INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 09, September 2025, pp : 283-289
www.ijprems.com
editor@ijprems.com
e-ISSN : 2583-1062
Impact Factor : 7.001

EXECUTION OF SMART GRID TECHNOLOGY IN DISTRIBUTION SYSTEM USING: MODEL SYSTEM

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DOI: https://www.doi.org/10.58257/IJPREMS43684

ABSTRACT

The development of smart grids from conventional power distribution systems has been fueled by the growing need for dependable, cost-effective, and sustainable electricity. Using a model system, this study investigates how smart grid technologies can be implemented in distribution systems. Smart grids combine cutting-edge automation, control, and communication technologies to provide dynamic load management, real-time monitoring, and improved fault detection. This work builds a model system that is a standard distribution network enhanced with smart grid features such as distributed energy resources (DERs), automated metering infrastructure (AMI), and demand response (DR) strategies. Reducing energy loss, optimising power flow, and incorporating renewable energy sources are essential components of the implementation.

Simulations are run to assess how well the model system performs in different operational scenarios, showing increases in sustainability, dependability, and efficiency. According to this study, smart grid technology could revolutionize distribution systems by tackling issues like energy losses, managing peak demand, and integrating renewable energy sources. According to the findings, smart grids are essential to building a robust and future-ready power distribution system.

Keywords: Resources for Distributed Energy (DERs). Infrastructure for Advanced Metering (AMI). Transmission Systems, Power Distribution Systems and Voltage Stability.

1. INTRODUCTION

Smart energy companies assist companies in reducing carbon emissions in a way that boosts energy productivity, creates efficiency, makes money, and saves consumers a significant amount of money as the globe works to reduce carbon emissions from peak levels. As the world attempts to reduce carbon emissions from peak levels, smart energy companies help businesses cut carbon emissions in a way that increases energy output, promotes efficiency, earns money, and saves consumers a large amount of money. Within this framework, the idea of a "smart grid" has gained traction as a potential enhancement and modernization tool. The foundation for a modern and more dependable electric power system is provided, which addresses some of the issues.

The foundation of the current global power structure was established at the turn of the century. The conventional grid uses a high-voltage, interconnected network to supply power from big central generators, usually over long distances. The electricity then travels via a few step-down transformers before reaching the customers (Diahovchenko, I. et al., 2020). Smart energy companies assist companies in reducing carbon emissions in a way that boosts energy productivity, creates efficiency, makes money, and saves consumers a significant amount of money as the globe works to reduce carbon emissions from peak levels.

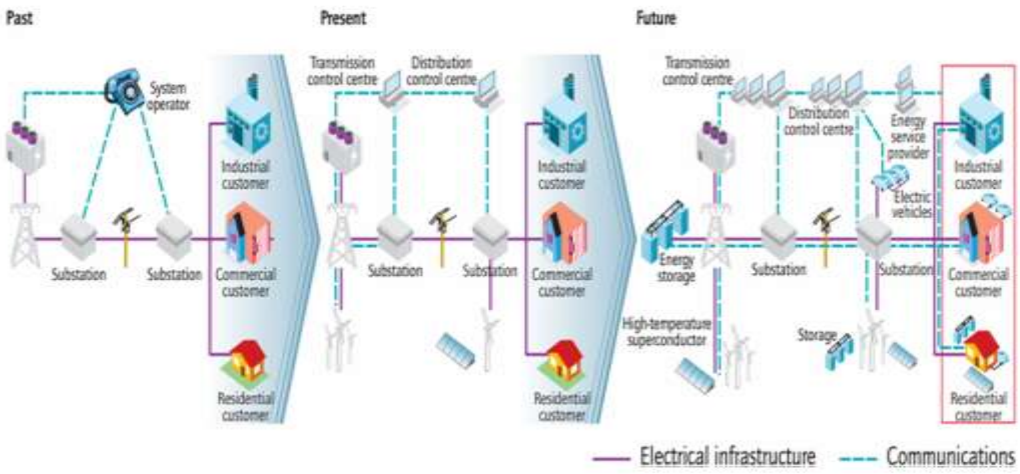

Figure 1: Smart grid evolution (Diahovchenko, I, et al,. 2020)

Furthermore, the business and industrial environment, etc. For instance, Americans are more likely to use demand response and smart metering when it comes to smart grid deployment, while Europeans are increasingly using distributed energy (distributed generation) and renewable energy technology. The Chinese State Grid Corporation aims to construct a powerful and resilient smart grid for the transportation of electricity from energy-rich West China to High Voltage Direct Current (HVDC) and Flexible AC Transmission Systems (FACTS) are also available in East China.

What sets smart grids apart from regular grids is that they use communication networks, which are far more crucial. (Ibrahim, A., and Mufana, M.W.2022).

2. BACKGROUND AND MOTIVATION

Stresses from declining reserve margins, rising electricity prices, operational issues, and the financial hazards of network expansion are putting further strain on advanced power systems. Power utilities have shifted towards electricity markets and restructuring because of these factors. The power system has evolved from a traditional system to a more decentralised network with an increasing proportion of renewable resources because of the management of the electricity market and the implementation of major changes in its structure and operations.

Another goal in the environment of the reorganised electrical industry is to increase the productivity and efficiency of the power system. Power companies are searching for innovative and creative ways to control losses, control expenses, and improve asset performance, and one of their objectives is to create energy-efficient networks. Therefore, it is important to create business models that align with the strategic goals of the electrical sector.

Climate change and the drive to lower greenhouse gas emissions are also major obstacles facing the electrical sector in the current climate. Probably one of the biggest issues facing the electrical sector is figuring out how to resolve this dilemma in sensitive and significant situations without increasing pricing. As a result, energy management initiatives need to be thoroughly rethought.

The smart grid is a crucial remedy for the problems. Grid modernisation projects have made new digital telecommunications systems and computer monitoring and control technology available to all levels of the electrical system, from transmission and distribution networks to end consumers.

Additionally, a platform for providing clients with smart prices has been made possible by the widespread deployment of smart meters. This has enabled variable electricity costs to be covered and alternative price rates to be offered. These infrastructures will make it possible to communicate and engage with customers to lower expenses, control energy use, and lessen peak demand.

Demand Response (DR), one of the most straightforward ways to deploy a smart power system, may provide a lot of demand flexibility, enabling the electrical industry to benefit from its financial and technological advantages.

The manifestation of this flexibility will be the capacity to alter the load within a specified time. Power firms, customers, energy policymakers, and regulators can all benefit from using DR as a prerequisite for decision-making. DR in the smart grid is a useful strategy for handling unexpected conditions, and it can affect various demand behaviours using various pricing or incentive schemes.

Nevertheless, there is a lack of understanding regarding the actual evaluation of DR programs for different utilities and customers. Naturally, the operator in the power sector should be able to accomplish his goals with the aid of DR products and services. Similarly, clients must be able to select appropriate DR plans according to their objectives. Thus, a goal-oriented categorisation of DR projects could provide a new perspective for improving the performance metrics. Concepts for disaster recovery applications may be reviewed because of disaster recovery plans moving to smart grid environments and the modifications required to address the new situation.

This requires adjusting the DR plans' practical elements while taking the smart grid's components into account. Reinterpreting the supporting technologies in various plans and identifying and categorising workable strategies in various customer groups are therefore necessary to provide the proper orientation. (M.E. Honarmand and colleagues, 2021).

3. EVOLUTION OF DISTRIBUTION SYSTEMS

A passive network with a one-way energy flow from power plants to the end user is represented by the three stages of generation, transmission, and distribution in the conventional electrical system model. Nonetheless, this system is undergoing significant changes because of the objectives of climate neutrality and the growing electrification of final energy consumption, which is highlighting its importance in accomplishing the socioeconomic development objectives of contemporary society.

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The traditional electrical system model is being replaced by one in which distribution networks play an active role due to the growing usage of distributed generation technologies. Distribution networks, which up until recently mainly served as passive means of delivering power from transmission grid interconnection points to the final consumer, are particularly affected by this.

To regulate energy flows intelligently and maintain service continuity and quality requirements, this new role necessitates the use of increasingly efficient technology (Sancioni, P, 2025).

Smart grid technology has been developed in response to the global desire for more efficient and sustainable energy systems. Many of the problems with the current power grid systems are brought about by ageing infrastructure, growing energy use, and the growing need for renewable energy. Smart grids can help with these problems.

Smart grids are triggered by the expansion of electrical distribution networks and the use of information and communication technologies to connect them. One essential feature of smart grid technology is its capacity to incorporate renewable energy sources, especially solar and wind power. (Abdulkader, R., et al., 2023).

Although socially favoured, these sources are intrinsically unstable and necessitate complex grid management technology to ensure system stability. Battery energy storage and pumped hydro storage, which store extra energy generated at the period of renewable source generation and feed it during times of high demand, mitigate the intermittency problem. (Aghmadi, A. and Mohammed, O.A., 2024).

Additionally, demand response systems give customers the ability to control their consumption in real time, improving the balance between producers and consumers. These technologies not only improve grid efficiency but also save consumers money and lessen the negative environmental impact because appliance users are encouraged to decrease or modify their energy use during peak hours. The primary focus of this project is the creation of a smart grid that combines energy storage, demand-side control, and renewable energy production. (Ahsan, F., et al., 2023).

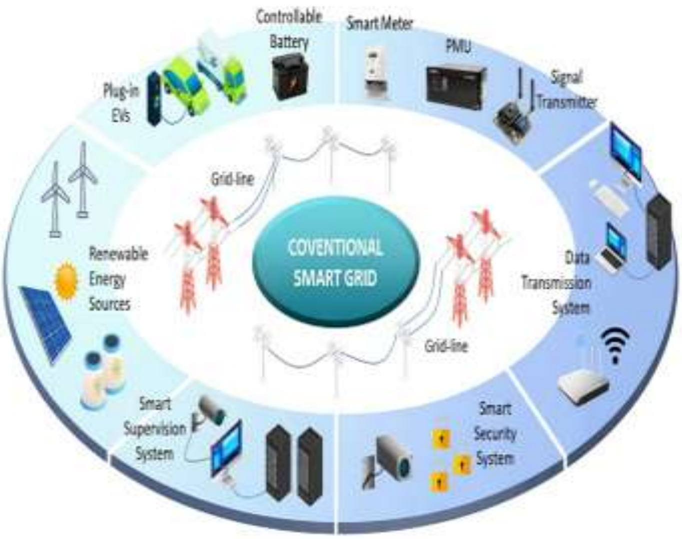

Figure 2: Evolution of smart grid (Meena, S.B, et al., 2024).

4. SMART GRID CONCEPT OVERVIEW

To improve markets, lower costs, increase efficiency, improve reliability and service, and lessen the impact on the environment, information and communications technology is incorporated into all facets of energy generation, delivery, and consumption in a smart grid. The following features are cited by many smart grid proponents as proof of the technology's potential.

Able to absorb energy from almost any fuel source, such as wind and solar, with the same ease and transparency as natural gas and coal.

Capable of incorporating all improved concepts and technologies (such energy storage technologies), which have been validated in the market and are prepared for online launch.

Eencouraging the utility to allow real-time communication with customers so they can customise their energy use according to personal choices, like cost and/or environmental concerns.

Opportunistic, using plug-and-play innovation to create new markets and possibilities when and where it is appropriate.

Quality-focused, capable of delivering the power quality needed, free from sags, spikes, disturbances, and interruptions, to power our increasingly digital economy and the data centres, computers, and electronics required to run it.

Green, slowing the advancement of global climate change and providing a genuine path to the environmental enhancement of electric power for the benefit of humanity.

Decentralised and strengthened smart grid security protocols will make the grid more resilient to attacks and natural disasters. (El-Hawary, M.E., 2014).

Specifically, the SG is an electric system that integrates information, computational intelligence, two-way, cyber-secure communication technologies, electricity generation, transmission, substations, distribution, and consumption to create a clean, safe, secure, reliable, resilient, efficient, and sustainable system. The whole energy system is covered by this explanation, from the source of power creation to the final locations where it is used. SG's anticipated requirements and benefits include the following:

1. Enhancing the quality and dependability of electricity.
2. Making the most of the infrastructure that already exists and refraining from building backup (peak load) power plants.
3. Increasing the current electric power networks' capacity and effectiveness.
4. Fortifying their resilience to disturbances.
5. Facilitating predictive maintenance and self-healing responses to system faults.
6. Advancing the usage of renewable energy sources.
7. Taking into consideration dispersed power sources.
8. Automating operations and maintenance.
9. Using new power sources and electric vehicles to cut greenhouse gas emissions.
10. Cutting down on the demand for inefficient generation during periods of high usage to reduce oil consumption.
11. Delineating prospects for enhancing grid security.
12. Promoting innovative energy storage technologies and the switch to plug-in electric cars.
13. Expanding the selection of options available to consumers.
14. Introducing new products, services, and markets. (Fang, X. et al., 2011)

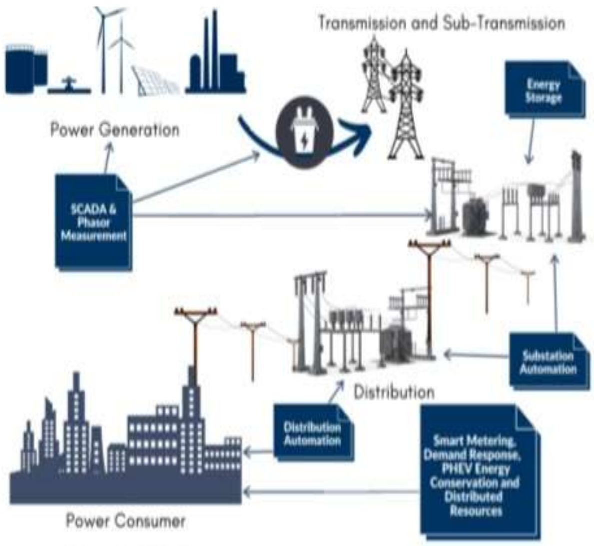

Figure 3: Smart grid concept (. Neffati, O.S. et al., 2021)

A comparison of the smart grid with the current grid

Current Grid	Intelligent Grid
The electromechanical	**Electronic**
One-sided dialogue	**Two-way dialogue**
Centralised production	**Dispersed generation**
Limited sensors	**Sensors all around**
Monitoring by hand	**Self-observation**

Restoration by hand	**Self-repair**
Restricted authority	**Pervasive authority**
Blackouts and failures	**Islanding and adaptability**
Limited options for customers	**Numerous options for customers**

5. OBJECTIVES AND SCOPE OF THE REVIEW

This review's main goal is to thoroughly examine the most current developments, difficulties, and real-world uses of smart grid technologies in transmission and distribution (T&D) systems, with an emphasis on model-based design, simulation, and optimization methodologies. While addressing the technical, financial, and regulatory obstacles that prevent widespread implementation, this review aims to shed light on how these technologies can improve operational efficiency, reliability, voltage stability, and integration of renewable energy sources (M. E.-Hawary, 2020,:H. Farhangi, 2020).

The review's particular goals are as follows:

Objective 1: To analyze how traditional T&D systems have changed to smart grid-enabled networks, with a focus on the contributions of automation, digitalization, and sophisticated communication infrastructures (R. A. Gupta and N. K. Singh, 2020).

Objective 2: Several model systems (such IEEE 33-bus and IEEE 69-bus) and simulation tools (OpenDSS,

MATLAB/Simulink, and GridLAB-D) used in smart grid research for operational planning and optimisation are evaluated. (S. K. Reddy et al., 2021:, M. H. Javed, et al., 2021).

Objective 3. Consider important enabling technologies including Distributed Energy Resources (DERs), Advanced Metering Infrastructure (AMI), Energy Storage Systems (ESS), and AI-based optimisation methods for voltage regulation, fault detection, and demand-side management.

(N. Shariat Zadeh et al., 2021,: Z. Wang et al., 2022).

Objective 4: To evaluate recent pilot projects and real-world implementation case studies, determining their economic viability, scalability, and technical performance (S. A. Mousavi et al., 2022, J. P. Lopes et al., 2023).

Objective 5: To draw attention to gaps in literature and in practice while making suggestions for future lines of inquiry and legislative frameworks that can hasten adoption (A. H. Etemadi et al., 2023).

The technical and operational facets of smart grid adoption in T&D systems are covered in this review. Model-based design, demand response mechanisms, cyber-physical security issues, hardware-software integration, and regulatory ramifications are all covered. This review aims to be a useful resource for researchers, utility operators, regulators, and technology developers by bridging the gap between academic research and industrial practice.

6. FUTURE SCOPE

1. HIGH-FIDELITY "MODEL APPROACH" VIA CO-SIMULATION AND DIGITAL TWINS

Future distribution studies should use co-simulation frameworks like HELICS to connect feeder simulators with market, transmission, EV-transportation, and communication simulators. Before field deployment, this method allows for stress-testing of control mechanisms and a thorough assessment of DER services. Additionally, digital twins (DTs) provide lifecycle optimisation, what-if analysis, and closed-loop testing (A. Al-Badri et al., 2025).

2. AI/ML-DRIVEN OPERATION AND AUTONOMY

Adaptive feeders will be based on probabilistic forecasting and reinforcement learning to optimise DER hosting while preserving stability. Accelerated controller design and enhanced real-world transferability are two benefits of integrating machine learning (ML) into co-simulation and DT frameworks (Z. Wang et al., 2025).

3. DER ORCHESTRATION AT THE GRID EDGE

Fast frequency response, islanding assistance, and voltage regulation are examples of auxiliary services that can be offered by a combination of DERs and EVs. Reliability and resilience benefits under different feeding situations must be assessed by model-based research (A. Boussaada et al., 2024).

4. CYBER-PHYSICAL SECURITY-BY-DESIGN

Co-simulation of communication networks and hostile scenarios aids in testing fail-safe recovery techniques and intrusion detection. DTs offer safe testing grounds for cybersecurity (HELICS Team, 2023).

5. STANDARDS COMPLIANCE AND INTEROPERABILITY TESTING

Systematic testing of aggregator functions and compatibility against changing grid codes and standards must be made possible by future models (NREL, HELICS, 2024).

6. PLANNING UNDER UNCERTAINTY AND EXTREME EVENTS

According to T. T. Nguyen et al. (2025), scenario-based co-simulation will direct investments in microgrid solutions, resilience enhancements, and non-wire alternatives in the face of climate variability and unpredictable EV growth.

7. CONCLUSION

The implementation of model-based techniques in distribution systems demonstrates significant promise for smart-grid execution. Co-simulation platforms, like HELICS and DT frameworks, lower the risks associated with field deployment while enabling comprehensive testing of controls, communication, and market functions. Recent research shows how probabilistic forecasting and AI/ML may improve operational decisions and feeder operations, respectively.

Assessing flexibility, durability, and dependability as DER usage increases will continue to depend heavily on model-driven research. However, challenges remain in interoperability, cybersecurity, and large-scale validation. Future work priorities ought to consist of: platforms for T&D distribution models that are integrated,

DT-in-the-loop AI controller validation, cyber-physical stress testing, and test suites that adhere to standards.

Utilities may go from pilots to scalable and repeatable smart-grid implementation with these components (NREL, HELICS, 2024).

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