Optimal Scheduling of Microgrid-Based Virtual Power Plants : A Review

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***Abstract*—** The increasing integration of renewable energy sources and the rising demand for decentralized energy systems have led to the emergence of microgrids and virtual power plants (VPPs) as key components of modern power systems. Optimal scheduling of these systems is crucial for ensuring efficient energy utilization, cost-effectiveness, and enhanced grid stability. This review explores the methodologies, technologies, and frameworks for optimal scheduling in microgrid-based virtual power plants. It examines the role of advanced optimization techniques, artificial intelligence, and machine learning in addressing the challenges posed by the intermittent nature of renewable energy, load uncertainties, and market dynamics. The review also highlights the importance of coordination between distributed energy resources (DERs), energy storage systems (ESS), and demand-side management (DSM) strategies to achieve optimal performance. Furthermore, it provides a comprehensive analysis of recent studies, comparing their approaches, objectives, and performance metrics. This study aims to serve as a valuable resource for researchers and practitioners working toward the development of more sustainable, resilient, and efficient energy systems.

Keywords*—*Virtual power plant, Optimal, Microgrid, Scheduling, DER.

I. Introduction

The global energy landscape is undergoing a transformative shift due to the rapid integration of renewable energy sources (RES), growing concerns over climate change, and the increasing need for energy security and sustainability [1]. Traditional centralized power systems are being complemented—and in some cases, replaced—by decentralized energy systems, which offer greater flexibility, efficiency, and reliability. Among these, microgrids and virtual power plants (VPPs) have emerged as innovative solutions for managing distributed energy resources (DERs) and meeting the dynamic demands of modern power systems [2].

Microgrids are localized energy systems capable of operating autonomously or in conjunction with the main grid. They integrate various DERs, such as solar photovoltaic (PV) systems, wind turbines, energy storage systems (ESS), and controllable loads, to form a self-sustaining energy network. On the other hand, virtual power plants aggregate multiple microgrids and DERs into a unified entity that can be optimized and controlled centrally to participate in energy markets and provide ancillary services [3]. The combination of microgrids and VPPs not only enhances energy reliability and resilience but also facilitates the transition toward a low-carbon energy future.

Optimal scheduling plays a pivotal role in unlocking the full potential of microgrid-based virtual power plants. It involves determining the most efficient operational strategy for DERs, ESS, and controllable loads to minimize costs, reduce emissions, and maximize energy efficiency. However, achieving optimal scheduling is a complex task due to several factors [4]. These include the intermittent and stochastic nature of RES, variability in energy demand, energy market fluctuations, and the need for real-time decision-making. Additionally, the integration of advanced technologies such as artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT) devices has introduced new opportunities and challenges in this domain [5].

This review focuses on the methodologies and frameworks developed for the optimal scheduling of microgrid-based virtual power plants. It provides an in-depth analysis of various optimization techniques, including linear programming (LP), mixed-integer programming (MIP), metaheuristic algorithms, and AI-driven approaches. The review also explores the role of demand-side management (DSM) strategies, energy storage optimization, and renewable energy forecasting in improving scheduling efficiency. Furthermore, the study highlights the importance of balancing technical, economic, and environmental objectives to achieve sustainable energy systems.

Recent advancements in optimization techniques and computational tools have enabled researchers and practitioners to address many of the challenges associated with microgrid scheduling. For example, AI and ML algorithms have shown promising results in predicting RES generation and load demand, thus enhancing the accuracy of scheduling decisions [6]. Similarly, blockchain technology has been proposed to improve transparency and security in VPP operations, while IoT devices facilitate real-time monitoring and control of DERs.

Despite these advancements, several gaps and challenges remain. These include the need for scalable and computationally efficient optimization models, effective coordination mechanisms among multiple stakeholders, and robust strategies for handling uncertainties and disruptions [7]. Additionally, regulatory and policy frameworks play a critical role in shaping the deployment and operation of microgrid-based VPPs, requiring further attention from researchers and policymakers [8].

This review aims to provide a comprehensive understanding of the current state of research in optimal scheduling for microgrid-based virtual power plants. By synthesizing findings from recent studies and identifying emerging trends and challenges, it seeks to contribute to the ongoing efforts toward building more resilient, sustainable, and efficient energy systems.

II. LITERATURE SURVEY

M. Tabatabaei et al. [1] presents a stochastic framework for the optimal coordination of a microgrid-based virtual power plant (VPP) participating in day-ahead energy and ancillary service markets. Microgrids often include diverse decentralised energy generating and storage systems. A two-stage optimisation formulation has been created to enhance the advantages of the virtual power plant while limiting energy acquisition costs for the Distribution System Operator (DSO). The proposed method determines the optimal commitment scheduling of energy resources by considering the capacity withholding options offered by the VPP and requiring that these opportunities be revealed by the DSO. The approach is assessed for use on the 123-bus IEEE test system to ascertain the effectiveness of the proposed model. The results demonstrate that the proposed technique optimally enhances profit from the virtual power plant while considering the penalty for capacity withholding.

A. K. Pandey et al.,[2] As nations strive to attain optimal reliance on sustainable energy sources, it is essential to address the foremost issues associated with the advancement of this evolving energy system. It is essential to note that a principal difficulty is the unstable nature of most renewable energy sources. The integration of renewable energy sources (RES) to achieve a carbon-neutral planet in the near future presents considerable hurdles for the existing energy infrastructure. A reliable energy storage system capable of managing intermittent and variable renewable energy sources is essential for using green power. A virtual power plant (VPP) might serve as a principal solution to address this requirement. A virtual power plant (VPP) is a cloud-based, decentralised power facility that integrates the capabilities of various distributed energy resources (DER) from diverse locations to enhance power generation and enable the trading of electricity in the market. This work aims to highlight the benefits of a virtual power plant and to analyse its numerous advantages over a conventional power plant, particularly concerning the reduction of harmful emissions, which are the primary source of the drawbacks associated with the latter. The creation of Virtual Power Plants (VPPs) is expected to promote the adoption and expansion of renewable energy sources and aid in the decarbonisation of society.

Y. Han et al. [3] indicate that the system governing the electricity market is undergoing progressive enhancements, enabling virtual power plant operators to operate as autonomous entities and actively participate in electrical markets. This will enable the aggregation of flexible resources, including dispersed generation, adaptive loads, and energy storage systems. This paper delineates the framework of virtual power plants participating in demand response, including particular instances from Jiangsu Province and Shanghai City. The involvement pattern of virtual power plants in the auxiliary service market is examined using Northern Hebei Province as a case study. The evolution of energy markets facilitates the analysis of many potential configurations of virtual power plants engaged in the trading of green certificates and carbon credits.

J. Xu et al. [4] assert that isolated microgrids, which use renewable energy sources, battery storage, and backup diesel generators, need efficient demand response to maximise energy utilisation and minimise diesel consumption. Conversely, because to issues with connection latency, real-time demand-side management has become very challenging. This study focusses on managing the demand for Electric Water Heater (EWH) units and proposes a distributed model-free approach as a solution. To autonomously manage the 150 EWHs using a virtual tariff, distributed artificial intelligence technology based on Reinforcement Learning (RL) has been used. Two alternative approaches are proposed as potential choices for producing the virtual tariff. This paper contrasts two ways to examine the impact of communication time-delay on the proposed RL algorithm in a real-time control context. The first methodology involves real-time monitoring of the battery's State of Charge (SOC), but the subsequent method use an Artificial Neural Network (ANN) to forecast the SOC 24 hours ahead. The data indicate that communication time-delay significantly affects the convergence outcome of the first strategy, but the second method exhibits considerable resilience to this effect. The results indicate that the proposed algorithm may reduce energy consumption by an average of 8.91% (6.675kW) per EWH, confirming the feasibility of the offered method.

A. Mnatsakanyan et al. [5] indicate that grid operators have substantial challenges in achieving cost-effective and efficient system balancing amid extensive integration of renewable energy sources into electrical networks. The predominant tactics for managing distributed variable generation include augmenting reserve margins, using energy storage, leveraging demand response resources, and temporarily limiting renewable energy, alongside enhancing generation forecasting capabilities. Alternative tactics may also be used. Similarly, the concept of a Virtual Power Plant (VPP), which entails the aggregation and management of diverse distributed energy resources, is increasingly gaining prominence in Smart Grids. This work presents the outcomes of a pilot VPP implementation within a vertically integrated utility system in Dubai, United Arab Emirates. The objective of this exercise is to demonstrate the effective integration of VPP into the grid using both real and simulated assets as members of the VPP coalition. This is a demonstration of the system architecture, several operational modes, and diverse integration scenarios. The case study analyses the consolidation of several distributed energy sources, including microgrids and utility-scale batteries, with an aggregate capacity of 1.8 megawatts (MW).

J. Lee et al. [6] indicate that the technology behind virtual power plants (VPPs) is continually enhanced to integrate the many types of distributed energy resources (DERs), each presenting its own intrinsic real-time uncertainty. To prevent unintended repercussions for the power system due to uncertainty, the VPP must comprehensively control the unpredictability of its internal resources. This paper proposes an optimal operational strategy for a Virtual Power Plant engaged in day-ahead and real-time energy markets. The objective of this study is to facilitate a distributed energy resource aggregation (DERA) in managing real-time variations induced by uncertainties while concurrently optimising its profitability. The proposed plan includes competitive bidding techniques for Distributed Energy Resource Aggregations (DERAs) such as microgrids, demand response aggregation, and electric vehicle aggregation, alongside the Virtual Power Plant (VPP). The VPP assesses its real-time responses to the day-ahead schedule and modifies the proposed pricing function parameters to determine the internal prices applied to the DERA. Concurrently, the DERA modifies its energy reserves. The VPP can autonomously develop an optimal operating strategy to manage real-time uncertainty by repeatedly executing the aforementioned coordination process. Scenario-based simulations may ascertain the efficacy of the proposed strategy by evaluating the DERA's capability to manage real-time volatility. The results suggest that the VPP might reduce expenses by 1.6%, even when the internal price assigned to the DERA is close to the maximum limit.

N. U. Padmawansa et al.,[7] This decade has seen significant expansion in the incorporation of renewable energy sources to achieve clean energy production objectives. Inverters are widely used devices for integrating renewable energy sources, such as solar and wind, into the power system. Synchronous generators serve as the cornerstone of conventional power generation methods, including coal, nuclear, and hydroelectric energy. The extensive integration of renewable energy facilities is resulting in a transformation of the power system towards inverter dominance. This might significantly impact the system's inertia response. However, inverters lack rotational masses and, thus, cannot contribute to the system's total inertia. Inertia is supplied by the revolving mass of conventional generators. The lack of inertia will adversely affect the system's stability when exposed to shocks. The system's frequency will therefore deviate from its permissible range. This complicates the integration of renewable energy sources into current systems. Conversely, inverters have a quick response and a high level of controllability, enabling them to replicate the effects of inertia. This work presents two novel controllers that may be used to model the inertia response. Both controllers have been created by the writers. The virtual inertia may be regulated by one controller, whilst the energy management might be administered by a second controller. Results are generated and examined in a simulated PV-Hydro microgrid experiencing a supply-demand imbalance.

C. Meng et al. [8] aim to achieve the aggregation of distributed energy by integrating several distributed energy sources, including wind farms (WPP), solar power plants (PV), small hydropower stations (SHS), and incentive-based demand response. The phrase "distributed energy aggregation" denotes a "virtual power plant" (VPP), while "price-based demand response" (PBDR) pertains to the user-side implementation of response measures. A VPP regular scheduling optimisation model is first built to maximise operational revenue while considering various constraints. These restrictions include load supply and demand equilibrium, unit operation clusters, and operational reserves. The last phase involves developing a VPP risk avoidance optimisation model using conditional value-at-risk (CVaR) and Lu Bar stochastic optimisation theory. This will enable you to delineate the uncertainty of WPP and PV. The verification is ultimately conducted utilising an autonomous microgrid situated in a park in eastern China as a case study. The findings demonstrate that: (1) the characteristics of diverse distributed power sources can be enhanced by Virtual Power Plants (VPP) to optimise energy utilisation, power generation, and economic benefits; (2) in light of uncertainty risks, this study advocates for a hybrid system that integrates distributed power sources with centralised power plants. The risk avoidance model posits that risk is handled by accurately adjusting the confidence and robustness coefficients. This mitigates the danger. Research indicates that when robustness falls below 0.85, uncertainty remains low although risk is elevated at this juncture.

C. P. Barala et al. [9] propose that a virtual energy storage system (VESS) serves as an innovative and economical alternative to traditional energy storage systems (ESSs) by using existing interconnected network assets characterised by changing demand. This is achieved by representing ESSs as a VESS. VESS may mitigate some challenges related to the operation of low-carbon power networks by synchronising demand response (DR) loads from the HVAC (heating, ventilation, and air conditioning) requirements of residential and commercial buildings with load management strategies. This study presents an optimal operational model for a microgrid that incorporates VESS to reduce daily operational costs. This work develops a mathematical model of VESS using the HVAC loads of residential and commercial buildings. The authors propose a mathematical framework using a linear switching model for continuous power inputs as an alternative to binary power values. The results indicate that the capacity of VESS functions similarly to electrochemical batteries, hence reducing the overall cost of the microgrid without compromising user satisfaction.

G. Niu et al. [10] assert that optimising energy usage may substantially improve the overall operating efficiency of the distribution court. The optimisation of energy utilisation in distribution networks now faces considerable challenges due to the integration of large-scale distributed generation. Achieving global optimisation of energy utilisation in a distribution network with many distribution courts is more challenging. This work provides a comprehensive solution to address the reported problem. Initially, we will discuss the goals for the efficient utilisation of energy in the distribution court. The technologies of virtual power plants, microgrids, and demand response are all delineated and compared. A concept is proposed for optimising energy usage in the multi-court distribution network via the integration and implementation of three primary supporting technologies. This illustration depicts the structural composition, functional structure, and optimal management of the multi-court distribution network intended for the implementation of the concept. The conclusion and future thoughts are presented in the conclusion.

D. C. Urcan et al. [11] provide a comprehensive examination of the concept of virtual power plants (VPP) in this study. This paper examines the definitions of virtual power plants, their components, and the supporting infrastructure. It also underscores the many tactics that may be used for optimising VPP operations. A virtual power plant infrastructure will be given at the completion of the project. This infrastructure will be available via a web interface, enabling control of a virtual micro-grid. The micro-grid will get data from virtual smart meters, which will provide various load profiles for consumption and dispersed generation locations.

X. According to Gao et al., [12] the V30 power plant exemplifies an effective method for integrating decentralised energy sources into power distribution networks in a manner that is secure, reliable, and economically efficient. This document provides an overview and explanation of the concept, operational principles, and regulatory approaches of a virtual power plant. It further juxtaposes a virtual power plant with a microgrid. This document introduces the applications of virtual power plants and the advantages associated with their use for resource integration, power market trading, and demand response. This document presents an analysis of the essential technologies necessary for the creation of virtual power plants and their possible uses.

III. CHALLENGES

1. Intermittency and Uncertainty of Renewable Energy Sources

- **Stochastic Nature of RES:** Renewable energy sources, such as solar and wind, are inherently intermittent and unpredictable due to weather conditions, leading to variability in power generation.
- **Forecasting Errors:** Accurate forecasting of RES generation and energy demand is critical for optimal scheduling, yet it remains a challenge due to uncertainties in meteorological and consumption data.
- **Resource Availability:** Managing sudden drops or surges in renewable energy output while maintaining grid stability is a complex task.

2. Scalability and Computational Complexity

- **High Dimensionality:** The large number of variables, including DERs, energy storage systems (ESS), and load demand, increases the dimensionality of the scheduling problem, making it computationally intensive.
- **Real-Time Optimization:** Achieving real-time scheduling decisions requires algorithms that are both scalable and computationally efficient, which can be challenging to develop and implement.
- **Multi-Objective Optimization:** Balancing conflicting objectives, such as minimizing costs, reducing emissions, and ensuring reliability, adds complexity to the optimization process.

3. Coordination Among Distributed Energy Resources

- **Heterogeneous Systems:** The diverse nature of DERs, including solar PV, wind turbines, ESS, and controllable loads, requires effective coordination to ensure optimal performance.

- **Communication and Control:** Establishing reliable and low-latency communication networks for real-time data exchange and control among DERs and VPPs is challenging, especially in remote areas.
- **Energy Storage Optimization:** Managing ESS effectively to balance supply and demand, account for degradation, and maximize lifecycle performance is a critical challenge.

4. Market Dynamics and Regulatory Constraints

- **Energy Market Volatility:** Fluctuations in electricity prices and market conditions make it difficult to develop stable and cost-effective scheduling strategies.
- **Regulatory Uncertainty:** Policies and regulations governing microgrids and VPPs vary across regions and are often unclear, hindering widespread adoption.
- **Incentive Structures:** Designing effective incentive mechanisms for stakeholders to participate in VPPs and adhere to optimal scheduling practices remains a challenge.

5. Integration of Advanced Technologies

- **Data Integration:** Integrating data from various sources, such as IoT devices, sensors, and smart meters, into a unified platform for scheduling is complex.
- **Artificial Intelligence (AI) Challenges:** While AI and machine learning (ML) offer significant potential for optimizing scheduling, their implementation faces challenges such as data quality, interpretability, and scalability.
- **Cybersecurity Risks:** The increasing reliance on digital technologies and IoT devices exposes microgrids and VPPs to cybersecurity threats, which can disrupt operations and compromise scheduling.

6. Uncertainty in Demand-Side Management (DSM)

- **Consumer Behavior:** Predicting and managing consumer behavior in response to dynamic pricing and demand-response programs is challenging.
- **DSM Participation:** Encouraging widespread participation in DSM programs requires effective communication, incentives, and consumer trust.

IV. CONCLUSION

The optimal scheduling of microgrid-based virtual power plants is a cornerstone for achieving efficient, reliable, and sustainable energy systems in the era of decentralized power generation. While significant advancements in optimization techniques, artificial intelligence, and energy management frameworks have improved scheduling capabilities, challenges such as the intermittency of renewable energy sources, scalability, market dynamics, and regulatory barriers persist. Addressing these challenges requires a multidisciplinary approach, combining technological innovation, robust policy support, and stakeholder collaboration. By overcoming these hurdles, microgrid-based VPPs can unlock their full potential, facilitating the integration of renewable energy, enhancing grid stability, and driving the transition toward a greener and more resilient energy future.

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