Genetic Algorithm-Based Contingency Ranking for the 500 kV JAMALI Interconnection System

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Abstract: The performance of an electric power system is strongly tied to how well it can handle disturbances. In daily operation, one of the most frequent and serious disturbances is the loss of a transmission line. When a line trips, its load must be shared by the rest of the network. Sometimes this redistribution is harmless, but in stressed conditions it can create overloads and trigger further outages. To reduce this risk, system operators rely on contingency analysis. The *(N-1)* criterion, which considers the effect of losing a single component, is the most common standard. However, when applied to a large network, the number of cases becomes very high, and the analysis can be time-consuming. In this work, contingency ranking using a Genetic Algorithm (GA) is studied for two systems: the IEEE 30-bus test grid and the 500 kV Java–Madura–Bali (JAMALI) interconnection in Indonesia. The GA follows the usual cycle of initialization, selection, crossover, mutation, and fitness evaluation, with the Voltage

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Performance Index (VPI) used to measure severity. Different parameter settings were tested. The results show that line 36 (bus 28–27) is most critical in the IEEE 30-bus system with a VPI of 56.5915, while line 35 (Bangil–Paiton) is most critical in the JAMALI system with a VPI of 95.3947. These outcomes highlight the usefulness of GA in identifying vulnerable transmission lines.

Keywords: Contingency, Genetic Algorithm Method, IEEE 30 Bus Electric Power System, JAMALI 500 KV Electric Power System.

Introduction

The Electric power systems are central to modern life. Beyond lighting homes, they drive industry, commerce, transport, and communications. In countries with growing economies, such as Indonesia, the annual increase in electricity demand is quite significant. This rise is not only linked to population growth but also to the expansion of industrial estates and the adoption of new digital technologies. Under these conditions, ensuring the security of supply has become a recurring concern for system operators.

In practical operation, one of the most serious threats to reliability is the outage of a transmission line. When a line trips, the power it carried must immediately be shared by the remaining network. If the system is lightly loaded, this may pass unnoticed. But in heavily stressed conditions, the redistributed flows may push other lines beyond their limits. The situation can escalate quickly: voltage deviations appear, overloaded lines trip, and in some cases, a local failure grows into a wide-area blackout (Billinton & Wangdee, 2006; Wood et al., 2013). Such events underline why utilities rely on contingency analysis in their daily planning. The standard *(N-1)* security criterion requires that the grid remain stable after the loss of any single element (Patel et al., 2022). Although simple in concept, applying this rule in large networks is far from trivial. Hundreds of possible outages must be studied, each involving a complete power flow calculation. Carrying out all of them is not always feasible, especially for interconnection systems with hundreds of lines and buses.

To reduce this burden, contingency ranking is widely used. Instead of examining every case with equal attention, ranking methods focus on the most severe outages. A performance index, such as the Voltage Performance Index (VPI), provides a practical way to quantify the severity of voltage violations (Jia et al., 2013; Sekhar & Mohanty, 2016) . The higher the index, the more critical the contingency, and the higher its priority in operational planning. Conventional ranking techniques are effective for small systems, but their efficiency drops as network size and complexity increase. For this reason, several researchers have turned to heuristic and metaheuristic approaches. Among these, the GA are particularly attractive because they can search broadly in complex solution spaces without relying on gradient information (Gholami et al., 2020; Kumar et al., 2020; Shrivastava et al., 2022). The GA has been used successfully in optimization problems such as optimal power flow and static security assessment, making it a strong candidate for contingency ranking. In this work, a GA-based contingency ranking method is applied to two networks of different scales: the IEEE 30-bus test system and the Java–Madura–Bali (JAMALI) 500 kV interconnection, which forms the backbone of the Indonesian transmission grid (da Silva et al., 2019). The study makes the following contributions:

1. Framework development: a GA formulation that uses the Voltage Performance Index to rank contingencies under *(N-1)* conditions.
2. Practical insight: an evaluation of GA parameters (population size and number of generations) to show how they affect the quality of ranking.
3. Real-system validation: an application to the JAMALI 500 kV system, highlighting the transmission lines most critical for secure operation.
4. Benchmark comparison: results on the IEEE 30-bus system are included to show scalability and to provide a reference for interpreting the JAMALI case.

The remainder of this paper is organized as follows. Section II reviews the theoretical foundation of contingency analysis and GA. Section III explains the methodology. Section IV presents and discusses the simulation results. Section V concludes the paper.

Research Background

The reliability of a power system cannot be separated from the performance of its transmission network. Transmission lines act as the backbone of electricity delivery, connecting generating plants to substations and ensuring that consumers receive a continuous supply. These lines are generally categorized into overhead lines, which dominate long-distance transmission, and underground cables, which are more common in urban or space-constrained areas. While both AC and DC can be used, AC transmission has historically been preferred because voltage levels can be stepped up or down using transformers, making it more economical and technically practical for bulk power transfer (Jabr, 2013; Valera et al., 2017).

In large interconnected systems, disturbances are inevitable. One of the most critical scenarios is the outage of a transmission line. This event, often referred to as a *contingency*, redistributes power flows across the network. Depending on where the outage occurs, the consequences can range from mild voltage deviations to severe overloads that may trigger cascading failures (Chang & Wu, 2011; Schäfer et al., 2018).To prevent widespread blackouts, system operators rely on contingency analysis as a preventive tool.

Contingency analysis is a process of simulating possible outages most commonly under the *(N-1)* criterion, which assumes the loss of a single component. This criterion has become a standard in security assessment because it represents a realistic compromise between reliability and computational effort. However, as the number of network elements increases, the number of possible contingencies grows rapidly, making full analysis computationally expensive.

For this reason, contingency ranking is introduced. Instead of analyzing every case equally, ranking methods help operators identify which line outages are the most severe. Among several indices proposed, the Voltage Performance Index (VPI) is widely adopted because it directly reflects the degree of voltage violation in the system (Adebayo & Sun, 2017; Canizares et al., 2002). The VPI can be expressed as.

$$\mathrm{IP} = \sum_{j}\left(\frac{V_j^{min}}{V_{j,\,i}}\right) + \sum_{j}\left(\frac{V_{j,\,i}}{V_j^{max}}\right) \tag{1}$$

where *IP* is the performance index, V_J^{min} and V_J^{max} are the allowable voltage limits at bus *j*, and $V_{j,\,i}$ is the voltage at bus *j* during the outage of line *i*. A higher value of *IP* indicates a more severe contingency, meaning the system is less secure.

The calculation of performance indices requires accurate power flow analysis. Power flow studies provide steady-state information on bus voltages, power injections, and line flows, all of which are fundamental for security assessment. Buses are classified into three categories: P–Q buses (load buses), P–V buses (generator buses), and a slack bus that balances the system. Several numerical techniques exist for solving power flow problems. Among them, the Newton–Raphson method is the most widely used, especially in large systems, because of its strong convergence properties and computational efficiency (Qin & Hu, 2018). For implementing such studies, researchers often rely on simulation tools. GNU Octave is an open-source numerical platform that supports matrix-based computation and visualization, making it suitable for academic experiments. In addition, MATPOWER, a MATLAB-based package, has become a standard tool for power flow and optimal power flow studies due to its simplicity, modifiability, and wide adoption in the research community (Hu et al., 2013).

Benchmark systems are commonly used to test contingency analysis methods before applying them to real grids. The IEEE 30-bus test system is one such standard. It consists of 30 buses, 41 transmission lines, and 6 generators, supplying a total load of 800 MW. Despite its moderate size, it is complex enough to capture key behaviors of real systems and has therefore been widely adopted as a test case Figure 1 below.

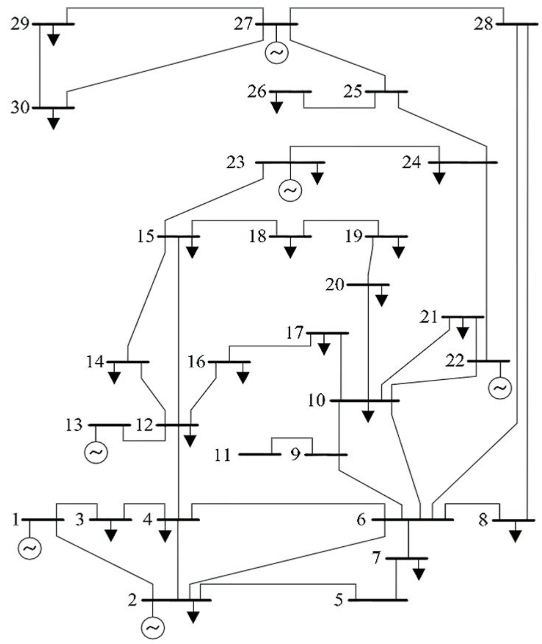

Figure 1 Single Line Diagram of IEEE 30 Bus

For a real-world case study, this research considers the 500 kV Java–Madura–Bali (JAMALI) interconnection system. With 50 buses, 62 transmission lines, and 20 generating units, it represents the backbone of the Indonesian power system. The system plays a crucial role in meeting electricity demand across Java and Bali, where consumption is concentrated. Its scale and complexity make it a suitable benchmark for testing advanced contingency ranking methods Figure 2 below.

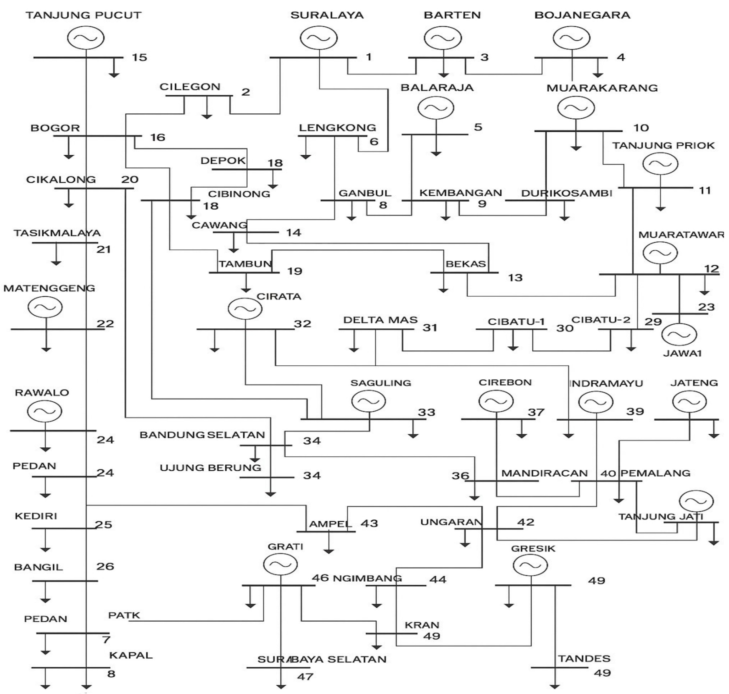

Figure 2 The 500 kV Java-Madura-Bali Interconnection System

To address the computational challenges of contingency ranking, metaheuristic algorithms are increasingly explored. The GA , inspired by the process of natural selection, has shown strong performance in solving nonlinear and complex optimization problems. The GA operates through a cycle of initialization, selection, crossover, mutation, and fitness evaluation (Hossain et al., 2015; Squires et al., 2022). When applied to contingency ranking, The GA offers the advantage of global search capability, reducing the risk of being trapped in local optima and allowing more accurate identification of critical outages. Finally, to measure the effectiveness of ranking methods, the capture ratio is often used. It compares the ranking sequence generated by the proposed method with that of a reference method or exact calculation. The capture ratio is given by:

$$Capture\ Ratio = \frac{k(p)}{N} \text{ x } 100 \quad (2)$$

where N is the total number of contingencies and $k(p)$ is the number of matches between the proposed and reference rankings. A higher capture ratio indicates that the method closely approximates the true ranking. In summary, this background highlights the importance of transmission reliability, the role of contingency analysis, and the potential of the GA as a tool for efficient ranking (dos Santos et al., 2015). These elements collectively motivate the methodology proposed in the next section.

Research Method

This research was conducted through several systematic stages designed to analyze and rank transmission line contingencies in power systems using a the GA. The study begins with the preparation of system data from two different networks: the IEEE 30-bus test system and the Java–Madura–Bali (JAMALI) 500 kV interconnection system. The data used include transmission line parameters, generator capacities, load demands, and bus voltage limits, which are essential for carrying out power flow studies and contingency simulations (dos Santos et al., 2015; Paranjothi & Anburaja, 2002).

The next stage is the power flow analysis under normal operating conditions, which serves as the reference for evaluating the system's response to line outages. The Newton–Raphson method is adopted in this study because it offers fast convergence and reliable accuracy for medium- and large-scale systems. Based on the results of the initial power flow analysis, the *(N-1)* contingency scenarios are simulated by disconnecting one transmission line at a time. Each outage condition produces a new power flow solution, from which the Voltage Performance Index (VPI) is calculated. This index provides a quantitative measure of how severe the impact of each contingency is on bus voltages and overall system stability (Kahouli et al., 2021).

Since evaluating every possible contingency in large systems such as JAMALI can be computationally demanding, this research employs a GA-based approach to optimize the ranking process. The GA is selected because of its strong global search capability, robustness against local optima, and effectiveness in solving nonlinear optimization problems, which makes it particularly suitable for contingency ranking in complex power networks. The algorithm begins with encoding solutions in binary form, where each chromosome represents a potential ranking of contingencies. A population of chromosomes is generated randomly, and each individual is evaluated using the VPI as the fitness function. The GA then proceeds through a cycle of selection, crossover, and mutation to produce new candidate solutions while maintaining genetic diversity. Iterations continue until the maximum number of generations is reached or convergence criteria are satisfied, after which the best individual, representing the most accurate ranking, is selected (Yadav et al., 2023).

Finally, the performance of the proposed method is validated through two case studies. The IEEE 30-bus system is used as a benchmark to test the correctness of the algorithm, while the JAMALI 500 kV interconnection system provides a large-scale and practical test bed for demonstrating applicability to real networks. The effectiveness of the GA-based ranking is assessed not only by identifying the most critical line outages through VPI values, but also by calculating the capture ratio, which measures the agreement between the GA results and conventional ranking methods (Hemad et al., 2022). The overall stages of the proposed methodology are summarized in the flowchart shown in Figure 3, which provides a visual overview of the entire research process.

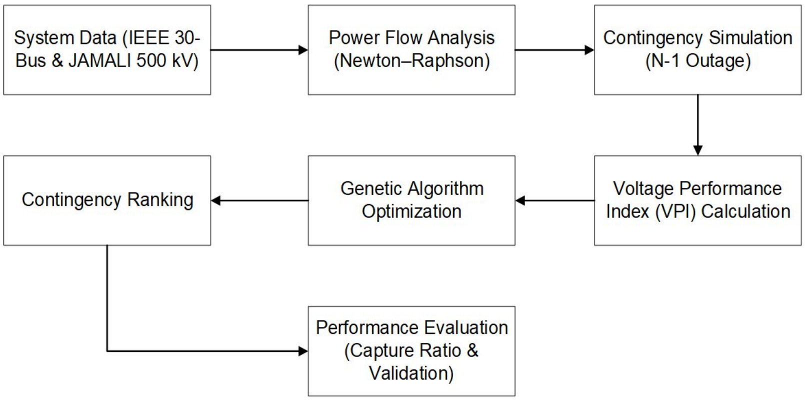

Figure 3 Flowchart of the proposed research methodology

The flowchart illustrates the overall framework of this research, starting from system data preparation to contingency simulation and optimization using the genetic algorithm. By combining conventional power flow analysis with a metaheuristic approach, the methodology ensures both accuracy and efficiency in identifying critical line outages (Ooka & Komamura, 2009). This comprehensive framework serves as the foundation for the results and discussions presented in the next section.

Result and Discussion

The proposed GA-based contingency ranking method was applied to two different networks: the IEEE 30-bus test system and the JAMALI 500 kV interconnection system. The results are presented in tables and followed by detailed discussion.

IEEE 30-Bus System

The first case study was performed on the IEEE 30-bus test system to validate the proposed GA-based contingency ranking method. Several simulations were conducted by varying the number of individuals and maximum generations to evaluate the effect of algorithm parameters on the accuracy of contingency identification.

The results consistently identified line 36 (connecting bus 28 and bus 27) as the most critical contingency in most configurations, yielding the highest Voltage Performance Index (VPI) value of 56.5915. This line emerged as the dominant outage scenario, indicating its significant impact on overall voltage stability. Other lines such as line 11 (bus 6–9) and line 29 (bus 21–22) appeared in subsequent rankings depending on the GA configuration, showing that parameter tuning can affect the order of less severe contingencies. Table 1 summarizes the top five ranked contingencies under different GA settings, while Figure 4 illustrates the trend of maximum VPI values obtained across all simulations. The figure shows that increasing the number of individuals and generations improves convergence and stability, reinforcing line 36 as the most critical outage in the IEEE 30-bus system.

Table 1 IEEE 30-Bus Power System Contingency Ranking Results

Simulation Setup	Line	From Bus	To Bus	Voltage IP	Ranking
41 ind., 50 gen.	37	27	29	56.5443	1
	38	27	30	56.5441	2
	34	25	26	56.5434	3
	33	24	25	56.5416	4
	39	29	30	56.5411	5
100 ind., 150 gen.	36	28	27	56.5915	1
	37	27	29	56.5443	2
	38	27	30	56.5441	3
	34	25	26	56.5434	4
	9	6	7	56.5430	5
200 ind., 200 gen.	36	28	27	56.5915	1
	11	6	9	56.5409	2
	29	21	22	56.5407	3
	32	23	24	56.5407	4
	20	14	15	56.5405	5

Table 1 presents the contingency ranking results for the IEEE 30-bus power system under three GA configurations. The results indicate that line 36 (bus 28–27) consistently emerges as the most critical outage when larger populations and generations are applied, yielding the highest Voltage Performance Index (56.5915). Other lines, such as line 37 (bus 27–29) and line 38 (bus 27–30), also appear frequently in the top ranks, but with slightly lower IP values. These findings highlight the robustness of the GA in identifying dominant contingencies across different parameter settings. To further illustrate the impact of GA parameter variation, the simulation results for the IEEE 30-bus system are visualized. The graph shows the highest Voltage Performance Index (VPI) obtained under different configurations of individuals and generations.

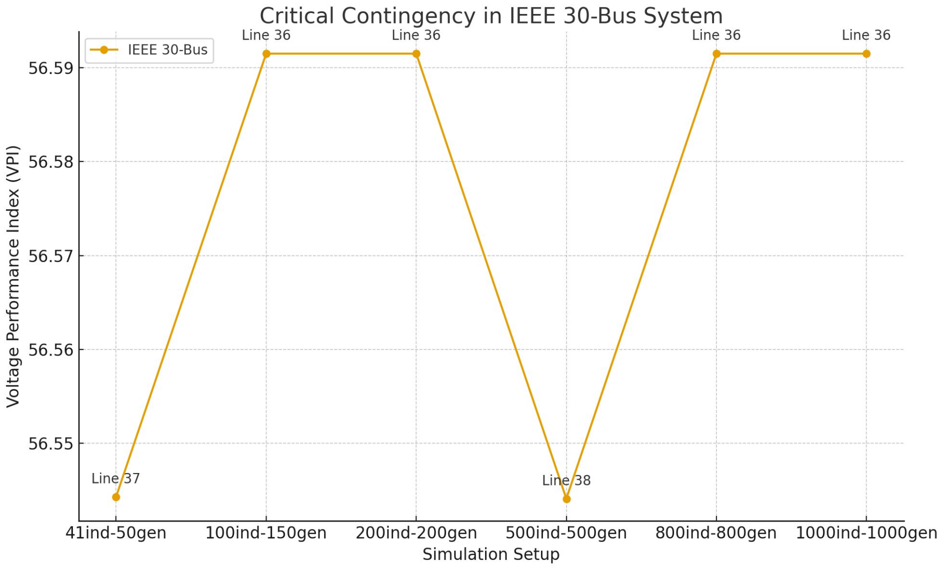

Figure 4 IEEE 30-bus Simulation Results

Figure 4 highlights that increasing the number of individuals and generations improves the stability of GA convergence. In all cases, line 36 (bus 28–27) consistently produced the highest VPI, confirming its role as the most critical contingency in the IEEE 30-bus network.

JAMALI 500 kV Power System

The second case study involved the JAMALI 500 kV interconnection, a large-scale practical system with 62 transmission lines. Similar to the IEEE test system, the GA-based approach was applied under six different simulation settings. The results show that line 35 (Bangil–Paiton) consistently ranked first in the majority of simulations, with the highest VPI value of 95.3947 recorded in the third simulation (300 individuals, 300 generations). This finding highlights the strategic importance of the Bangil–Paiton corridor, which serves as a backbone for power transfer across the JAMALI network.

Other lines, such as line 55 (Ampel–Ungaran) and line 34 (Kediri–Bangil), also appeared in high rankings with slightly lower VPI values, confirming their influence on system performance. A special case was observed when line 56 (Krian–Gresik) was disconnected, where the simulation yielded a NaN result because the system became islanded, preventing power flow calculations. This situation was resolved by isolating the affected buses for further analysis, which confirmed the severity of this outage scenario. Table 2 summarizes the contingency rankings across different the GA configurations, while Figure 5 illustrates the variation of results. The graphical representation clearly shows line 35 as the dominant contingency, with other lines clustering around lower VPI values.

Table 2 JAMALI 500 kV Power System Contingency Ranking Results

Simulation Setup	Line	From Bus	To Bus	Voltage IP	Ranking
62 genes, 100 ind., 150 gen.	35	26 (Bangil)	27 (Paiton)	95.3947	1
	55	45 (Ampel)	46 (Ungaran)	95.3902	2
	34	24 (Kediri)	25 (Bangil)	95.3899	3
	52	42 (Ungaran)	43 (Pedan)	95.3895	4
	33	23 (Grati)	24 (Kediri)	95.3891	5
62 genes, 200 ind., 200 gen.	35	26 (Bangil)	27 (Paiton)	95.3947	1
	55	45 (Ampel)	46 (Ungaran)	95.3901	2
	34	24 (Kediri)	25 (Bangil)	95.3899	3
	52	42 (Ungaran)	43 (Pedan)	95.3896	4
	33	23 (Grati)	24 (Kediri)	95.3890	5
62 genes, 300 ind., 300 gen.	35	26 (Bangil)	27 (Paiton)	95.3947	1
	55	45 (Ampel)	46 (Ungaran)	95.3903	2
	34	24 (Kediri)	25 (Bangil)	95.3900	3
	52	42 (Ungaran)	43 (Pedan)	95.3895	4
	33	23 (Grati)	24 (Kediri)	95.3892	5

Table 2 presents the contingency ranking results for the JAMALI 500 kV power system under different GA parameter settings. Across all configurations, line 35 (Bangil–Paiton) consistently emerged as the most critical contingency, producing the highest VPI value (95.3947). Other lines, such as Ampel–Ungaran (line 55) and Kediri–Bangil (line 34), also appeared frequently among the top five but with slightly lower VPI values. These findings confirm the dominant role of the Bangil–Paiton transmission corridor in maintaining the stability of the JAMALI backbone system. To complement the tabulated results, the performance of the GA in ranking contingencies for the JAMALI 500 kV system is also visualized. The graph highlights the highest VPI values obtained under different GA configurations.

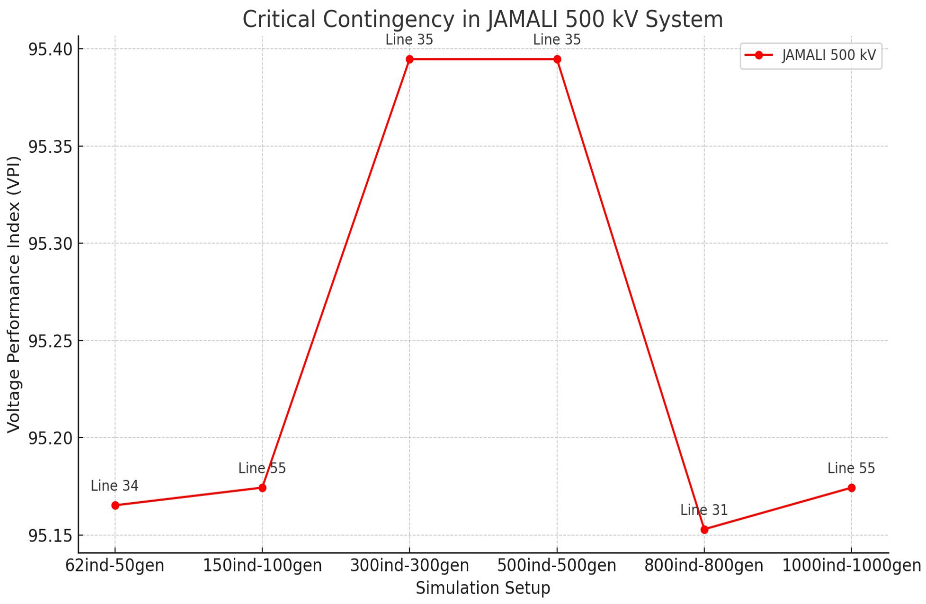

Figure 5 JAMALI 500 kV Simulation Results

Figure 5 confirms that line 35 (Bangil–Paiton) consistently produces the highest VPI across all parameter settings, reinforcing its role as the most critical transmission line in the JAMALI network. The figure also shows that other lines, such as Ampel–Ungaran and Kediri–Bangil, appear in close succession but never surpass line 35. This stability across simulations demonstrates the robustness of the GA in identifying dominant contingencies even in large-scale, complex systems.

Comparative Discussion

A comparative evaluation between the IEEE 30-bus benchmark system and the JAMALI 500 kV interconnection confirms the effectiveness of the GA method. In the IEEE system, the disconnection of line 36 was consistently ranked as the most critical contingency, while in the JAMALI system, line 35 (Bangil–Paiton) was identified as the most vulnerable. This consistency across different system scales highlights the robustness of the GA-based approach.

The results also indicate that increasing the GA parameters (population size and maximum generations) improves the reliability of the ranking process, although it increases computational effort. The use of the Voltage Performance Index as a fitness function proved effective in quantifying severity, with simulation results matching manual calculations in smaller test cases. Practically speaking, the findings suggest that maintenance and monitoring strategies should prioritize transmission corridors like Bangil–Paiton in the JAMALI system. By efficiently identifying weak points in both small and large networks, the GA method provides a reliable decision-support tool for system operators to enhance security and stability.

Conclusions

This study has demonstrated the application of the GA for contingency ranking in two different power system networks: the IEEE 30-bus test system and the JAMALI 500 kV interconnection system. For the IEEE 30-bus system, repeated simulations consistently identified line 36, which connects bus 28 and bus 27, as the most critical contingency. The disconnection of this line produces the highest Voltage Performance Index (VPI), highlighting its strong influence on system stability. In the case of the JAMALI 500 kV system, which represents a large and complex real-world network, the GA also successfully identified the most severe contingency. Line 35's outage, which connects bus 26 (Bangil) and bus 27 (Paiton), ranked as the most critical event. This finding underlines the importance of the Bangil–Paiton transmission corridor in maintaining the stability of the JAMALI backbone.

Overall, the results confirm that the GA method is effective for contingency ranking in both benchmark and large-scale systems. By implementing the algorithm in Octave software, this research provides a flexible and reliable tool for power system analysis. The proposed method not only reduces computational effort compared to exhaustive analysis but also delivers accurate results that can support operators in enhancing the security and reliability of transmission networks. Although the proposed approach has shown promising results, several directions remain open for future research. First, the application of other metaheuristic techniques, such as particle swarm optimization, ant colony optimization, or hybrid GA, could be explored to compare performance and efficiency in contingency ranking. Second, the study may be extended to consider *(N-2)* contingencies or multiple simultaneous outages, which represent more realistic but computationally challenging scenarios in large-scale systems. Finally, integration of the method into real-time decision support tools for system operators would be a valuable step toward practical implementation, enabling faster and more reliable responses to disturbances in modern power grids.

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