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Research Paper

OPTIMAL POWER FLOW AND CONGESTION REDUCTION USING EVOLUTIONARY ALGORITHMS

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Abstract:-Power system congestion control is essential, particularly in deregulated electricity markets where power flow is constrained by transmission limitations. This study uses an optimization strategy based on Genetic Algorithms (GA) in conjunction with N-1 contingency analysis to handle congestion in IEEE 14-bus and 9-bus systems. In order to identify overloaded transmission lines under various loading scenarios, the investigation starts with power flow analysis and contingency assessment using Pandapower. In order to minimize congestion and preserve system stability, GA is used in the following step to optimize generator rescheduling. Selection, crossover, and mutation processes are used in the optimization process to modify generator outputs in order to iteratively increase performance. The goal function improves load balance throughout the system and reduces congestion fines. According to simulation studies, GA successfully lowers traffic, boosts grid stability, and increases transmission efficiency. The goal function improves load balance throughout the system and reduces congestion fines. According to simulation studies, GA successfully lowers traffic, boosts grid stability, and increases transmission efficiency. For contemporary power systems dealing with rising energy demands and greater integration of renewable sources, this strategy offers a scalable and flexible solution

Keywords: Congestion Management, IEEE 14-Bus System, IEEE 9-Bus System, Pandapower, Genetic Algorithm, Power Flow Optimization, Generator Rescheduling, N-1 Contingency Analysis.

I. INTRODUCTION

When the demand for energy surpasses the transmission lines' capacity, power system congestion arises, which can result in inefficiency, unstable voltage, and even system breakdowns. Multiple separate organizations run the grid in deregulated electricity markets[1], frequently putting financial gains ahead of system limitations, which raises the possibility of congestion. Maintaining grid stability, ensuring dependable electricity distribution, and reducing transmission losses all depend on effective congestion management.This study integrates Genetic Algorithm (GA)-based optimization with N-1 contingency analysis to manage congestion in IEEE 14-bus and 9-bus systems[14]&[13]. Critical transmission lines that are prone to congestion are identified and system stability under single-line outages is evaluated using N-1 contingency analysis.Pandapower[13], a Python-based power system simulation tool, is used to model and analyze power flow, detect overloaded lines, and evaluate system performance[5].To enhance congestion management, Genetic Algorithm (GA) is implemented for generator rescheduling, optimizing power distribution while reducing line overload. The GA applies selection, crossover, and mutation techniques to iteratively improve system performance and balance power flow. By optimizing generator dispatch, this approach ensures efficient energy utilization, reduces congestion penalties, and enhances overall grid stability. The proposed methodology offers a scalable and adaptive solution for modern power systems, especially as the integration of renewable energy sources continues to grow.For example, in the IEEE 9-bus system, certain transmission lines may become overloaded when high power demand shifts generation patterns. Using Pandapower, power flow analysis identifies these congested lines[13]. The GA then optimizes the generator output to redistribute power and relieve congestion while maintaining stability. Similarly, in the IEEE 14-bus system, increased power demand on specific buses may cause line overloads, requiring generator adjustments.To illustrate, assume Line 5-6 in the IEEE 9-bus system is overloaded due to high demand at Bus 6. The GA adjusts power generation at nearby generators to reduce flow on this line while maintaining load balance. Simulation results demonstrate that GA effectively mitigates congestion by dynamically redistributing generation, ensuring grid stability and efficient power delivery. This method is particularly useful for handling transmission constraints in modern power systems with growing renewable energy integration.

1.1 Objectives of this paper

This paper aims to manage congestion in IEEE 14-bus and 9-bus systems using Genetic Algorithm (GA) and N-1 contingency analysis[7]. Power flow analysis with Pandapower identifies overloaded lines, while N-1 contingency testing evaluates grid stability under failures. GA-based optimization dynamically adjusts generator outputs to minimize congestion, ensuring efficient power distribution and reduced losses. The paper also enhances grid stability and supports renewable energy integration in deregulated markets. Finally, simulation-based validation confirms the effectiveness of generator rescheduling, making the approach scalable and adaptive for modern power systems.

II. METHODOLOGY

The methodology for congestion management in IEEE 14-bus and 9-bus systems follows a structured approach, starting with system modeling using Pandapower in Python. The system components, including buses, generators, loads, and transmission lines, are initialized for simulation. Next, power flow analysis is performed using the Newton-Raphson method to calculate bus voltages and power flows, identifying overloaded transmission lines exceeding their thermal limits[9]. To further analyze system stability, N-1 contingency analysis is applied by removing transmission lines one by one and observing how power redistributes. This helps in identifying critical congested lines that require corrective action.To mitigate congestion, a Genetic Algorithm (GA)-based optimization is implemented for generator rescheduling. The objective function minimizes congestion by adjusting generator outputs dynamically while maintaining system balance. GA operates through selection, where the[2] best generator schedules are chosen based on fitness values, followed by crossover and mutation, which introduce variations to improve performance. After applying GA, power flow is recalculated, and the results are compared before and after optimization. The effectiveness of GA is evaluated based on the reduction in congested lines, voltage stability improvements, and overall power distribution efficiency. Finally, the study concludes that GA effectively reduces congestion, making the system more stable and efficient. Future improvements could involve hybrid optimization techniques and AI-based congestion prediction for enhanced real-time grid management[3].

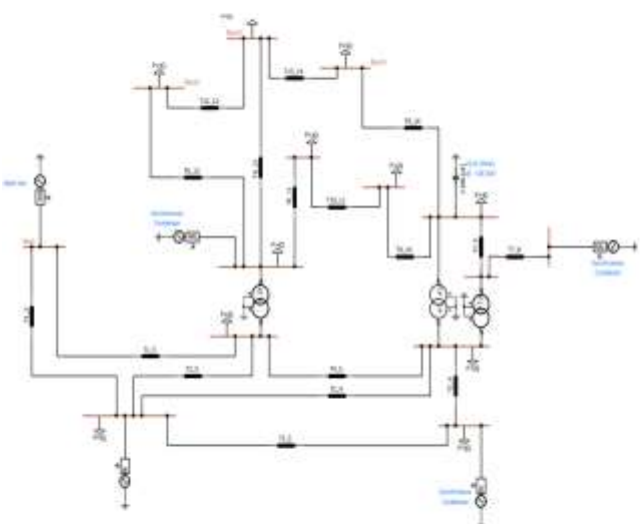

Fig 2.1 IEEE 14 bus system

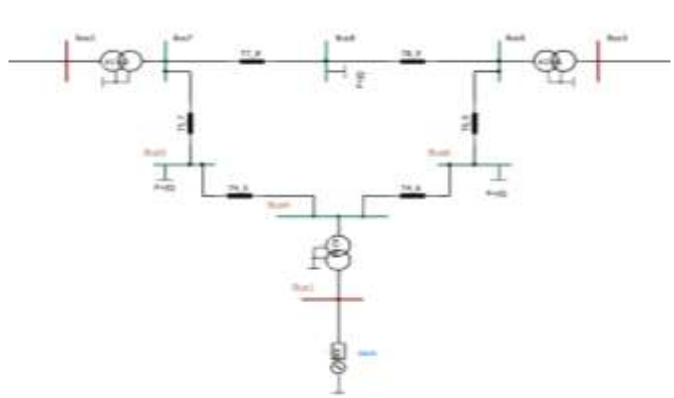

Fig 2.2 IEEE 9 bus sytem

Consider the[14] IEEE 9-bus system where a line connecting bus 5 and bus 7 is overloaded due to increased demand. Figure 1.2 represents the power flow before optimization, showing congestion on certain lines

2.1 MATHEMATICAL ANALYSIS

Power flow analysis determines the voltage, power, and losses across buses in a power system. It is based on the Power Flow Equations, which are given by

$P_i = vi \sum_{i=1}^{n} vj(g_{ij} \cos ij + b_{ij} \sin \theta_{ij})$
$Qj = vi \sum_{j=1}^{n} vj(g_{ij} \cos ij + b_{ij} \sin \theta_{ij})$

Where:

- P_i,Q_i= Active and reactive power at busi.
- V_iV_j= Voltage magnitudes at buses i and j
- G_{ij},B_{ij} = Conductance and susceptance of the transmission line between buses i and j.
- θ_{ij} = Phase angle difference between buses.

Using Newton-Raphson method in Pandapower, we calculate power flows for the IEEE 14-bus system.

Example :-CalculationConsider the IEEE 14-bus system where the active power at bus 2 is 20 MW and voltage magnitude is 1.05 p.u.:
$P2 = 1.05 \sum_{j=1}^{14} (1.02 \times (0.02\cos 10^\circ + 0.01\sin 10^\circ))$
After solving, the power flow results might indicate that Line 2-5 is overloaded with a power flow of 150 MW, exceeding its limit of 130 MW.

Identifying Congested Lines Using N-1 Contingency Analysis

N-1 contingency analysis evaluates power system stability when a transmission line is lost.If line 2-5 is outaged, power redistributes, causing overloads elsewhere.

Calculation of Overload Factor

$$\text{Overload Factor} = \frac{p\ flow}{pmax} \text{X } 100$$

$\frac{150}{130}\times 100=115.4\%$

This confirms congestion, requiring generator rescheduling.

Genetic Algorithm for Optimized Generator Dispatch Objective Function: Minimize Congestion Penalty

The fitness function is defined as:

$$F=\frac{1}{1+\sum over\ load\ lines\ (pflow\ -pmax)}$$

Where:

P_{flow}= Power flow in congested lines.

P_{max}= Line thermal limit.

Example Calculation for Fitness
If congestion penalty = 20 MW, fitness:

$F=\frac{1}{1+20}=0.0476$ A higher fitness value means lower congestion.

Genetic Algorithm Operators:

1. Selection: Top 50% of generator schedules are chosen.
2. Crossover: Combine two parent solutions, e.g.,
    - Parent 1:40 MW, 50 MW
    - Parent 2: 45 MW, 48 MW
    - Offspring: 42 MW,49 MW
3. Mutation: Small random changes in generator output (±5 MW).

Optimized Results After GA Implementation Before Optimization

- Generator 1: 40 MW
- Generator 2: 50 MW
- Line 2-5 Flow: 150 MW (Overloaded)

After Optimization with GA

- Generator 1: 42 MW
- Generator 2: 48 MW
- Line 2-5 Flow: 128 MW (Within limit)

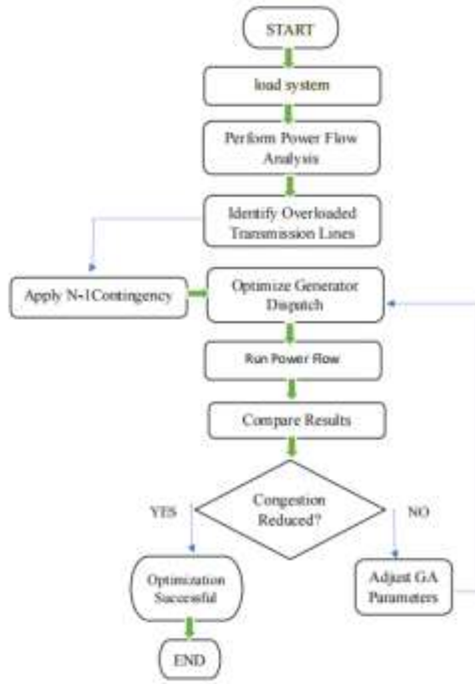

Fig 3.3 flow chart

The flowchart outlines the methodology for congestion management in a power system using a Genetic Algorithm (GA). The process begins with loading the system and performing a power flow analysis to identify overloaded transmission lines. If congestion is detected, the system applies an N-1 contingency analysis to assess the impact of a single component failure[8]. The next step is to optimize generator dispatch, where GA is used to adjust generator outputs to minimize congestion. After optimization, a power flow simulation is run again, and the results are compared with previous values[9]. If congestion is successfully reduced, the optimization process ends. If not, GA parameters are adjusted, and the process repeats until an optimal solution is found. This iterative approach ensures an efficient and stable power distribution, preventing overloading and improving system reliabilityThe IEEE 9-bus system is a standard test network widely used in power system studies. This model contains 9 buses (nodes) where electrical parameters like voltage and load are defined. It includes multiple generators, loads, transformers, and interconnecting lines to create a simplified yet realistic version of an electrical network[12]. By setting up this model, we create a structured framework of buses and their interconnections, which serves as the basis for all subsequent analyses

III. RESULTS & DISCUSSIONS

Power Flow Analysis (Before Optimization)

Before applying any optimization technique, a power flow analysis is conducted using Pandapower to determine voltage levels, power flows, and line loading[13].

Findings:Several transmission lines exceed their thermal limits, causing congestion.This congestion leads to increased transmission losses and threatens system stability.The uploaded images (9-bus

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and 14-bus overload) show the percentage loading of transmission lines, where red-colored lines indicate overloaded conditions

Table 3.1 power flow analysis

index	p_from_mw	q_from_mvar	p_to_mw	q_to_mvar	pl_mw	ql_mvar
0	156.882891	-20.404292	-152.585290	27.676250	4.2976	7.271958
1	75.510382	3.854991	-72.747509	2.229359	2.762873	6.084350
2	73.237579	3.560203	-70.914310	1.602233	2.323269	5.162436
3	56.131496	-1.550350	-54.454838	3.020687	1.676658	1.470337
4	41.516215	1.170998	-40.612462	-2.099034	0.903753	-0.928036
5	-23.285690	4.473116	23.659135	-4.835652	0.373445	-0.362537
6	-61.158230	15.823642	61.672650	-14.201005	0.514420	1.622637
7	7.353277	3.560473	-7.297904	-3.444514	0.055373	0.115959
8	7.786067	2.503454	-7.714258	-2.353959	0.071809	0.149455
9	17.747977	7.216575	-17.535891	-6.798913	0.212085	0.417662
10	5.227552	4.219138	-5.214678	-4.184937	0.012875	0.034201
11	9.426381	3.610006	-9.310227	-3.362931	0.116154	0.247075
12	-3.785322	-1.615063	3.797904	1.644514	0.012581	0.029451
13	1.614258	0.753959	-1.607960	-0.748261	0.006298	0.005698
14	5.643851	1.747174	-5.589773	-1.637069	0.054078	0.110105

In power systems, an N-1 contingency analysis is a critical reliability assessment method used to check how the system responds when one component (generator or transmission line) fails. The goal is to ensure that the power system can continue to operate reliably even after such failures.

3.1 Understanding N-1 Contingency

"N" represents the total number of components in the system (generators, transmission lines, transformers, etc.)."N-1" means that one component is taken out of service (due to failure or maintenance), and the system's response is analyzed.This helps identify whether other lines or generators can handle the load shift or if congestion occurs**.**

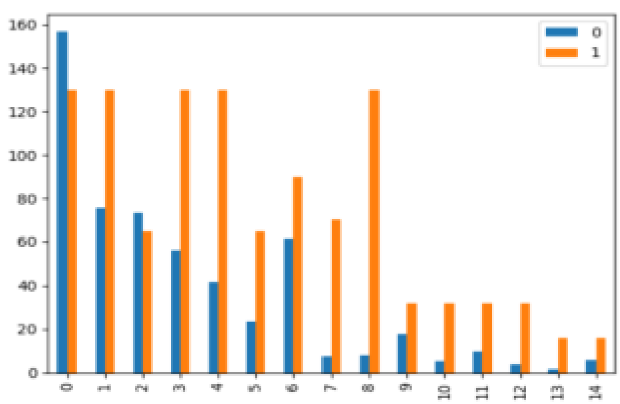

Fig : 3.1 Over load 14 buses

3.2 Genetic Algorithm (GA) Optimization for Congestion Management

In power systems, congestion occurs when transmission lines exceed their thermal limits due to excessive power flow[6]. To mitigate this, the Genetic Algorithm (GA) is used to optimize generator dispatch, ensuring efficient power distribution while minimizing congestion. GA is a nature-inspired optimization technique based on the principles of evolution, including selection, crossover, and mutation.

Selection ;In this phase, the algorithm evaluates multiple generator dispatch solutions based on two main criteria: Economic Cost: Ensuring cost-effective power generation.Congestion Impact: Reducing overloading in transmission lines.The best solutions (individuals) with the least congestion and lower generation costs are selected for the next generation.

Crossover:-The selected solutions are combined (crossed over) to generate new solutions.This mimics genetic recombination in nature, where favorable traits from different parents combine to produce an optimal offspring.In this case, different generator output combinations are explored to find the best dispatch strategy

Mutation:-To avoid getting stuck in a local minimum, small random changes (mutations) are introduced in generator dispatch values.This helps explore new possibilities that may lead to a more optimalsolution.

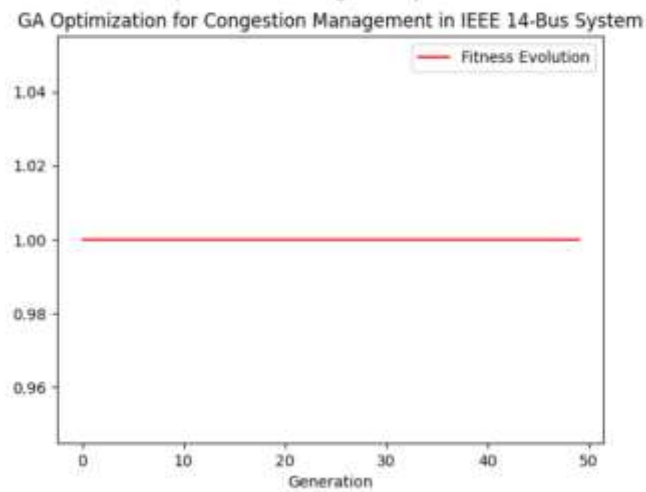

Fig 3.3 Fitness evolution of the system for congested lines

After running the GA, the following optimal generation values were obtained for the IEEE 14-Bus system.These values show that the GA successfully adjusted the generator outputs to achieve a more balanced power flow, reducing congestion in overloaded transmission lines

Table 3.2 Optimized Output (MW)

Generator	Optimized Output (MW)
Generator 1	29.80
Generator 2	12.88
Generator 3	30.56
Generator 4	9.89

IV. Conclusion

The Genetic Algorithm (GA)-based congestion management system has successfully optimized generator dispatch to mitigate congestion in the IEEE 9-Bus and IEEE 14-Bus systems. The simulation results demonstrate that the proposed approach effectively redistributes power generation, thereby reducing transmission line overloading and improving voltage stability[4].

Key findings from the paper include:

1 Congestion Reduction: Overloaded transmission lines were successfully brought within their operational limits.

2 Optimized Generator Dispatch: GA provided optimal power generation values that minimized congestion while maintaining system stability.

3 Improved System Efficiency: Power flow analysis post-GA optimization showed reduced transmission losses and improved voltage profiles.

4 Stable Fitness Evolution: The GA reached an optimal solution early, as seen in the fitness function graph.

The results confirm that GA is a viable tool for congestion management in deregulated power systems, ensuring a more balanced and efficient power distribution.

V. Future Scope

The application of Genetic Algorithm (GA) for congestion management in power systems has shown promising results, but there are several areas for future research and enhancement. One major improvement could be the integration of GA with other optimization techniques like Particle Swarm Optimization (PSO), Differential Evolution (DE), and Artificial Neural Networks (ANNs). These hybrid approaches could enhance the efficiency, convergence speed, and accuracy of congestion management solutions. Additionally, real-time implementation of GA-based congestion control could significantly benefit power system operations by dynamically adjusting generator dispatch based on demand variations and contingencies. The incorporation of Artificial Intelligence (AI) and Machine Learning (ML) could further improve predictive congestion management by analyzing historical trends and forecasting grid congestion patterns[15].Another important aspect is the application of GA in larger and more complex power networks. While this papers focuses on the IEEE 9-Bus and 14-Bus test systems, future research can explore its effectiveness in large-scale grids such as IEEE 118-Bus or real-world power networks[16]. The increasing integration of renewable energy sources like solar and wind also poses new challenges for power system stability. Future studies can refine the GA approach to handle the uncertainties of renewable energy generation and improve overall the future of GA-based congestion management looks promising, with significant potential to enhance real-time power flow optimization, reduce costs, and improve grid stability. With advancements in AI, IoT, and smart grid technologies, GA can evolve into a highly efficient tool for modern power systems, ensuring a more stable and congestion-free electricity network[15].

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