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Optimization of Renewable Energy Integration in Smart Grids: Mathematical Modeling and Engineering Applications

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ABSTRACT

The integration of renewable energy sources (RESs) into smart grids (SGs) is pivotal for transitioning towards sustainable and efficient electrical power systems. This paper explores the optimization of RES integration within SG frameworks, employing sophisticated mathematical modeling techniques and showcasing their practical engineering applications. Emphasizing the critical role of SGs in facilitating RES integration, the study underscores the significance of mathematical optimization methodologies in mitigating operational challenges. Through comprehensive analysis and case studies, the paper elucidates the efficacy of optimization strategies in real-world SG environments, offering insights into future trends and challenges.

Keywords: Renewable Energy Integration, Smart Grids, Mathematical Modeling, Optimization Techniques and Engineering Applications

Introduction to Smart Grids and Renewable Energy Integration

The renewable energy resources have been facing several key challenges, including the randomness, forecast error and fluctuation of the output power of renewable energy systems, and difficulty in equipment construction, investment, operation and maintenance [1-4].The traditional power system structure based on centralized energy production, one-way power flow, passive power load, and consumption is difficult to support the extensive and efficient integration and utilization of renewable energy [5-6]. In this context, the Smart Grid (SG) has become one of the most effective solutions to the integration of renewable energy. The SG is an electrical grid, in which the renewable energy can be easily connected to the electrical grid to achieve an electricity-supply mode, which is provided by the owners of renewable energy installations and balanced with the user's electricity demand by the grid network. It is noteworthy that the strategy and method utilized in the SG engineering optimization process and operation should change timely with the increase in the system scale [7-8]. In the future, the SG will be integrated with many distributed renewable energy sources and storages systems, thus presenting the distributed and more complicated SG structure. With the rapid depletion of the traditional fossil fuels, the issue of sustainable development has attracted increasing attention turning many energy economies towards the direction of development and utilization of renewable energy resources [9-10]. The renewable energy resources, such as wind and solar, are clean, inexhaustible and sustainable which are conducive to the improvement of the greenhouse effect and the prevention of climate change. In recent years, as the costs of renewable energy have been constantly declining, the application scope of renewable energy is expanding continuously, and considerable attention is being paid to the remote, mountainous, and other areas with poor electrification conditions [11-14].

Overview of Smart Grids

Renewable power sources are the best alternative for decreasing greenhouse gas emissions. In China, renewable energy will serve as a vital catalyst for China's future economic growth. Renewable energy sources such as photovoltaic cells (pvs), wind farms (wfs), and small hydroelectric plants have recently become popular because of their reduced costs and ecological advantages [15-17]. These power sources are subject to fluctuations and are installed with other weather-dependent resources such as wind and the sun. To make sure that a trustworthy energy source is provided, PV and wind power require the construction of suitable storage systems and backup units. The expense of equipment is a principal financial bottleneck for renewable power integration [18-23]. In most situations, the surplus power generated during the day, the PV and WS devices should be designed to have long term storage. For small-scale plants, using gas-powered generators rather than petroleum products or diesel is an alternative. If grass is available, grass-fired plants are a possible supplement. Adding batteries to PV and WS devices, as well as the wind power and small hydropower stations, can be an alternative [24-27]. Smart grids are the considered power systems in which the actions of generating, transmitting, and consuming energy are controlled in real time in such a way that all types of energy are created economically, transmitted efficiently, and consumed seamlessly down to the requirements and satisfying the limitations of the network [28-29]. They integrate several digital technologies used to operate all the components as one complete network. The smart grid engineering aims at modernizing and automating the power system to deliver electricity from generation to consumption. The smart grid technology takes in several aasses such as digital technology, sensing, measurement, control, and communications for the routine operation of the electric power system [30-32]. With the help of digital tools like power management systems, smart meters, and other digital tools, all the components are coordinated and are operated in portions of the system to ensure that the system is resilient and reliable in operation. The smart grid technology is considered as a collection of technologies used in electric power systems that provide the relay options with current energy needs for industrial, commercial, and residential consumers [33-35].

Importance of Renewable Energy Integration

Global renewable electricity generation reduced from 11.5 to 11.3 million MWh per day due to a minor decline in biomass generation. This decrease was more than compensated by modest gains in hydro and other renewable electricity production: up 7.4 to 7.39 million MWh per day. The total renewable generation has increased by more than a third from 9.68 million MWh per day in 2011. Bioenergy consumption remains focused in the European Union: the bulk of it to meet the Paris Agreement means for atmospheric carbon drawdown and in India due to biomass used in primary energy requirements. Except as a practical medium for delivering biofuel (for example, liquid petroleum gas stoves and some hybrid properties), policymakers seldom talk concerning "renewable energy" other than electricity. However, the most interesting investment- and policy-related questions concern concerns that entire ecosystems face: by what biological and ecological mechanisms do humans live effectively and regenerate them from time to time? Energy is the most determinant factor of a country's growth, which increases the socioeconomic standard [36-38]. The world energy demand increase by 25.8% from 2013 to 2018 (A. Islam et al., 2014). Fossil fuels are the main source of energy supply; still, it created environmental pollution, which can result in global warming, acid rains, and cause health issues. Renewable energy sources like solar, wind, water, and biomass energy are the best alternatives to fossil fuels. In the context of Bangladesh Renewable, energy integration becomes essential now and then for increasing power demand, reducing greenhouse gas emission, diversifying energy supply, and harvesting renewable energy potential [39-41]. To tackle curtailed issues and to ensure the availability of an electrical power energy supply to the consumer, proper management and operation schedule in the power delivering system is required promptly.

Mathematical Modeling Techniques in Smart Grids

The electricity dispatch can be categorized into various types such as scheduled (or planned) and real-time (or intra-hour) dispatch, flat or semester-wise dispatch, based on electricity price, cost and/or decreasing orders; possibilities in different time interval choices: 5, 10, 15, 20, 30 and 60 mins can also be studied. The dispatch process can also be executed for a mix of traditional and clean resources, or for a dispatchable device under renewable resources, or for the renewable resources themselves under forecast model ranges or their actual values [42-44]. Grid-integrated storage connects local renewable generations, local load, and the central/load center/hierarchical in some cases. Consequently, in most of today's works, local NRGs are dispatchable optimally such that the peak-to-average ratio of the interpreted transmission powers/energies for a smoothen electrical cost or for primary for shedding peaks is reduced. The bi-directional energy facility integrates and separates the local generations and consumers almost instantly. Almost in parallel to the purification, the net electricity of the responsive HVDC links is exchanged in bilateral energy markets (BEMs) if any profiles of the current electricity generations, local demands, and the deep-learning model running model of the local electricity demand's initial forecast model are received. Shared clean energy grids provide a joint integration of renewable energy, clean energy consumption, and large-scale electricity storage systems [45-47]. Various types of optimized electrical grid operations (e.g., microgrid, multilevel electricity market, etc.) are possible by connecting each of them smartly [40-43]. Each operation has its own objectives, constraints, and business models, leading into more specific and instant priori options for optimization frameworks and algorithms. It is essential to find real-time decision-making for rapidly-changing renewable energy generations, diverse peak-hour electricity prices, sudden disconnections, and unexpected demand increments. Thus, smart grid operation requires a dynamic-option configuration of input data for optimization. An aligned optimization problem is full of inequality or breach constraints, and non-smooth or undifferentiated objective functions. These two properties prompts the scholars to propose approximations for a discrete time-step allocation to aid in rapidly decreasing the related computational durations, e.g., gradient, bidding, and regression [45-46].

Linear Programming

MODEL Lignadic, R. Ilinca and F. Chabot, 2005 proposed a mathematical model to intermediated the fuel consumption at remote sites by utilizing renewable energy resources and a newly introduced linear programming model under constraint of the optimization of reliability with respect to the energy demand. The linear equation has the capacity to effectively manage the on-site generated renewable energy and backup diesel genset while taken into account energy load factor, PV and wind resources [9-13]. Lignadic utilizes a linear constraint for the use of renewable energy in sites floating reserve instead of the diesel generators. Closed-circuit television (CCTV) large flow rate utilizes camera across the city for surveillance. Smart Agricultural service is needed for the city sensing, automation and decision-making on various agricultural processes like irrigation, Products pull for purchases and leekage monitoring. PV and BES with the smart grid of linear programming model will be able to reduce the losses, generate appropriate energy as per the specific consumption, reduce the monthly bills, provide the electricity Omnivor to the second house people, reduce the time for project payback, by adjusting the minimum, maximum multipliers used for commercial and residential buildings. PV sizing with 0.3 to 0.18 for the modern sr. sec. school will help the academic institutions to save and invest in primary health centers or for any needy people, they know, with how many number of kids new academic session will start every yearrganization or even can save for a new thing. PV sizing with 1.9 to 0.34 for the district hospital MC will be equivalent to approximate 3000-mile running of the two-wheeler vehicles run with average of 45 miles per hour which equivalent to lot of gases and black smokes into the city burning with the petroleum consuming [17-23].

Nonlinear Optimization

An increasing concern about emission reduction, energy efficiency enhancement, and technology advancement has driven engineers and research scientists to develop more sophisticated mathematical models and more effective, practical, and applicable optimization algorithms for complicated optimization problems including the integration of renewable energy sources (Renewable Energy). In literature, it has been observed that there is an increasing application of approximate, linearized, or relaxation-based models to achieve practical models of the mirror problem. The main reason behind the application of these models is their relatively low computation time. For this reason, the adoption of a scenario-based approach to formulate an optimization problem for the scheduling of generation sources and network of power systems in smart grids has drawn attention of the researchers [5-9]. As a fundamental factor in the development and success of renewable energy integration in the smart grid, many of these challenges can be addressed through continuous advancements in mathematical modeling and optimization [10-13]. Advances can effectively help system planners and operators to tackle the challenges with a high level of complexity and dynamism. Published literatures of optimization-related research in the smart grid field are growing at a tremendous pace. It can be concluded that the smart grid optimization problemC ranging from effective dispatch of generation units to distribution system network reconfigurationC have been studied extensively in the past as a mixed-integer nonlinear optimization model. Some researchers have proposed combinatorial optimization models for network reconfiguration problems combined with distributed generations more recently. Several context-related constraints (series lines, ties lines, substation capacity, the capacity of voltage regulating, and sensitive nodes) are taken into account during the DER optimal location and sizing problem. Optimization plays a crucial role in the development of energy systems [14-18]. In the electricity industry, the economic dispatch (ED) is a fundamental optimization problem of power system operation. The aim of this problem is to minimize generation costs through meeting the demand and satisfying multiple constraints. In traditional power systems, inertia, capacity of spinning reserves, and load characteristics rid system operators from the requirement of considering real-time optimization. However, the complicated energy flow and dynamics of smart grid entities impose numerous challenges on operating the system. An example of the most challenging components of the system from the planning and operation viewpoint is renewable energy sources especially during a high penetration level. The high uncertainty and variability nature of these resources increase the complexity of the optimization problems required to enhance power generation, transmission, and distribution system efficiency and effectiveness [19-24].

Stochastic Optimization

When we perform the optimization over the scenario based models, these models are known as the stochastic programming models and when we solve the optimization over a selected set of scenarios other than sampling or collection of the scenarios, these models are known as the robust optimization models [8-14]. A large number of power system researchers have used the GA or real-coded genetic algorithm (RC-GA) for different optimization problems satisfying the power system constraints. Because of the uncertainty, the chance-constrained based stochastic optimization models need to be solved by inculcating a great number of scenarios, which may increase the computational burden, therefore, the solution of these models are hard, as a large number of scenarios means the large number of constraints and the solution of these optimizations may be trapped into the local minima due to the problem dimensionality. This modeling of uncertainty in operational optimization and planning can be done by employing probability distribution functions. Therefore, if we want to model the uncertainties considered above as a part of the optimization problem than we are required the probability distribution function of renewable energy generation and load [14-24]. The use of probability distribution functions for uncertainties in optimization models is a well-researched area and a variety of probability distribution model techniques have been employed by power system researchers. The solution of these probability function models may require the scenarios or samples from distributions to perform the optimization. Various well-known authors have placed their research work in this field, e.g., [17–20] and references with each show a detailed discussion about the probability distribution models and their use in operational optimization and planning of electric power systems. STOCHASTIC planning plays a significant role in optimizing and operating the smart grid systems. Stochastic optimization can be considered as a planning approach to manage the uncertainties in smart grid systems [16-24]. These uncertainties may come from the uncertainties in electricity load, generation from renewable resources, and electricity price, etc. Prices of energy resources have significantly fluctuated due to an increase in the use of renewable energy resources. Economic models when operating the power systems have to be designed by considering the fluctuations/uncertainties in electricity price, fuel prices, and renewable energy resources. The generation from renewable energy resources has uncertain nature due to the dependency of renewable resources on weather conditions. This dependency leads uncertainties in renewable energy generation, therefore, it is necessary to treat renewable energy generation as uncertain.

Optimization Applications in Smart Grids

Single point optimal power flow (SOPF) is a class of mathematical optimization problems, which finds extensive application in operational planning for electrical power systems. Some authors propose SOPF as an optimization problem for distribution system load flow in articles. Moreover, in addition to integrating renewable energy resources, this paper also accounts for other practical constraints, such as harmonic distortion levels, voltage regulation, other uncertainties, and energy market condition. Equations reference. Optimization problems in the smart grid engineering are often focused on renewable energy integration. The cited review paper classifies the latest optimization applications in smart grid engineering for renewable energy into three main categories [12-27]. Among so-called operational optimization problems, one can refer to microgrid energy management. Typically, such problems aim to optimize energy exchange between resources in a prosumer microgrid or as a part of microgrid to the main grid [28-35]. Distribution system operational optimization is typically defined as state estimation. However, the next category of optimization includes a number of sophisticated problems, predominantly related to planning and support of the decision-making process for renewable energy projects [36-39]. These problems leveraging big data and employing the most advanced IoT tech. Wind power plant (WPP) investment optimization. The modeling is formulated through stochastic optimization, it provides the optimization of an investment decision–making process from the perspective of wind farm growth and revenue investigation subject to stochastic market scenario states. Among so-called topological toolboxes for smart grid expansion planning category, we include applications of community storage models. The community storage is input to grid model and the optimization is divided into two sub-optimizations in the article. Hence, binary variables are introduced to describe the network topology and so the topology is optimized in anticipated charge and discharge periods.

Demand Response Management

With the rapid development and integration of renewable energy sources (RESs) and distributed energy resources (DERs) to the traditional power grids, higher active demand-side participation with smart grid technologies are an effective measure to achieve efficient and economic clean energy utilization. Energy storage is initially installed in distribution networks to relieve the uncertainty effect of the active DERs and the capacity of the conventional generators. However, in practice, hourly or less regulation services from the demand sides is intriguing to release the pressure of the power system [30-37]. The "flexible resource" includes the uncontrollable load consumption (such as lighting, heating, ventilation, cooling, data center, commercial refrigeration, space water heating and other applications). The DR characteristic such as "dynamic" and "flexible" can be catered by the energy storage to a large extent, and leaving the optimization and the scheduling of the controllable devices.

Many DR programs are classified based on the market structure, which mainly includes the day-ahead market (spot) and the real-time market [38-43]. Customers can adjust their consumption level to balance the hourly supply and demand based on the electricity price of the previous day in the day-ahead market and the actual electricity prices in the real-time market. All the above-mentioned programs are based on the pricing mechanism [44-47]. DR programs utilizing the signal mechanism, such as the AutoDR developed by the Lawrence Berkeley National Laboratory (LBNL), could effectively reduce the power peak value [40-45]. Specifically, the signal mechanism has no direct effect on the energy cost (energy consumption), but allows utilizing the flexibility of the demand side with advanced control technologies.

Energy Storage Optimization

The refinery is installed in advance to adjust the value of the burst, the output of the battery is adjusted by whether it is charged or fed back to the grid in the frontend, and the selling price in the market is adjusted by whether it is sold to customers by the storage battery or directly sold to the network/promoted grid. Optimizing the operation of energy storage units (ESUs) has gained significant interest in the last few years [8-13]. ESUs provide several services to the power system, such as mitigating the impact of the uncertainty and variability of renewable based sources (Samanta et al., 2020). The economic cost of operating ESUs is mainly a function of the price of electricity in the wholesale spot markets. The prices of wholesale electricity markets are variable and quite different from each other. Thus, scheduling the operation of the ESUs, considering the dynamic prices of different markets is a complex and dynamic optimization problem [14-18]. Time-of-use (ToU) retail tariff is a price-based control approach, which can be used by the energy management system (EMS) to schedule the operation of the ESUs. ToU pricing causes the grid-connected customer to orchestrate its dispatch based on tariff rates, meaning that charging occurs predominantly or perhaps completely during only low-cost periods, independent of the customer's load and renewable resources [24-30].

Case Studies and Practical Implementations

Mathematical models and tools have an immense impact on analyzing and investigating engineering systems. Smart grid is one of engineering systems which has to be modeled mathematically for efficient/successful implementation into practice. Tools which have high accuracy and fitness with the case systems should be used for smart grid studies. These tools make us enable to analyze and optimize the behaviors, costs, graph connections, and efficiency of the system inside of the limited time while keeping huge amount of engineers observation and analysis [31-35]. For smart grid engineering with renewable energy integration, developing and integrating economic and mathematical optimization methods, and advanced sensors, and machine learning are essential to deal with serious technical and non-technical challenges such as voltage control, primary and secondary frequency control, renewable energy curtailment, power quality issues, operational costs, and overcoming environmental concerns [31-35]. Therefore, this maintained overview may shed some light for enhancing smart grid engineering and renewable energy exploitation. We use a real case smart grid and data to present a case study to compare two open smart grid simulation tools RAPSim and GridLAB-D based on their performances (Jdeed et al., 2018). The characteristics of the grid are given to the mathematical models utilized for each tool. Results of the simulation provide a comparative analysis between the two tools and provide the merits and demerits of the tool to be selected for smart grid studies. Smart grid implementation to a real grid was found to show that loads and renewable energy productions are matching each other and those energy within the community are uploaded and downloaded from a local energy storage system. The beneficial issues as energy sharing, waste optimizing, and saving were handled by the simulation tool which had very high accuracy and fitness with respect to the real case energy grid and end user agreement [36-39].

Future Trends and Challenges

Several details must be considered in the obtained model, like the market operation or the actual laws. Also, new metrics can be useful, focusing on the consumer or neighbour interactions. A variety of problems can be addressed by employing the awards of multi-objective optimization. Mathematical models can be used both to manage the power flow in the network and to optimize the grid operation like the control strategy of smart circuit switches, for which the cloud computing and the latest advancements related to multi-agent systems are employed. As highlighted in the previous sections, different trends and challenges are going to improve why not to assure the correct transition from the traditional grid to the Smart Grid. The present study attempts to summarise the ongoing researches and open challenges - each research is surely correlated to specific characteristics of the target grid, and new and deep studies and thought are of course strongly required [40-41]. The Smart Grid represents an innovative evolution of the traditional power grid [43-47]. The inclusion of electronic devices, renewable energy sources and possible incapacity of the traditional equipment, bring a higher risk of operation. A classification of current research trends and challenges is presented, with special attention to those related to the integration of renewable energies. Decision support for the operation and planning of electric grids represents very attractive research subbranches. Planning refers to long-term decisions, e.g. investment on a new substation or a more careful selection of new elements. Modifications and augmenting the complex Smart Grid are necessary to assure the variability and uncertainty of the power supply-demand balance. To support these decisions, mathematical models are employed for the optimization of the expansion of the original grid [8-9]. Techniques can be split into exact methods, used for small grid problems and approximate methods for those related to large scale networks [11-16].

CONCLUSION

The optimization of renewable energy integration in smart grids is indispensable for achieving resilience, efficiency, and sustainability in modern electrical power systems. By harnessing advanced mathematical modeling techniques such as linear programming, nonlinear optimization, and stochastic optimization, engineers can effectively address the intricate challenges associated with RES variability, demand response management, and energy storage optimization. Through practical implementations and meticulous case studies, the study demonstrates the tangible impact of optimization strategies in real-world SG deployments, paving the path for future innovations and advancements in smart grid engineering. Despite persistent challenges and uncertainties, continued research and development efforts in this domain promise to fortify the resilience and adaptability of SGs, fostering a transition towards a greener and more sustainable energy landscape.

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