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A Study of Optimization of Smart Grid Power Flow.

Sachin Suke [1] * , Dr. Mrs. A. A. Miraje [2]

1. Research Scholar, Shridhar University, Pillani, Rajasthan, India
sachin.suke_281984@rediffmail.com ,
2. Professor, Shridhar University,Pillani, Rajasthan, India

Abstract: Optimal Power Flow (OPF) is a fundamental concept in the management and operation of modern electrical power systems, particularly within the context of smart grids. As the demand for electricity continues to grow and the energy landscape evolves towards greater sustainability, the need for efficient, reliable, and adaptive power systems has become more critical than ever. The primary objective of OPF is to determine the most efficient way to operate the power system while satisfying various technical and operational constraints. This involves the optimization of several variables, including generator outputs, voltage levels, and power flows, to minimize costs, reduce losses, and enhance system reliability. Smart grids can enhance their resilience to disturbances, support the efficient use of renewable energy, and provide reliable electricity to consumers.

Keywords: Optimal Power Flow, power systems, Smart grids, technology, Renewable energy

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INTRODUCTION

In the pursuit of achieving sustainable and efficient energy distribution, the integration of advanced technologies within power systems has become imperative. Among these technologies, Smart Grid systems stand out as a promising solution for enhancing the reliability, resilience, and flexibility of power networks. At the heart of Smart Grids lies the optimization of power flow, a critical process that ensures efficient energy transmission while maintaining system stability. With Smart Grids in particular, the Optimal Power Flow (OPF) issue poses a serious concern for power systems engineers. Finding the sweet spot between meeting demand, operating limits, and cost minimization is the goal of optimal usage of generation, transmission, & distribution facilities. Sophisticated optimization algorithms designed to tackle the unique challenges of modern power grids are essential due to the complexity of these systems, which are marked by numerous energy sources, bidirectional power flow, and varied demand patterns.

The demand from customers is skyrocketing due to the proliferation of electrical & electronic goods used in daily life and the automation of industries brought about by the Industry 4.0 revolution. The load fluctuations are unpredictable due to the fact that its consumption varies with time, making it very dynamic. Because of this, optimizing electricity generation in a way that benefits utilities & customers alike becomes increasingly important and complicates the process. In an ideal world, the cost of producing electricity would be as low as possible. The current electricity system needs to be converted to a smart grid in order to meet the difficulties posed by things like rising demand, an aging utility infrastructure, the workforce, & environmental impact of greenhouses. As a result, the current grid must be supplemented with renewable energy sources. As a digital communication system that can go both ways, Smart Grid (SG) technology is well-known. When it comes to smart grid energy management in real time, Distribution Generation (DG) is crucial. Different types of modular power generators can be situated at or close to the site of power consumption, a practice known as distributed generation. So, distributed generation refers to the process of generating electricity at the distribution side through the use of renewable energy sources such as solar photovoltaic panels, small wind turbines, battery storage systems, diesel engines, combined heat and power, biomass combustion, or fuel cells fired by natural gas.

SMART GRID

A "smart transmission grid" is one that uses digital technologies & communication to monitor and operate electricity transmission networks from afar. A smart grid is an advanced, digitally controlled power system that allows for more efficient, flexible, & reliable distribution of electric power to users than the current, conventional power system. By managing electric vehicle charging more efficiently, making better use of renewable energy sources, and reducing peak demand, among other things, Smart Grid helps. An integral part of any smart grid is the control and monitoring center. In order to make the system fully observable, it records a number of electrical metrics at each bus, including voltage, current, and power flow (Samantaray et al. 2017).

The traditional power station grid system, which is integrated with the generation system, can operate in a unidirectional fashion. Renewable energy sources are used by transmission & distribution systems to produce consistent power. Traditionally, the electricity grid has included three main components: generation, transmission, and distribution. One feature of smart grids is the ability to control the flow of power in both directions. The measurement device plays a crucial role in smart grid by calculating the flow of voltage & current. A smart grid system allows for cooperative, intelligent, integrated, & adaptable electricity generation. Because they use resources that can be controlled across the network, the grid is able to adapt. In a passive network, the capacity to manage any kind of load is built into the network itself. To improve power transmission, the smart grid must control the load and reactive power adjustment within the distribution system (Chen & Abur 2006).

There have been numerous large-area power outages in the United States and Europe in the past few days, all of which are associated with severe frequency instability and have had significant social and economic consequences. The usage of Phasor Measurement Units (PMU) improves the efficiency and accuracy of the control center's functioning. According to Zhao et al. (2017), the electric network shown above consists of four bus grid systems that link renewable energy sources to the main grid. Two PMUs are be than enough to monitor the four bus systems, as shown in Figure 1. The term "Distributed Generation units" (DGs) describes these grid-connected renewable power sources. It is common practice to employ PMUs for monitoring the network's buses. To make all four buses fully observable, PMUs are positioned at two of them here. Due to smart meters, all the loads & DGs are linked to the grid.

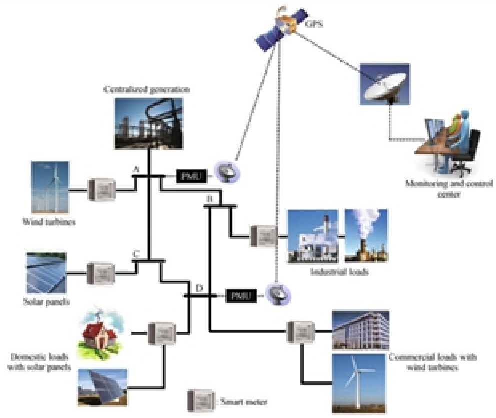

Figure 1: Standard 4-Bus Smart Grid

OPTIMAL POWER FLOW

According to Wood (1996) & Wollenberg (1996), Optimal Power Flow (OPF) has been the subject of much discussion in power system operation & planning since its 1962 presentation by Carpentier. Using OPF, we can find the sweet spot for a number of power system control variables. To achieve this, for each set of input loads & system parameters, the optimization process involves maximizing a small subset of objective functions while adhering to strict equality & inequality constraints. Active powers of generators, bus voltages of generators, transformer tap ratios, and reactive power generation of shunt compensators are the control variables. The primary goal of OPF problems is often the total production cost. It is possible to incorporate other goals, such as lowering network loss, improving the voltage profile, and increasing voltage stability. This is because, because to developments in computing, it is becoming easier to define and resolve complicated problems involving large-scale data sets. Restrictions on power system dependent variables' operational limitations & limits on control variables are examples of inequality constraints, whereas power balancing equations are examples of equality constraints. With both continuous & discrete control variables, OPF is a multimodal optimization problem that is large-scale, non-linear, and non-convex. Even without discrete control variables, the issue is non-convex due to the presence of nonlinear power flow limitations (Wood, A.J. and Wollenberg, B.F., 1996).

As the need for energy continues to rise, the formulation of the OPF problem has become increasingly important for the efficient planning & operation of power systems. In order to efficiently meet the electrical demand of consumers and run smoothly, OPF is crucial for system operators. In order to maximize the operation of the electric power system while overcoming the physical constraints imposed by electrical laws and technical limits, any optimization problem that aims to do so is included in OPF. There are a number of reasons why renewable energy supplies must be integrated into the grid, including environmental emissions, fossil fuel depletion, & astronomical price of fossil fuels. Renewable Energy Resources (RESs) integration into the grid has become necessary due to the depletion of fossil fuel supplies and concerns about environmental protection. Adding RESs with unknown reliability, however, makes things even more difficult. The conventional power grids are progressively giving way to the more advanced smart grids as new technologies like distributed generation, storage devices, communication networks, & dispatchable loads are integrated into electrical networks. Smart grid's one and only goal is to integrate RESs & encourage more user involvement in electricity network operations. By controlling the demand, both consumers and electrical utilities can reduce electricity usage and costs. In smart grids, OPF plays an essential role in reducing transmission losses, fossil fuel emissions, & cost of energy generation.

IEEE STANDARDS FOR SMART GRID

Smart grid technology is very essential for the future power system. Standards were very important before implementing the technology. Various standards are identified for various levels of the smart grid are renewable power generation, power consumption, distribution, power security, data interchange, and storage. Some of the standards are discussed in the topics and their benefits. International Electrotechnical Commission (IEC), International Electrical and Electronics Engineering (IEEE), Brits Standard Institutions (BSI) and European Committee for Standardization (ECS) are providing the standards for communication, substation automation, storage, and security. Table 1 shows the various types of international standards and their functions to develop efficient system management.

Table 1: Types of international standards and their functions

Area	Standards	Description
Renewable power generation	• IEC 62282-X-X • VDI 2067 • IEC60193 • IEC-EN 61727	• This deals with the Fuel cell operation and conditioning • Geothermal power generation, monitoring and control • Hydrothermal development and testing • Integration and implementation of the solar PV systems
Distribution system	IEC60834 IEC60870	• Provides the protocol for transmission, distribution and standards of the equipment
Energy management	IEC61970 IEC61850	• Common information module for energy management • Communication protocol between the intelligent devices and agents • Substation automation
Energy Storage	IEEE 1547 IEEEP2030-3 IEC62196	• Standards for equipment testing and interconnection • Guideline for energy storage in electrical vehicle
Advance metering infrastructure	IEC62058	• Provide the standards for development and testing for AMI

The above table shows some important standards for the development of the future power grid. This standard provides smooth and efficient operation of the grid also it helps the product developers.

SMART GRID TECHNOLOGY OF RENEWABLE ENERGY SYSTEMS

Lightner et al (2010) The United States Department of Energy (DOE) organised a workshop in September

2001 to plan the transformation of the electricity system through the use of distributed energy resources' communication & control technology. Concepts and a vision for an interactive and flexible power system evolved from this and following collaborations with businesses, universities, and other research organisations. Nowadays, "smart grid" is a popular term for this idea.

The Department of Energy (DOE), its national labs, & industry partners have been making great achievements in smart grid deployments, demonstrations, & research since 2009, when they received substantial funding from the federal government. Ensuring a system with dependable performance to the economy and society it services is a necessity behind these actions, which contribute to the smart grid transition. This document provides a concise overview of the existing smart grid initiatives, lays out the priorities for smart grid implementation, and outlines the trajectory of DOE-funded R&D.

As stated by Bose et al. (2010) "Smart Transmission Grid Applications & Supporting Infrastructure" presupposes that all high-voltage substations will have extremely high rates of time-synchronized readings. The author looked at how this data can be used better for both immediate operations and future decisions. When compared to current real-time measurements, this new data is distinct in terms of both quality and quantity.

Although still at the conceptual phase, new and improved applications show promise for operating the power system more reliably and effectively. Additionally, it has been acknowledged that the current system is not suitable for handling this type of real-time data. However, not even preliminary plans for the necessary infrastructure to store and transmit the data have been finalised. Since the amount and velocity of data would make centralised data storage impractical, the author of this study initially proposed the necessities of an information infrastructure to manage omnipresent phasor measurements.

According to the 2010 proposal by De La Ree et al., Synchronised Phasor Measurement Applications in Power Systems, phasor measurements are now a well-established technology, and a number of companies around the world provide commercially available Phasor Measurement Units (PMUs) that conform to the current standard for synchrophasors.

A significant current effort is the installation of PMUs on the power transmission networks of most major power systems. Presenting a concise overview of PMUs and WAMS technology, this paper serves as a starting point for further reading. It went over how these measurements can be used to better watch, safeguard, and manage electricity networks.

Rogers and colleagues (2010) published "An confirmed Control Framework for Distributed Voltage Support on the Smart Grid," A variety of home gadgets, both current and future, can supply reactive electricity. At now, the power system does not make use of inverters, which link distributed generation to the grid. This includes things like solar panels and Pluggable Hybrid Electric Vehicles (PHEVs). In order to offer voltage support to the grid, the authors have looked at the possibility of integrating these end-user reactive-power devices through a secure communication architecture.

In their study titled "Intelligent Systems for Improved Reliability and Failure Diagnosis in Distribution Systems" (Russell et al., 2010), the authors discuss how smart grid technology can automate switching to restore service and decrease the number of customers affected by protracted outages. Despite their usefulness, such technologies are reactive, meaning they only kick in when a problem has already happened and an outage has been identified. It is assumed that the feeder portions that are not faulted and any alternate feeders can handle the additional power flow.

Although the data and calculation requirements are far higher than those of digital relays and power-quality metres, they are still within the realm of possibility with today's electronics. Several instances of failures foreseen by smart Distribution Fault Anticipation (DFA) algorithms are presented in this research. Identifying these failures is covered, along with the data requirements and processing analysis. We lay forth the issues that arise when trying to implement the suggested system utility-wide. Concepts for overcoming these obstacles are proposed by the writers based on experience gathered from their long-term study.

In 2010, Moslehi and Kumar were joined by A Reliability View of the Smart Grid, There is an ongoing pressing need for a revolutionary advancement in the utilisation of communication & information technologies due to the following: the ever-increasing complexity of power grids; the ever-increasing demand for these systems; and the ever-increasing demands for their efficiency, security, and reliability. Many people call this advancement a smart grid. The installation of critical analytical capabilities and the convergence of urgently needed standards are both made possible by a framework that allows for the coherent integration of different technologies. Major smart grid resources, including storage, demand response, and renewable energy, are examined in this research in a comprehensive analysis of their effects on reliability. The authors state that when these resources are optimally combined, the net demand is flattened, which in turn makes dependability issues more apparent. To address these issues and enable contemporary cyber security measures, an IT architecture framework that spans the entire grid is proposed. Over time scales ranging from milliseconds to milliseconds and beyond, this design enables a plethora of hierarchical monitoring and control operations that are both spatially and temporally coordinated.

LITERATURE REVIEW

Benedetto-Giuseppe Risi et al. (2022) OPF problem has gained more and more attention since smart grids were introduced because of its importance in power system functioning. The concept of optimal power flow emerged as a vital tool for improving the efficiency of electrical power networks and for resource planning. The electric power system can be optimized in relation to a wide variety of objective functions, such as transmission line losses, total generation costs, voltage deviations, total power transfer capability, voltage stability, emission of generation units, system security, etc. It is common practice to employ metaheuristic optimization techniques when dealing with optimal power flow problems, as classical approaches can become stuck in local optimums when dealing with nonlinear situations. The present study discusses the state-of-the-art optimization algorithms utilized to address optimal power flow problems, based on the authors' assessment of the most relevant works. Classification of the optimization methods is based on their origins; these include algorithms that are inspired by humans (e.g., tabu search, teaching learning-based optimization, harmony search), algorithms that are inspired by evolution (e.g., genetic algorithms, differential evolution), and methods that are inspired by physics (e.g., PSO, cuckoo search algorithm, firefly algorithm, ACO algorithm, etc.).

Anil Kumar Dsouza et al. (2022) suggests a hybrid method for improving the smart grid's power quality

(PQ) and managing power flows (PF). The two-stage design of the proposed methodology consists of power flow control and power quality improvement. To achieve its primary goal of "controlling the way that power flow requires variation of source & load side parameters deliver the highest PQ," the suggested solution use the Simplified Binary Sailfish Optimizer (IBSFO) technique to manage power flow in its first stage. When applied to variations in active and reactive power, the IBSFO method identifies the control signal. Combining Kho-Kho optimization (KKO) with Radial Basis Function Neural Network (RBFNN), K2ORBFNN implements the second phase of power quality enhancement. The K2ORBFNN method is used to adjust the proportional integral (PI) controller's gain parameter in relation to the load current, DC link, or voltage sources. Minimizing the error acquired by the RBFNN technique is achieved by the prediction of the ideal control signal. To achieve harmonic compensation in non-linear load currents, reactive load power requirements, & unbalanced load currents, the proposed method is used. Lastly, the suggested system is tested in the MATLAB environment and its results are compared to those of previously established methods. Efficiency reaches 99.1673%, 99.4567%, 99.8402%, and 99.9879% for the 100, 200, 500, and 1000 trial conditions, respectively.

Dr. Ganapathia Pillai Kannayeram et al. (2021), an elite power flow management (PFM) method involving PV, FC, battery, & SCAP in a smart grid (SG) system is suggested in this publication. Supercapacitors, fuel cells, battery storage, & photovoltaic (PV) generators with Maximum Power Point Tracking (MPPT) & power limitation modes are all part of the suggested design. We call the suggested technique the BALSO method because it combines the binary adaptation of the ant lion optimizer (BALO) with the squirrel search optimizer (SSO). Depending on the power transfer and assortments between the source and load sides, BALO is generated by the inverter control pulses in this case. A multi-objective function that takes into account the power that is available from the grid & active and reactive power that is generated is necessary. In this case, we use SSO to get that control pulse online by analyzing power flow types. On top of that, we offer a way to control power flows based on the worldwide SOC of energy storage and the demand for power. The last step is to run the BALSO system on the MATLAB/Simulink server. Through comparison with other systems, the BALSO system's efficiency is examined. We compare the current method's elapsed time to that of the proposed one.

Syed Muhammad Arif et al. (2020) offer a technique for distribution generation optimal area & size optimization that combines analytical methods with traditional PSO—the analytical hybrid PSO (AHPSO) algorithm. To accommodate loads that are evenly dispersed, increasingly distributed, centrally distributed, or randomly distributed in traditional power systems, the AHPSO algorithm is placed into operation. Using two examples, we evaluate the normal PSO algorithm's convergence speed & optimization performance to that of the suggested AHPSO technique, proving that it is successful. In the first scenario, an IEEE 10-bus system is used to compare the two methods' performances for four distinct load distributions. In the second scenario, we compare the algorithms' performance on the IEEE 10-bus, IEEE 33-bus, and IEEE 69-bus systems as well as a functional Korean distribution system. The suggested AHPSO algorithm converges much more quickly than the conventional PSO, according to the simulation findings. The outcomes of the suggested algorithm are comparable to those of an analytical algorithm.

Sureshkumar Kumaravel et al. (2020) suggest a hybrid approach to optimally regulate the power flow of a hybrid renewable energy source (HRES). Here, the suggested approach is called the IB4SA technique since it combines the features of two algorithms: Improved Bear Smell Search (IBSS) & Sparrow Search Algorithm (SSA). Here, the power exchange variety among the source side & load side informs the generation of the voltage source inverter control signals by the IBSS. Because the suggested study incorporates the Bear Smell Search (BSS) through a mutation & crossover function, it is referred to as IBSS. The grid's active and reactive power kinds are designed according to the available source power, and the multi-objective function is one of them. Through its parallel implementation, the SSA method ensures the identification of online control signals despite variations in active and reactive power. In response to changes in power flow, the control method based on the suggested approach enhances the power controller's control parameters. The suggested method regulates the smart-grid system's power flow management in response to changes in source & load side parameters. In order to meet the grid's power needs, the suggested method is in charge of managing energy sources, which include renewable electricity and energy storage devices. Using the MATLAB/Simulink work site, the suggested method is run and its performance is compared to that of the existing methods. Cases 1, 2, and 3's statistical analyses, utilizing both new and old methods, are examined. Parameter values for Case 1 using the suggested method are 0.528 for the mean, 0.512 for the median, and 0.033 for the standard deviation. In Case 2, the suggested method yields a mean of 0.671, a median of 0.656, & standard deviation of 0.026.

Metody GEORGIEV et al. (2019) suggest an application that can optimize energy flows in smart power systems that include electric vehicles (EVs), distributed energy sources (DERs), flexible loads, & bidirectional storage. Electric automobiles, electric storage devices, and photovoltaic generators make up the energy distribution system that is optimized here. The optimal distribution of power throughout the system is optimized by defining and solving a nonlinear optimization problem with linear constraints. In order to increase the power flow to the EVs while simultaneously satisfying PV production conditions, a multi-objective issue is established. A method is suggested for solving the multi-objective optimization issue optimally. Controlling energy flow and analyzing DER behavior are two areas where this method shines. When distributed energy resources (DER) systems incorporate storage & PV generation units, the multi-objective problem-solving technique is applicable. The benefits of using external storage in distributed systems are demonstrated.

Vadim Z. Manusov et al. (2018) provides justification for the necessity of optimizing intellectual network mode using the SG concept. This mode must have a two-way energy flow function that is supplied by both the energy system and self-distributed generation sources. It is for this reason that the term "Generating Consumer" is first used. One can minimize the financial expenditures of power use and flexibly regulate energy flows and load balancing with its help. The merging of distinct natural subsystems (holons) into a hierarchical structure, or holarchy, introduces a novel holonic method. The research proposes a mathematical model of optimal power consumption as a system of linear algebraic equations (SLAE) with two-way energy flow, taking into account a two-zone electricity tariff. This model would be utilized by the generating consumer. Considering the potential for energy storage, the model offers a set of guidelines for the best mode balance of intellectual networks. The optimization problem is solved using the universal method based on the priority of rules in the Swarm Intelligence algorithm. Within the SG concept, a new idea called a holonic approach is introduced and justified. Another term, "Generating consumer-holon" (GC-holon), is introduced, which means that energy consumers can generate their own electricity from renewable sources, store it, and then trade it with other GC-holons or the basic generating system. The development of the priority system for generating source selection is done with the goal of minimizing financial costs for the energy user.

CONCLUSION

Optimal Power Flow (OPF) in smart grid systems represents a significant advancement in the efficient and reliable management of electrical power. OPF techniques enable the optimization of power generation, distribution, and consumption by balancing supply and demand, minimizing operational costs, and reducing transmission losses. The integration of renewable energy sources, energy storage systems, and demand response mechanisms further enhances the flexibility and resilience of the grid. The benefits of OPF in smart grids are multifaceted. It improves the economic efficiency of power systems by optimizing the dispatch of generation units and the flow of electricity through the network. As the power grid continues to evolve, ongoing research and development in OPF methodologies will be essential to address emerging challenges and to fully realize the potential of smart grid technologies.

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