless integration of LVDC building networks, rooftop solar PV, electric vehicle charging infrastructure, and community energy storage systems. Equally important are the robust communication networks—such as IoT platforms, 5G networks, power line communication (PLC), and wireless sensor networks—that support high-bandwidth, low-latency data exchange. Such communication layers are essential for enabling demand response, distributed control, and real-time power flow optimization.

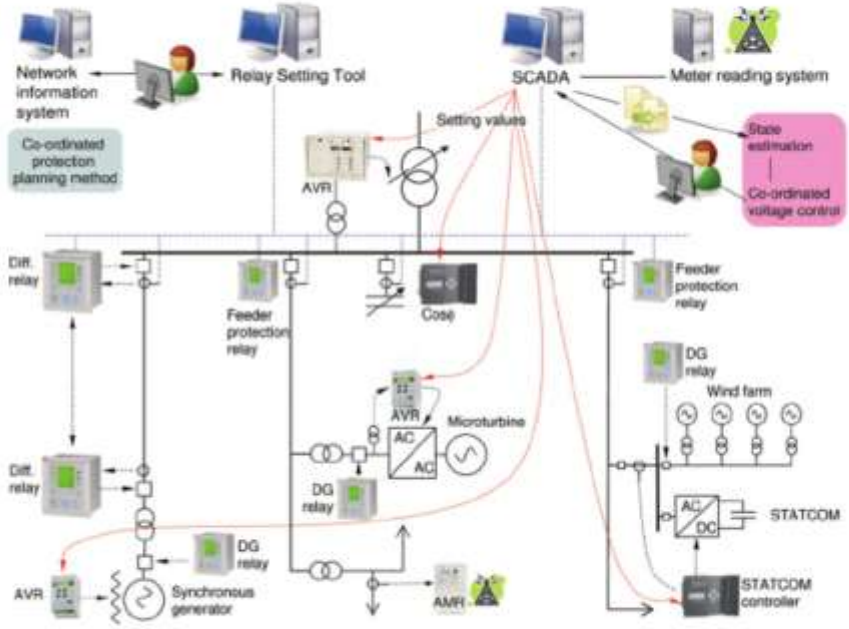

Fig 2. Overview of the active distribution network in the ADINE project.

Advanced control algorithms further enhance the functionality of ADNs by enabling predictive, adaptive, and coordinated decision-making across distributed assets. Model Predictive Control (MPC), AI-driven forecasting tools, and machine-learning-based energy management systems analyze large volumes of real-time data to optimize load scheduling, forecast renewable generation, and manage ESS charging and discharging. Artificial intelligence improves grid stability by detecting anomalies, predicting failures, and coordinating DERs to ensure minimal operational cost and maximum efficiency. These intelligent control layers support coordinated energy exchange between buildings, EV fleets, DERs, and the main grid. Through this sophisticated architectural framework, active distribution networks achieve higher flexibility, greater reliability, enhanced renewable integration, and improved overall performance in managing both supply and demand.

VI. CHALLENGES IN SMART CONSUMPTION & DISTRIBUTED GENERATION

Despite significant technological advancements, smart consumption and distributed generation in active distribution networks face a number of technical challenges. The intermittent nature of renewable energy sources such as solar and wind introduces frequent fluctuations in power supply, making real-time balancing a complex task. Voltage and frequency deviations become more common as distributed generation increases, especially in feeders with high PV penetration. LVDC and hybrid AC/DC systems add further complexity due to the absence of well-established protection standards. Fault detection, isolation, and coordination in multi-bus DC networks remain difficult because DC faults propagate faster and require specialized breakers. Coordinating DERs and ESS units to maintain power quality, manage congestion, and optimize system-level performance requires advanced algorithms and fast communication systems, which are not always available in traditional distribution networks.

Communication and interoperability challenges also pose significant barriers to widespread adoption of intelligent distribution systems. With numerous manufacturers providing smart appliances, sensors, inverters, and metering devices, achieving universal compatibility remains difficult. The absence of standardized communication protocols limits seamless integration of DERs, EVs, HEMS, and microgrids. Cybersecurity threats are an increasingly serious concern as more grid components become interconnected via IoT platforms. Unauthorized access to smart meters, DER controllers, or EV chargers can disrupt grid operations, compromise consumer privacy, or lead to intentional manipulation of power flows. Building robust cybersecurity mechanisms and establishing secure communication channels is essential for maintaining trust and operational integrity in ADNs.

Economic and policy-related challenges further slow down the transition toward smart and distributed energy systems. Although ESS and bidirectional EV chargers offer significant operational benefits, their initial costs remain relatively high, discouraging widespread adoption. Uncertain payback periods and fluctuating electricity tariffs increase financial risk for consumers investing in rooftop PV, home batteries, or EV-based V2G systems. Policy inconsistencies—particularly in net metering regulations, feed-in tariffs, and grid interaction rules—confuse potential prosumers and hinder long-term investment decisions. Many regions also impose restrictions on V2G and B2G participation due to concerns over equipment wear, protection issues, or lack of regulatory clarity. These combined challenges highlight the need for stronger policies, improved interoperability standards, and continued research into cost-effective, secure, and scalable active distribution network solutions.

VII. CONCLUSION

Active distribution networks represent the future of modern power systems, driven by the increasing integration of smart appliances, LVDC building systems, HEMS, and prosumer technologies such as B2G, V2G, and S2G. Distributed power generation and microgrids enhance reliability, flexibility, and sustainability by enabling localized control of renewable energy and storage. Despite promising advancements, challenges remain in standardization, consumer participation, protection strategies, and DER coordination. Future ADS deployments will rely on intelligent control, IoT connectivity, and AI-based forecasting to enable a fully grid-interactive energy ecosystem.

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