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SMART GRID ENERGY PRODUCTION AND TRANSMISSION SYSTEM MODELING AND COMPUTATIONAL ASSESSMENT METHODS

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A B S T R A C T

Based on the continuous growth of the economy, widespread adoption of intermittent renewable energy sources, and extensive use of information and communication technologies, conventional electric power systems are no longer able to meet the enormous demands of the information age. Diverse renewable energy technologies have been quickly developed to address the energy issue and environmental damage. However, since renewable energy sources are unpredictable and erratic, the widespread use of different renewable energy technologies has consequently put significant strain on the security and dependability of conventional power networks. The Smart Grid (SG) is a modernized electrical network that makes use of cutting-edge communication, control, and information technology to facilitate the integration of renewable energy sources, increase energy efficiency, and improve dependability and security. The invention of computational modeling and evaluation methodologies for SG energy transmission and production networks is the main topic of the research. The Internet of Energy (IoE), which will eventually replace the conventional power production and distribution networks, increases the need to be familiar with the proper computing tools in order to conduct any future SG investigation. The software for simulation that is significant to the modeling and analysis of electrical power production, transmission, distribution, and related systems is examined in this research. The study's conclusions are anticipated to aid in the creation of power generation and transmission systems that are more effective, dependable, and sustainable.

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1. INTRODUCTION

Due to falling prices, government incentives, and corporate sustainability objectives, renewable energy resources are quickly becoming a crucial component of power-generating inventories across the globe. Massive renewable energy systems on a transmission network may have possible effects on the quality and dependability of the power that is provided, including voltage and frequency changes, higher system losses, and increased wear on protective equipment (Forcan, and Maksimović 2020). A transmission network's estimated maximum hosting capacity may be used to calculate the greatest use of renewable energy it can support without significantly impairing the grid's dependability and the quality of the electricity it delivers (Akeyo et al., 2020). Technology development calls for an exponential rise in the production of power. Fossil fuel supplies are now in limited supply as a result of closing this gap (Ibrahim et al., 2020). In order to meet future energy demands, provide clean energy, and reduce greenhouse gas emissions, dependency on fossil fuels must be replaced by renewable energy resources (Alper et al., 2020). The SG is an advanced electricity infrastructure that uses modern communication and information technologies to enable more efficient and reliable energy production, transmission, and consumption (Quan et al., 2019). It is a complex system that involves multiple components, including power generators, transmission lines, substations, and distribution networks (Mufana, and Ibrahim 2022). Figure 1 denotes the structure of the smart grid.

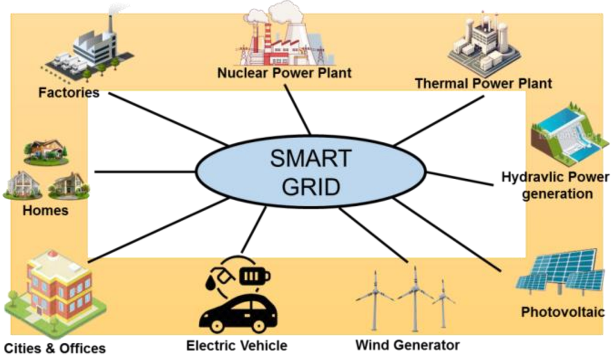

Figure 1. Structure of smart grid

This allows grid operators to respond more quickly to changes in demand and supply and to optimize the use of available resources (Ahmed et al., 2019). Smart grids also enable consumers to participate in the energy market by providing real-time information about energy prices and consumption (Babar et al., 2020). This can help consumers to make more informed decisions about their energy use and to reduce their overall energy costs (Vale et al., 2021). Assessment computational methods are used to evaluate the performance and effectiveness of an SG energy production and transmission system (Pallonetto et al., 2019). Power system modeling is used to create a virtual representation of the SG system, and Economic analysis is used as an assessment financial the effectiveness of the SG system.

The other sections of the article are as follows: section 2 lists similar studies, section 3 presents the suggested methodology, section 4 presents the findings and a discussion, and section 5 provides a summary.

2. RELATED WORKS

According to the Gunduz and Das (2020), a smart grid is necessary to adapt to changing electrical needs, and intelligent technology is being used. A smart grid system attaches to the Cyber-Physical Systems (CPS) concept, in which physical systems and information technology (IT) infrastructure are combined. Ghasempour, (2019) analyzed the risks and possible remedies associated with an IoT-based smart grid. We concentrate on several forms of cyberattacks and provide a thorough analysis of the smart grid's level of cybersecurity. Hasan et al., (2022) provided a thorough analysis of blockchain implementations in relation to smart grid energy data safeguards and perceptions of cyber security. As a consequence, we outline the main security challenges that big data and blockchain can address in smart grid scenarios. Minh et al., (2022) conducted an in-depth analysis of systems of edge computing with IoT-enabled smart grids. Then, modern frameworks for smart grids based on IoT and edge computing are investigated, critical requirements are given, and unsolved issues and barriers are emphasized. Ranjbar and Hosseini (2019) offers a brand new two-level model for the joint planning of merchant DERs and transmission systems. A set rate of return on Distributed Energy Resources (DER) investments is guaranteed at the higher level, which adopts the viewpoint and seeks to minimize line investment costs and costs associated with purchasing electricity from conventional producers and DERs. Successful integration of distributed generation into a previous conventional energy system requires smart monitoring and management of linked systems. This role may be played by smart grid technology based on electric automobiles. In order to attract new investment sources, create a reliable and flexible grid system, and prevent becoming stuck with an outdated energy system, smart grids are essential (Hasan et al., 2023). Modern system safety and protection mechanisms have greatly benefited from the use of ML-based "Intrusion Detection System (IDS)" techniques. Due to the widespread usage of shared networks and the resulting risks in smart grid computing systems, security risks have dramatically risen (Sahani et al., 2023). Ghorbanian et al., (2019) addressed the large data issues in smart power systems is extensively evaluated. The context and driving forces behind the big data paradigm in smart power systems are presented first, followed by an analysis of the significant problems with big data architectures, essential technologies, and standardizations in such systems. Gai et al., 2019) suggested a model called "Permissioned Blockchain Edge Model for Smart Grid Network (PBEM-SGN)" to combine blockchain and computational edge methods to handle the two major challenges in the intelligent grid, protecting privacy and security of power.

Telecommunications systems may be used to conceptually organize the physically limited energy consumers in power networks into Virtual Microgrids (VMGs). A Stackelberg game in which the producer's lead and consumers follow may be used to mimic the energy trading interactions between producers and consumers in a VMG in order to maximize the advantages to consumers (Anoh et al., 2019).

3. METHODOLOGY

Modeling and assessment of the SG are essential for understanding its behavior, optimizing its performance, and designing new technologies and policies to support its development. In this section, we discuss some of the computational methods used for Smart Grid modeling and assessment.

3.1 Smart grid energy production

Smart grid energy production refers to the generation of electricity using various energy sources, such as fossil fuels, nuclear power, and renewable energy sources, including solar, wind, hydro, geothermal, and biomass. The smart grid enables the incorporation of various forms of energy into the electrical grid and optimizes their use to increase conservation, dependability, and energy savings. Distributed Energy Resources (DERs) techniques for storing energy, endeavors to meet demand, and the utilization of cutting-edge technology and command systems are also covered. These technologies enable the smart grid to adjust the supply of electricity in response to changes in demand and grid conditions. For instance, renewable energy sources like solar and wind can be variable in their power output, but with the smart grid, this variability can be managed by using devices for storing extra energy at times of high output times and releasing it during periods of high demand. Moreover, smart grid energy production enables the deployment of electric vehicles (EVs), which can serve as mobile storage devices that can be charged during periods of low demand and discharged during peak periods. The smart grid can also enable bidirectional power flow, allowing EVs to feed electricity back into the grid when the demand is high and the vehicle is not in use. The study aims to create a more sustainable and efficient power system that can meet the growing energy demands of society while minimizing its environmental impact.

3.2 Computational methods

Computational methods for smart grid energy production and transmission system modeling can be broadly classified into mathematical optimization, simulation, and machine learning techniques. Here are some of the commonly used computational methods: Table 1 depicts the computational methods of the smart grid.

Table 1. Computational methods of smart grid.

Computational Method	Equations	Software Tools
Mathematical Optimization	Linear Programming, Mixed-Integer Linear Programming, Quadratic Programming	GAMS, AMPL, MATLAB Optimization Toolbox
Simulation	Power Flow Equations, Dynamic Simulation	PSCAD, PowerWorld, OpenDSS
Machine Learning	Neural Networks, Decision Trees, Random Forests	Python (scikit-learn, Keras, TensorFlow), MATLAB
Hybrid Approaches	Optimization-Simulation, Simulation-Machine Learning	Any combination of the above software tools

Mathematical Optimization

Optimization techniques can be used to design and optimize various aspects of the smart grid, such as the placement and sizing of technologies for energy storage, demand-side management initiatives, and alternative energy supplies. These optimization techniques involve formulating mathematical models that capture the objectives and constraints of the problem and solving those using algorithms such as linear programming, mixed-integer linear programming, and quadratic programming.

Linear Programming Equation

A linear programming equation is a smart grid model used to optimize a linear objective function, subject to a set of linear constraints.

$$Minimize\ f(x) \tag{1}$$

$$Subject\ to{:}\ Ax\ =\ b \tag{2}$$

$$\mathrm{l} <= x <= \mathrm{u} \tag{3}$$

Where f(x) is the objective function, A is the matrix of constraint coefficients, b is the right-hand side vector of constraints, x is the decision variable vector and l and u are the lower and upper bounds on x.

Simulation

Simulation methods involve creating a virtual model of the smart grid and simulating its behavior under various scenarios, such as changes in energy demand or the integration of new renewable energy sources. These simulations can be used to evaluate the performance of the smart grid under different conditions and identify areas for improvement. Simulation techniques can range from simple spreadsheets to complex power system simulation software.

Power Flow Equations

The power flow equation, also known as the load flow equation, is a mathematical expression that describes the flow of electrical power in a power system. It is used to determine the steady-state operating conditions of the system, including the voltages, currents, and power flows at various points in the network.

$$P_i = V_i * (sum(Y_{ij} * V_j * \cos(theta_i - theta_j)) + G_i) \quad (4)$$

$$Q_i = V_i * (sum(Y_{ij} * V_j * \sin(theta_i - theta_j)) - B_i) \quad (5)$$

Where P_i and Q_i are the real and reactive power injections at bus i, V_i and $theta_i$ are the voltage magnitude and phase angle at bus i, Y_{ij} is the admittance between bus i and j, G_i, and B_i are the real and reactive power injections from shunt elements at bus i.

Machine Learning

Machine learning algorithms can be used to analyze large volumes of data generated by the smart grid, such as energy consumption data, weather data, and power flow data. These algorithms can identify patterns and trends in the data and use them to make predictions and optimize the performance of the smart grid. Machine learning techniques can include supervised learning, unsupervised learning, and reinforcement learning.

Neural Network Equation

A neural network is a kind of computer model that gets its inspiration from the way the human brain works, both structurally and functionally. It is made up of a huge number of processing components known as neurons, which are linked to one another and collaborate with one another to carry out a certain function. The equation of a neural network is a mathematical description of the manner in which the neurons in the network interact with each other in order to achieve the result that is intended.

$$y = f(w * x + b) \quad (6)$$

Where y is the output of the neural network, x is the input vector, w, and b are the weight and bias vectors, and f is the activation function.

Hybrid Approaches

Hybrid approaches combine two or more of the above techniques to model and optimize the smart grid. For example, optimization techniques can be used to design the smart grid and simulation techniques can be used to evaluate its performance under various scenarios. Machine learning techniques can then be used to analyze the data generated by the simulation and optimize the performance of the smart grid further.

These equations and methods can be used to model and optimize various aspects of the smart grid, including energy production and transmission systems.

3.3 Generation of electricity

Usually, power is gradually added to large voltage networks from traditional sources. The balance between supply and demand is the main issue to be addressed. Therefore, a consistent supply of energy may be maintained by monitoring the supply at each network node and at all times. For this, the producing units are run simultaneously to only serve the actual demand for power. The supply-follows-demand viewpoint is the one used in this instance.

However, a stochastic approach is presently being used by SG to supply energy from distributed generators (DGs) and RERs to fulfill demand. The stochastic methodology has made it possible to offer low voltage rating grids using the "presumption" method. Grids with a high voltage rating are further supplied with power. In addition, a realistic futuristic strategy would emphasize the request-follows-generation viewpoint instead of the generation-follows-request perspective. Dynamic pricing is required by this change in viewpoint. Real-time information on pricing changes should be available to the end user.

3.4 Transmission and distribution of electricity

Power networks are needed to transport the power from the producing unit to the area of demand. The transmission network is made up of high-voltage networks that move electricity from the manufacturing facility to a substation close to the demand. DNs are used to deliver low-voltage electricity to users. These networks' entire cost is made up of capital, operating, and maintenance expenses. The network operators are increasingly worried about these expenditures. Furthermore, the price is less significant in tariffs with a pricing component. The only input utilized to address this problem is the overall cost.

The network's users are then split up among this cost. Similar to consumers, merchants and power networks are needed to transport the power from the producing unit to the area of demand. The transmission network is made up of high-voltage networks that move electricity from the manufacturing facility to a substation close to the demand. DNs are used to deliver low-voltage electricity to users. These networks' entire cost is made up of capital, operating, and maintenance expenses. The network operators are increasingly worried about these expenditures.

The only input utilized to address this problem is the overall cost. The network's users are then split up among this cost. Similar to consumers, merchants, and purchasers. In typical energy systems, distribution is the last stage before the power is delivered from the transmission system to a specific customer, which has an impact on distribution costs. In SG, distributed generator (DG), enabled with new price allocation mechanisms and assumption, also contribute to cost anticipation.

Furthermore, in SG, a DN's power flow is two-way. Thus, it is claimed that location-based pricing may end up playing a significant role in regulatory policy. Location-based pricing functions in a system that uses an aggregator to start demand-side load control by keeping the cost low and enticing more users to sign up for the service. In typical energy systems, distribution is the last stage before the power is delivered from the transmission system to a specific customer, which has an impact on distribution costs. In SG, distributed generators (DG), enabled with new price allocation mechanisms and assumptions, also contribute to cost anticipation. Furthermore, in SG, a DN's power flow is two-way. Thus, it is claimed that location-based pricing may end up playing a significant role in regulatory policy. Location-based pricing functions in a framework that uses combined to start request-side load control by keeping the cost low and enticing more users to sign up for the service.

3.5 Power System Flexibility

The DSM's capacity to retain flexibility across resources has led to its designation as an emerging approach for energy management. Additionally, by allowing for flexible system management, it lowers the need for power. An SG with a high mix is unable to meet the maximum power needed when compared to a traditional power system powered by fossil fuel generators, which results in high-impact power outages such as financial and significant blackouts. Other services, such as Battery Storage Systems (BSSs), play a part in resolving such problems. In the event of low production across RERs, peak energy consumption time may be decreased using DR. Additionally, it may be an extremely helpful strategy for maintaining the adaptability of the most recent nuclear power plants.

3.6 Power System Reliability

The reliability characteristics of an electricity system depend on its phases of design, preparation, and operation. Power system dependability is made up of power system capabilities and security. The first prioritizes the needs of the consumer by assigning the necessary hardware. The latter, however, categorizes its activity in response to the unexpected disruption inside the power system. Furthermore, the classification of the system in terms of generation, transmission, and distribution is necessary for dependability studies of power systems.

4. RESULT AND DISCUSSION

This section includes a list of the simulation tools that are available for power generating and distribution systems. Each tool includes a brief summary that mentions its availability, probable sources, and usually uses. Although certain instruments have a diverse variety of uses, the usual uses connected to each topic are listed in the appropriate sections. Tools are classified as being restricted in number, open source, and free to use. Open source software is freely usable, while "limited" tools are confined to a certain group or organization or whose availability status is unknown in the references. Table 2 shows the computational tools of energy generation.

Table 2. Smart grid energy production and transmission system modeling and computational tools.

Smart grid energy production and transmission system modeling and Tools:	Description
1) PC-VALORAGUA, APS	Controlling hydroelectric power producing systems for maximum efficiency and doing cost-benefit analyses
2) Samnett, Samlast, EOPS,	Long-term and short-term hydropower generating scheduling as well as expansion planning
3) Hydro-Clone	Modeling and analysis of hydropower system components
4) Hydro Power Library	Modeling and control of hydroelectric power plants
5) MAXHYDRO	Monitoring, modeling, and performance enhancement of hydropower systems in real time
6) OptiPower	The simulation and administration of hydroelectric power generating
7) SHOP, SHARM	Modeling and improving the efficiency of hydropower generating
8) SIMSEN, SIMSEN-Hydro	Modeling and analysis of load flow and hydropower distribution networks.

Load leveling is a technique used in smart grid systems to manage the demand for electricity by shifting the usage of electricity from peak times to off-peak times. This technique helps to balance power generation and consumption, leading to a more stable and efficient power system. The initial networks (high/medium voltage stations) of the traditional distribution network (DN), along with other active DN sources, provide the energy needed to charge the SG during low load times. The exact amount of energy produced by a smart grid system per day depends on the size of the grid and the sources of energy used. The SG may incorporate a range of various renewable energy methods such as hydroelectricity, geothermal energies, solar, and winds, as well as traditional sources such as natural gas, coal, and nuclear power. Similar to this, Figure 2 depicts the power exchange between the modeling of the SG energy production and transmission system.

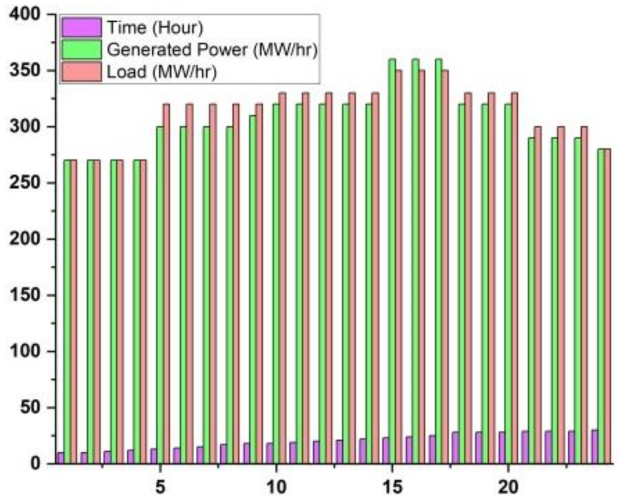

Figure 2. Modernized SG energy production per day

It also examined the optimum placement, size, and constraints of SG networks' energy generation capacity. This study's analysis revealed little power loss and voltage stability, but other participants were less enthusiastic about the associated investment costs. The capacity for energy production in DN is employed in a variety of ideal sites and sizes. However, the capability for producing energy and the SG in DN still need considerable improvements.

In a modernized SG, energy production commitment is typically managed using advanced algorithms and software tools that allow utilities to optimize the use of different energy sources to meet demand while minimizing costs and reducing carbon emissions. These algorithms consider factors such as weather patterns, consumer behavior, and the availability of sun and wind influence, among other energy-producing sources. This section methodically reviews many types of calculations, such as numerical techniques and metaheuristic optimization algorithms. Figure 3 shows the "charging" and "discharging" condition of energy output throughout the course of a single day.

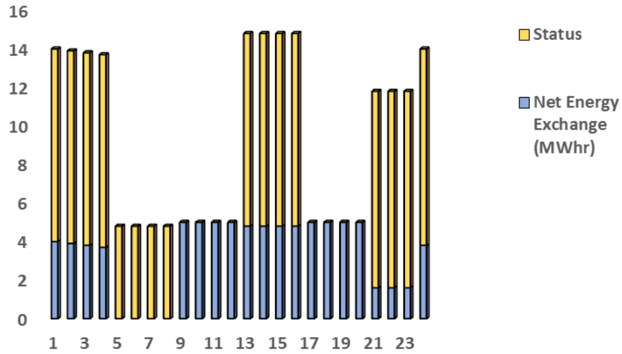

Figure 3. SG's dedication to the interchange of modernized energy production throughout a single day

The energy production commitment towards a modernized smart grid over a single day will depend on a wide range of factors and will be managed using advanced software tools and algorithms to optimize energy production and distribution while minimizing costs and reducing carbon emissions.

4. CONCLUSION

Smart grid technology has revolutionized the way we produce and transmit energy. With advanced sensors, automation, and communication systems, smart grids enable efficient and reliable energy management, and increased use of renewable energy sources.

The integration of distributed energy resources, such as solar panels and wind turbines, has led to more decentralized and sustainable energy production. Moreover, smart grid technology enables better grid stability and resiliency, reducing the likelihood and impact of blackouts and other grid disturbances. This article makes the case that there are a sizable number of computational instruments accessible to power production, transmission, distribution, and associated fields. A comprehensive description of the tools, together with the necessary information, is provided here in order to increase knowledge of them. However, there are still obstacles to be conquered, such as concerns around regulations and public acceptability of the technology. Despite this, the potential advantages of smart grid technology make it an essential instrument for the achievement of sustainable energy in the foreseeable future.

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