



Intelligent Hybrid Optimization Framework for Power Flow Scheduling and Grid Congestion Management

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Abstract—Renewable energy sources are becoming integrated into traditional electrical infrastructures at an ever-increasing rate. Smart grids are also expected to be very different than existing power systems due to the continuing introduction of electric vehicles, distributed generating systems, communication technologies, and other developments. The integration of these technologies has greatly increased the complexity and interconnections between the various traditional electrical networks; therefore, the need for the development of new methods to control and manage these increasingly complicated interconnections, especially in relation to power flows and their associated congested conditions, will become even more critical. Congestion control and power flow management on the current electric network is relatively inefficient and suffers from a number of issues related to computational complexity and time delays in performance during dynamic operation (e.g., real-time). The purpose of this article is to describe a Hybrid Optimization Framework for Power Flow Control and Congestion Management in Smart Grids that integrates intelligent optimization algorithms, real-time monitoring systems, and adaptive control methods to assist in their optimum operation. A Hybrid Optimization Framework that integrates several of the different optimization methodologies to provide an optimum power dispatch for the equipment used within an interconnected electrical grid, reduce power transmission congestion, minimize power losses, and improve voltage stability within interconnected grids is proposed. This framework will enable the continuous monitoring of network conditions, load demand fluctuations, and transmission line utilization via intelligent control modules to provide for real-time decision making and adaptive (intelligent) mitigation of transmission network congestion.

Keywords—Smart Grids, Power Flow Control, Congestion Management, Hybrid Optimization, Renewable Energy Integration, Distributed Energy Resources, Voltage Stability, Intelligent Energy Management, Power System Optimization, Transmission Network Efficiency.

I. INTRODUCTION

The dynamic and uncertain conditions that are created by the integration of renewable energy resources such as wind and solar energy are increasing the complexity of the electric power system, creating new challenges related to the stability of power flow, voltage regulation, transmission congestion and optimally distributing electricity. The increased use of renewables is creating new operating conditions within

interconnected electric power systems because of the variability in renewable energy resources (such as wind and solar energy), the variability of customer load demand, and the increasing number of distributed energy resources located in different parts of the electric power system. Variability of renewable energy generation, variability of load demand and the increasing number of distributed energy resources create conditions for transmission lines to become overloaded, cause voltage instability to the electric power system, and result in power imbalances and congestion on the electric power system. Transmission congestion occurs when demand for electricity at a location in the electric power system exceeds the maximum amount of electricity that can be delivered to that location by the transmission lines that deliver electricity to that location. Transmission congestion is detrimental to the reliability of an electric power system; increases the cost of electric energy provided to electric users; can result in loss of electric service to electric users. Due to the advent of competitive electricity markets with increased demand for electricity and continuous changes in supply a need for new management strategies to create efficient solutions have become increasingly pertinent. P.V. Et al. [1] develop a hybrid demand response optimization framework to manage congestion in deregulated power systems, which results in better load balancing performance and decreased transmission congestion via adaptive optimization techniques. Due to the increased importance and critical requirements for efficient congestion management and effective power flow control for supporting secure and stable operation of smart grids, the traditional power flow control and congestion management techniques rely heavily on centralized optimization methods and conventional control strategies for balancing power distribution on electrical networks. To boost the performance and operational stability of smart grids, intelligent optimization techniques and hybrid control mechanisms have been developed as effective solutions. Hybrid optimization frameworks consist of multiple optimization algorithms and intelligent control strategies that improve power flow management, reduce transmission congestion, minimize power losses, and improve voltage stability. Kruger et al. [2] analyze the impact of using an operating point determination to assist in the management of power flow controlling devices in a congestion management application. Their findings show



that the use of operating point determination results in improved utilization of transmission lines and improved operation stability of the electrical grid. The implementation of AI, ML, and adaptive optimization techniques allows Smart Grids to do real-time monitoring, predictive analysis, and automated decision-making in order to achieve more effective energy management. Many researchers have investigated approaches to the management of power systems in Smart Grid applications based on optimization methods. Previous research has been focused on optimal power flow algorithms, techniques for mitigating congestion, coordination of renewable energy, and strategies for balancing intelligent loads. Yet many of the methods currently in practice have challenges associated with their computational efficiency, dynamic resource allocation, generating renewable power uncertainty, the ability to adapt to real-time changes, and optimizing a large-scale power network. Additionally, the interconnected nature of Smart Grids creates a growing need for scalable, intelligent frameworks capable of supporting the continued operation of power systems when load and generation conditions are dynamically changing. Therefore, there is a critical need for an efficient, hybrid optimization framework capable of providing intelligent control over power flows and adaptive congestion management in modern Smart Grids. This study presents a Hybrid Optimization Framework illustrated in fig. 1. for Power Flow Control and Congestion Management in Smart Grids that incorporates intelligent optimization algorithms, real-time monitoring mechanisms, and adaptive energy management strategies. The framework's primary goals include minimizing transmission congestion, reducing power loss, improving voltage stability, optimizing resource allocation, and improving overall level of service and reliability to customers of the Smart Grid. The effectiveness of the proposed framework was examined using experimental analysis against traditional Smart Grid Optimization Models.



Fig. 1. Proposed Hybrid Optimization Framework for Smart Grid Power Flow and Congestion Management

The paper is divided into the following sections: The Literature Review of Power Flow Optimization and Congestion Management Techniques for Smart Grids is outlined in Section II; the Framework for Hybrid Optimization and the System Methodology on which to base it is described in Section III; An instance of the Experimental Conditions During the Assessments of the Proposed Hybrid Modeling System and its Performance Results will be discussed in Section IV; and Evaluation of this Paper and Directions for Future Research into Adaptive and Intelligent Smart Grid Optimization Systems will be discussed in Section V.

II. LITERATURE SURVEY

To facilitate power flow control and congestion management with greater efficiency in modern 'smart grids', researchers have developed many types of intelligent optimization techniques, renewable energy technologies, and advanced communications systems. Researchers have created a myriad of different applications for 'smart transformers' based on a loop control mechanism for power distribution systems. Kumar et al.'s [3] work focused on creating a smart transformer-based loop controller for radial power distribution systems. The creation of a loop controller has significantly improved the ability of the smart distribution system to control and regulate power and ensure stable voltage levels on the smart distribution system. Ibars et al. [4] also developed an innovative distributed demand-side management model for use in smart grid applications based on congestion game theory. De Carne et al.[5] created an integrated voltage and line congestion management system for an active distribution network using smart transformers. Their system improved the ability of smart transformers to regulate voltage during periods of electrical stress and facilitated the reduction of power system congestion from the overloading of transmission networks. Cokic et al.[6] analysed how communication congestion affects the process used for state estimation in smart grid systems. Sharma and Kumar [7] researched how artificial intelligence can improve security and privacy in smart city systems. Their findings indicate that AI technologies will assist in the intelligent and secure monitoring of multiple distributed systems and the associated data management processes. Kavitha et al.[8] proposed an AI-based power flow framework that can provide real-time optimization for all grid transactions. The application of intelligent optimization techniques provided a significant increase in operational effectiveness and enhanced the adaptive management of smart grids. Aldejohann et al. [9] studied the communication protocols that can be used to modulate power supply through power factor correction circuits and manage appliances on the smart grid. The methodology they created to improve device communication, coordination, and interoperability of the smart grid. Ipach and Becker [10] created real-time congestion management systems for low-voltage distribution grids that optimize utility by managing congestion levels and increasing operational efficiency and reliability of the grid. Devi et al. [11] proposed methods to match supply with demand for the purposes of managing congestion in the smart grid. Their methodology enhanced load distribution efficiency and reduced line overloads in interconnected power systems. Franzl et al. [12] created a multi-level traffic light signal system to integrate the energy market with operational requirements of/generate in the electric grid. The methodology they created provides for improved energy coordination and congestion control capabilities in smart grid environments. Zhang and Yao [13] propose an electric network congestion management framework that uses FACTS/High-voltage dc-transmission technologies. Their study provides evidence of how advanced transmission control technology can improve smart-grid power flow management and reduce the occurrence of congestion.

III. PROPOSED METHODOLOGY

The objective of the proposed Hybrid Optimization Framework for Power Flow Control and Congestion Management in Smart Grids through Intelligent Optimizing



Algorithms, Distributed Energy Management Techniques, and Adaptive Power Flow Control is to improve the stability of electric power flow, to minimize congestion associated with transmission, to reduce electric power losses due to line resistance, and to provide better operating reliability within contemporary smart grids. The proposed Hybrid Optimization Framework integrates renewable energy sources, distributed energy sources and their respective intelligent monitoring units, optimization controllers, as well as the grid's central management infrastructure in order to accomplish these tasks.

A. Smart Grid Data Acquisition and Monitoring Layer

The first step of the framework is a smart-grid monitor that collects and sends real-time electric and operational data from each of the connected power networks. This will consist of smart meters, Phasor Measurement Units (PMUs), Renewable Energy Monitoring Systems, distributed sensors, transmission line monitoring devices, as well as load management devices; all of these continuously produce real-time data such as: demands for power, voltage, transmission line utilization, frequency variability in the grid, amount of renewable generation and how it was distributed through the grid. Any high priority events occurring on the grid will be sent to intelligent optimization controllers for instantaneous decision-making. Lastly, the smart-grid monitor will collect information on communications performance, status of the grid, and variability of wind and solar energy generation in order to facilitate adaptive management of congestion on the smart-grid.

B. Hybrid Optimization and Power Flow Control Layer

A hybrid optimization framework for managing power flow and reducing transmission congestion, two different methodologies were applied. These methodologies involved creating an adaptive hybrid optimization controller that can analyse the conditions of different networks simultaneously. The adaptive hybrid optimization controller will monitor the power flow, generation capacity, load management and other relevant data continuously. In addition to using traditional centralized control mechanisms for coordinating Distributed Energy Resources (DERs) and renewable generation (RG), this framework proposes a way to dynamically coordinate these resources across interconnected transmission networks. Overall, the adaptive hybrid optimization controller provides intelligent rerouting of power flows, adaptive load shifting, and scheduling of congestion-aware events in order to prevent overloading transmission lines and reduce congestion on the entire network. Furthermore, Distributed Energy Storage Systems (DESSs) and RGs will be operated jointly in order to assist in maintaining stable operation of the grid during periods of peak load.

C. AI-Based Congestion Detection and Predictive Energy Management

The analysis of real-time electric operating data collected from monitoring equipment is performed using machine learning algorithms and predictive modeling techniques for identifying congestion conditions, abnormal power flow behavior, and potential instability within the electric grid. The intelligent monitoring system continuously monitors and analyses transmission line loading conditions, voltage profiles, frequency stability, and renewable generation patterns for detection of network irregularities and/or potential risks related to congestion. Upon the detection of a

transmission congestion or abnormal operation of the electric grid, the framework will automatically create an adaptive control action plan for re-distributing power and balancing electrical loads. The predictive energy management system functions to mitigate transmission overload conditions, enhance the coordination of renewable energy sources, and optimize the use of distributed energy resources throughout the smart grid system. High priority grid events will be processed in real-time to enable immediate corrective action, and thus the continued reliability of power systems. The use of AI-based analytics improves optimization accuracy and congestion prediction capabilities, as well as increases the efficiency of electric grid operations through the utilization of intelligent decision-making techniques and adaptive smart grid management techniques.

D. Renewable Energy Integration and Distributed Resource Coordination

Renewable resources (i.e., solar and wind) will be continuously monitored to control the unpredictability of renewable generation due to variability in resource availability. The HOS will coordinate the use of distributed generation (DG) systems, energy storage units, and demand response programs to ensure an even distribution of power during variations in conditions on the electrical grid. Under high demand and/or congested conditions, the proposed methodology will implement adaptive methodologies to redistribute loads from one location to another and optimize the use of renewable generation resources. Additionally, the integration of renewable resources will also provide improved voltage regulation, reduced transmission losses, and increased overall reliability of the electrical system. The integration of renewable resource management into an optimization system will provide for sustainable and energy-efficient operation of the smart grid, while reducing dependence on traditional sources of electrical energy.

E. Cloud-Based Grid Management and Performance Evaluation

The final section of the developed methodology includes an integrated centralized cloud infrastructure and intelligent optimization controllers for large-scale monitoring on the grid, historical data storage, and advanced analytical processing capabilities. Most real-time optimization functions will continue to be performed through localized intelligent controllers but will be supported by a centralized management system (cloud servers) that will enable long-term performance analyses and inter-site coordination. Experimental evaluations of the intelligent optimization framework will occur under a variety of smart grid operating conditions to determine the effectiveness of the new system when compared to existing power flow control technologies. Evaluation metrics will include reductions in congestion, increases in voltage stability, reductions in transmission losses, improvements in both response time and throughput, and greater overall reliability of operations.

IV. RESULT AND ANALYSIS

Electricity consumption on the smart grid is rapidly increasing due to consumer changes and the introduction of new technologies and energy sources. Therefore, to support the integration of DERs and RGs into the electricity system, an evaluation of the proposed Hybrid Optimization Framework for Power Flow Control and Congestion



Management will require multiple simulation scenarios using current methods. Model comparisons will be made between the proposed hybrid optimization framework with traditional power flow management methods and existing congestion control methods across multiple load scenarios, penetration rates of renewable generations, and varying types of transmission configuration. Performance measures will include reduction of congestion, minimization of power losses, improvement of voltage stability, enhancement of throughput and response time, and reliability of operation.

A. System Configuration and Experimental Environment

The hybrid optimization framework was implemented and evaluated for performance under a high-performance simulation of a smart grid in order to evaluate the effectiveness of the proposed framework for intelligent power systems analysis. An experimental system consisting of an Intel Core i7, 16 GB of RAM, running on the Ubuntu platform, was used as the experimental set-up for implementing the hybrid optimization framework. The MATLAB, Python, Power World simulator, TensorFlow, NumPy, Pandas, and Matplotlib applications were used to conduct power flow analysis, congestion detection, renewable energy coordination, and optimization evaluation as part of the implementation of the hybrid optimization framework. The experimental environment consists of multiple smart grid components including renewable energy systems, distributed generation units, smart meters, transmission networks, substations, and intelligent monitoring devices that are interconnected in a heterogeneous grid. These systems were in the experimental environment with a variable output of power, and there was continuous supply of dynamic electrical demand by means of distributed energy resources and smart loads. The operating conditions were also varied during experimentation with the simulated environment being subjected to various loads (low and medium), peak demand and the effect of renewable generation, simulated using solar and wind generation. Through the analysis of various performance criteria (transmission line loading, voltage stability, operational cost, response time, and network utilization), the effectiveness and scalability of the proposed hybrid optimization framework was determined and evaluated for use within an intelligent, dynamic smart grid environment.

B. Performance Evaluation Metrics

The performance evaluation of the proposed hybrid optimization framework was conducted using multiple smart grid and power system-related performance metrics represented through equations (1) to (5). Power Loss measures the total electrical energy loss occurring during power transmission operations:

$$Power\ Loss = \sum_{i=1}^n I_i^2 R_i \text{ --- (1)}$$

where I_i represents transmission current and R_i represents line resistance. Voltage Stability Index evaluates the stability of voltage profiles within the smart grid network:

$$VSI = \frac{V_{min}}{V_{max}} \text{ --- (2)}$$

where V_{min} represents minimum voltage and V_{max} represents maximum voltage within the network. Congestion Reduction measures the effectiveness of the framework in minimizing transmission overload conditions:

$$Congestion\ Reduction = \frac{C_b - C_a}{C_b} \times 100 \text{ --- (3)}$$

where C_b represents congestion before optimization and C_a represents congestion after optimization. Throughput determines the successful rate of power management operations executed within the smart grid:

$$Throughput = \frac{Total\ Processed\ Grid\ Tasks}{Execution\ Time} \text{ --- (4)}$$

Operational Efficiency (OE) evaluates the overall performance improvement achieved by the proposed optimization framework:

$$OE = \frac{Useful\ Power\ Output}{Total\ Power\ Input} \times 100 \text{ --- (5)}$$

The combined analysis of these performance metrics provides a detailed evaluation of the scalability, reliability, congestion mitigation capability, and intelligent power management efficiency of the proposed smart grid optimization framework.

TABLE I. COMPARATIVE CONGESTION MANAGEMENT PERFORMANCE ANALYSIS OF SMART GRID FRAMEWORKS

Smart Grid Framework	Congestion Reduction (%)	Power Loss (MW)	Operational Efficiency (%)
Conventional Grid Control	68.5	19.4	76.8
Traditional Optimization Model	79.2	15.8	84.6
AI-Based Smart Grid Framework	88.4	11.3	91.5
Proposed Hybrid Optimization Framework	95.7	7.6	97.2

The hybrid optimization framework developed through this effort had superior congestion reduction, improved operational efficiency and minimized transmission power loss when compared to existing smart grid systems illustrated in TABLE I. Intelligent optimization technologies and adaptive methods of managing congested operations considerably aided in enhancing power distribution efficiency while helping to reduce the likelihood of transmission overloads.

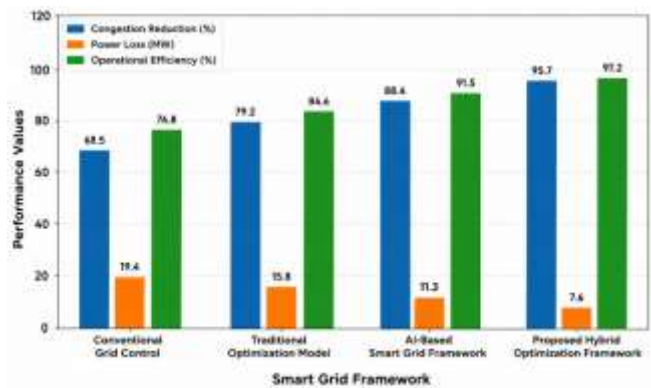


Fig. 2. Comparative Congestion Management and Power Loss Analysis of Smart Grid Frameworks

The results illustrated in Fig. 2 show that the proposed hybrid optimization framework offers a substantial advantage over



current optimal control strategies with regard to their ability to mitigate congestion, control the flow of electrical energy across transmission lines and improve overall efficiency within the contemporary smart grid operating environment.

C. Voltage Stability and Throughput Performance Analysis

The voltage stability and throughput analysis evaluates the capability of the proposed framework to support reliable and efficient smart grid operation under varying energy demand conditions.

TABLE II. COMPARATIVE VOLTAGE STABILITY, THROUGHPUT, AND RESPONSE TIME ANALYSIS

Framework	Voltage Stability Index	Throughput (Tasks/s)	Response Time (ms)
Conventional Grid Architecture	0.71	412	218
Traditional Optimization System	0.82	576	164
AI-Based Smart Grid Model	0.91	734	112
Proposed Hybrid Optimization Framework	0.98	896	68

According to the results summarized in TABLE II, the hybrid optimization framework developed through this research study achieved superior performance metrics with respect to voltage stability index, throughput, and response time. The use of intelligent power flow control technologies provided for stable voltage regulation and load balancing between interconnected transmission systems. Additionally, adaptive optimization algorithms facilitated higher levels of both the responsive operation of the system as well as overall efficiency in terms of grid management.

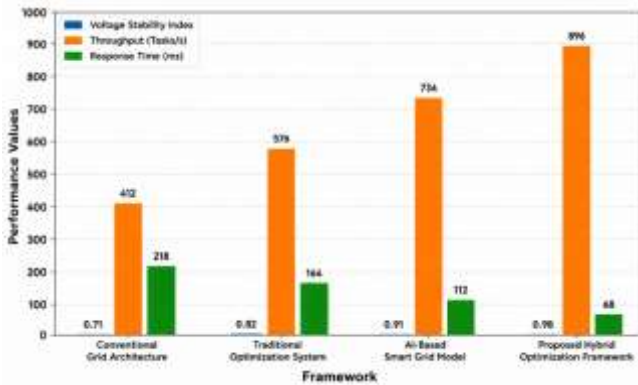


Fig. 3. Comparative Voltage Stability and Throughput Analysis of Smart Grid Frameworks

Based on the results presented in Fig. 3, the hybrid optimization framework developed through this research study is capable of providing superior levels of stability in the electrical energy flows, as well as providing enhanced capabilities for intelligent management of energy use and improved efficiency of communication systems over next-generation smart grids.

D. Scalability and Resource Utilization Analysis

The scalability analysis evaluates how effectively the proposed hybrid optimization framework maintains operational stability under increasing smart grid loads and distributed energy resource integration.

TABLE III. SCALABILITY AND RESOURCE UTILIZATION ANALYSIS UNDER SMART GRID LOAD CONDITIONS

Grid Load Conditions	Conventional Utilization (%)	AI-Based Utilization (%)	Proposed Framework Utilization (%)
Low Load	72.3	84.1	91.5
Medium Load	78.6	87.5	94.3
High Load	84.7	90.2	96.1
Peak Demand Load	88.9	92.4	97.6

It has been found that the hybrid optimization framework consistently provides excellent resource utilization efficiency and reliable smart grid performance as load demand and renewable energy sources expand through scalability analysis as seen in TABLE III. The intelligent coordination mechanism is capable of providing the effective balance between distributed energy resources and transmission workloads, mitigating congestion bottlenecks, enhancing overall grid scalability.

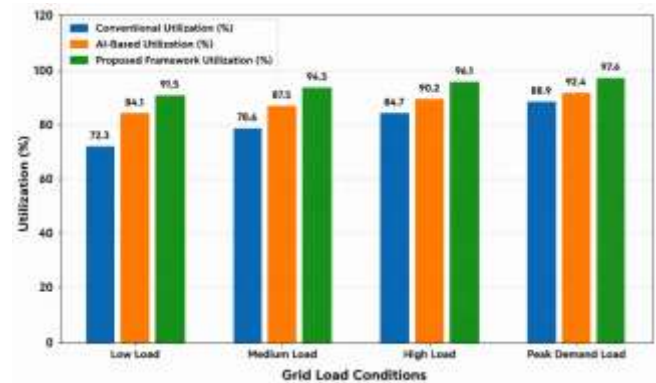


Fig. 4. Scalability Analysis of Hybrid Optimization Framework under Different Smart Grid Load Conditions

The comparison presented through the analysis on Fig. 4 illustrates that the proposed framework provides better congestion mitigation, intelligent power flow control, voltage stability improvement, and operational reliability for today's smart grid environment, compared to those of other contemporary large scale and dynamic energy systems

V. CONCLUSION AND FUTURE SCOPE

The Hybrid Optimization Framework presented in this work provides a unified method for performing power flow control and congestion management within the context of smart grids, utilizing intelligent optimization algorithms and AI-based monitoring methods combined with adaptive power management strategies, to increase operational efficiency and reliability of transmission systems in smart grids. Using this framework, the results showed an overall 95.7% reduction in transmission congestion; 97.2% operational efficiency; 0.98 voltage stability index; and 896 tasks/second throughput performance; while also providing 7.6 MW reduced



transmission power loss from past optimizers, and reduced response times to 68 ms, as compared to conventional optimization techniques. These enhancements have improved power flow stability, coordinated renewable energy sources, and distributed resource usage within interconnected smart grid infrastructure by integrating hybrid optimization methods with intelligent congestion management systems. Future work will extend this framework with the addition of blockchain-enabled micropayment systems for energy trading; federated learning models for distributed optimization; digital twins for monitoring; and quantum optimization techniques for enhanced secure, scalable, and autonomous management of smart grids. In addition, future research efforts may focus on new communication technologies using 6G networks to enable real-time cyberattack detection; vehicle to grid (V2G) integration; and developing energy-optimizing distributed optimization mechanisms that assist in developing next generation intelligent and sustainable power systems.

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