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Original Article

Multi-Objective Optimization Approach for Power Distribution Network Reconfiguration using Hybrid Particle Swarm and Genetic Algorithm

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Abstract *- Power distribution networks are a critical component of the electric power distribution system. Hence, numerous research has focus on distribution network reconfiguration systems, intending to minimize power losses and interruptions, namely, Customer Average Interruption Index (CAIDI), System Average Interruption Frequency Index (SAIFI), Energy Not Supplied (ENS), and Voltage Profile (VP) improvement, either by Genetic Algorithm (GA) or Particle Swarm Optimization (PSO). Nonetheless, existing research has not simultaneously employed a hybrid of GA and PSO optimization methods to ascertain which optimization method is better in terms of improving the reliability indices, such as CAIDI, SAIFI, and ENS, while minimizing power losses and improving the VP, thus leaving a gap in the literature. Hence, the proposed research work seeks to utilize the synergy of GA and PSO optimization techniques on the IEEE 33-bus and IEEE 69-bus systems with the aforementioned reliability targets to unearth which of the optimization techniques is better than the other. Meanwhile, the obtained results indicate that the GA exhibits a higher voltage level enhancement of 2.75% with a corresponding SAIFI reduction of 33%. Nonetheless, the PSO unveils superior or enhanced power loss reduction of 61.75%, ENS reduction of 48%, and CAIDI reduction of 30% with a corresponding computational speed of 0.24 seconds. Hence, based on the aforementioned analysis of the results, it can be concluded that the selection of the optimization algorithm depends on the network's specific operational requirements, as no single algorithm performs optimally across all parameter measurements. Besides, while the PSO performs excellently in terms of loss, ENS, and CAIDI reduction, the GA performs well in terms of voltage enhancement and SAIDI reduction.*

Keywords *- Distribution network, IEEE 33-bus reconfiguration, IEEE 69-bus reconfiguration, Multi-Objective, GA optimization, PSO optimization, Reliability Indices.*

1. Introduction

The Distribution Network Reconfiguration (DNR) is an engineering technique for opening and closing Distribution Network Switches (DNS) with the aim of a significant reduction of power losses, improving the voltage profile, and enhancing system reliability. Despite extensive research in the field of DNR, based on two basic optimization techniques, namely, the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), there is still a research gap in the current literature in that the GA and PSO have not been simultaneously compared head-to-head and analyzed based on the system reliability indices, namely, System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), Energy Not Supplied (ENS), Voltage Profile (VP), and system efficiency. To unveil which of the aforementioned optimization algorithms is cost-effective for system reliability on DNR.

Hence, this research aims to simultaneously model, analyze, and compare the GA and POS to address the aforementioned research gap. Furthermore, enhancing DNR reliability indices has been a key issue, as in past decades of research, it has not received much research attention [1].

Nonetheless, it is imperative to emphasize that extensive research on DNR in [2] considered both GA and PSO optimization techniques; the design objective functions were limited to Power Loss (PL) and ENS during the network phase reconfiguration, and also, only the IEEE 33-bus configuration was considered, leaving other equally imperative reliability indices. Hence, this proposed research aims to consider PS and ENS, not excluding CAIDI, SAIFI, efficiency, IEEE 33-bus and 66-bus reconfigurations, and also establish which of the optimization techniques, namely, GA and PSO, presents the optimal optimization technique over the other.

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Meanwhile, DNR no doubt continues to lead as a good or effective solution for operational losses reduction in the Power Distribution Grid (PDG); nonetheless, existing literature tends to depict that the key metaheuristics on DNR are GA, PSO, Simulated Annealing (SA), etc., with the objective functions being limited to PS reduction and voltage profile enhancement, with an improved load profile being widely researched on DNR to unearth an advanced optimization technique to be utilized on DNR optimization and initiate further improvement by scholars and researchers in the DNR field [3]. Moreover, when these metaheuristics are separately analyzed, it becomes difficult to fairly conclude that one metaheuristic is better than the other.

To maximize the electrical distribution network efficiency, a reconfiguration method was utilized to optimize the reliability indices, meanwhile, the GA has been established for effectively on hand for solving or improving optimal problems in DNR, besides, the power network losses, which are key contributors to efficiency reduction and as a demerit can be classified into two distinct groups, namely, reactive power network power losses owing to the reactive component of the network, and the real power network power losses due to the resistance of the network [4]. Moreover, the GA optimization technique was presented for solving the problem of improving voltage stability, while the Binary PSO optimization (BPSO) technique was utilized in solving the problem of power loss reduction and load balancing in DNR [5-7]. Nevertheless, it is important to note that, from an optimization point of view, it is neither fair nor objective to conclude that one technique is superior when it has not been compared with other optimization techniques. Hence, this proposed research aims to address this gap.

Recently, the electrical power system has become instrumental in the energy generation or electricity production markets, where any disruption or system failure to conform to normal established system functions of a standard Distribution Network (DN) will lead to significant economical and social cost, to avert this situation from occurring in a radially design network, the reconfiguration technique of the system network configuration is implemented by incorporating extra design switches, moreover, numerous research focusing on key multi-objective design parameters optimization technique have mitigated the reconfiguration in term of Radially Design Distribution Network (RDN) since, it first publication was presented in the scientific research field with the aim of loss reduction in the power distribution system [8, 9].

Meanwhile, the PSO technique has been utilized in [10] to solve optimization issues, and the unveiled results depict that the synergy of demand response programming and distribution network configuration in energy management in microgrid networks demonstrated optimal supply via the distribution system side and the load system side. Furthermore, the PSO algorithm has been widely utilized in some design applications in metaheuristic optimization and has been identified as a successful implementation, especially in optimal power flow systems such as an alternating current transmission system [11].

Nonetheless, a multi-objective model was proposed in [12] to simultaneously analyze network reconfiguration of the distribution feeder and power dispatch in a distributed generation system to solve optimization issues by ensuring power loss reduction, operational cost, and voltage stability; besides these objective functions, extensive studies were conducted in 33-bus and 25-bus systems.

Meanwhile, in [13], radial distribution network system reconfiguration is imperative or critical for adjusting the flow of power via the system network. Besides, the research presented a unique technique for analyzing the configuration of distribution network issues, with the key aim of reducing real (true) power losses and enhancing the voltage profile simultaneously via PSO on IEEE bus test systems, namely, 33-bus and 69-bus configurations. Although the obtained results depict voltage profile enhancement and true power loss reduction, they did not address the current research gap of using PSO and GA optimization techniques simultaneously on the IEEE 33-bus and IEEE 69-bus systems to determine which optimization technique outperforms the other in terms of key performance indicators.

Furthermore, PSO has been effectively and extensively utilized in [14, 15] to show that it is effective in minimizing useful power losses with a corresponding enhancement in voltage profile on selected IEEE bus system configurations such as IEEE 33-bus and IEEE 69-bus. Moreover, an extensive review in [16] depicts that GA is efficient when utilized in distribution network system reconfiguration in terms of power loss reduction, with a corresponding enhanced convergence and higher accuracy design performance.

Meanwhile, the reliability of the power system can be defined as the capacity of the power system network to continuously operate to satisfy the electricity expectations of the customer based on the quantity or the demand of the supply and the quality of the supply, and is validated by reliability indices such as SAIFI, ENS, CID, SAIDI, Customer Durations (CIDs), which are key in DN operational analysis and planning issues [17-24].

However, from the extensive aforementioned review and analysis of Radial Distribution Network Reconfiguration (RDNR) with gap identification in the literature, which currently depicts that the synergy of PSO and GA algorithms have not been simultaneously analyze to unveil which of the optimization techniques is best in analyzing the power system reliability in term of SAIFI, CAIDI, ENS, while minimizing power losses, voltage deviation, system efficiency and not excluding system convergence on IEEE 33-bus and IEEE 69-

bus systems, this proposed research aim to model, optimized and analyzed the IEEE 33-bus and IEEE 69-buss using PSO and GA simultaneously to addressed this identified research gap.

Firstly, the novelty of the proposed design analysis of the DNR system using PSO and GA optimization techniques under the same optimization constraints and conditions is its ability to determine which of the aforementioned optimization techniques is best for the DNR system and to serve as a design benchmark for performance evaluation in terms of replication or future research work on hybrid (synergy) optimization of DNR, hence addressing the identified research gap reported in this paper.

Secondly, the proposed design extensively covered some key design data or components, namely, power loss reduction, voltage enhancement, optimization convergence speed, reduction of reliability indices, and design computational time, which are key in DNR to ensure a reliable power supply system. Thirdly, the synergy optimization methods using PSO and GA considered in this research for DNR address the uncertainty of which optimization technique, between PSO and GA, is best for optimizing power loss reduction, voltage profile enhancement, and reliability index reduction in the DNR research field.

2. Materials and Methods

The modelling of the RDNR for the IEEE 33-bus and IEEE 39-bus systems was analyzed in MATLAB using a hybrid optimization technique, namely, PSO and GA algorithms. Meanwhile, the multi-objective functions considered are SAIFI, CAIDI, ENS, Power Loss (PS) reduction, voltage deviations, and system efficiency.

Meanwhile, Figure 1 depicts the single-line design diagram of the IEEE 33-bus radial power distribution system, while Table 1 presents the base case performance values under or during the initial operating (configuration) condition, thus, when all operating switches are opened to buttress the analysis.

Moreover, Figure 2 illustrates the 69-bus configuration system, while Table 2 presents the detailed base case values during the initial reconfiguration condition, thus, when all operating switches are opened to buttress the analysis of the 69-bus configuration system. Furthermore, the test parameter comparison of both 33-bus and 69-bus configuration systems has been illustrated in Table 3 to intuitively enhance the analysis of both topologies. Moreover, the optimization flow charts of the GA and PSO are illustrated in Figures 3 and 4, respectively, to buttress the optimization analysis.

Table 1. Performance base case values for the IEEE 33-bus design

Parameter specifications	Value
Total active power loss	202.67 kW
Minimum bus voltage	0.9338 p.u
Energy Not Supplied (ENS)	51.53 kWh/year
System Average Interruption Frequency Index (SAIFI)	2.5966 interruptions/customer/year
Customer Average Interruption Duration Index (CAIDI)	5.5851 hours/interruption

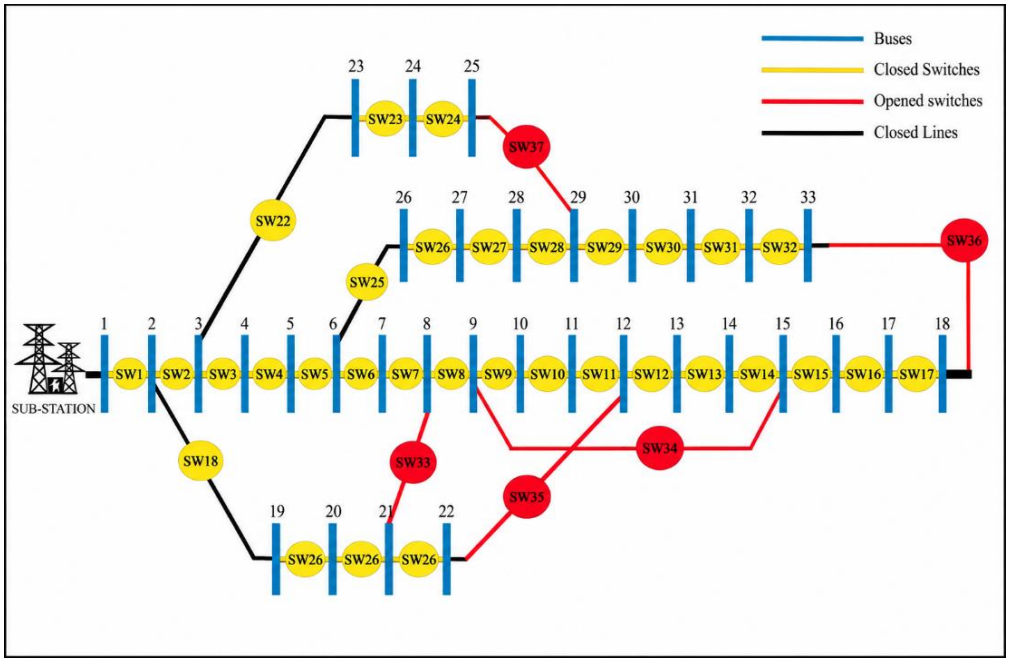


Fig. 1 Single-line diagram of IEEE 33-bus radial distribution system reconfiguration

Table 2. Performance base case values for the IEEE 69-bus design

Parameter Specification	Value
Total active power loss	224.98 kW
Minimum bus voltage	0.9078 p.u
Energy Not Supplied (ENS)	462.30 kWh/year
System Average Interruption Frequency Index (SAIFI)	2.7654 interruptions/customer/year
Customer Average Interruption Duration Index (CAIDI)	4.6791 hours/interruption

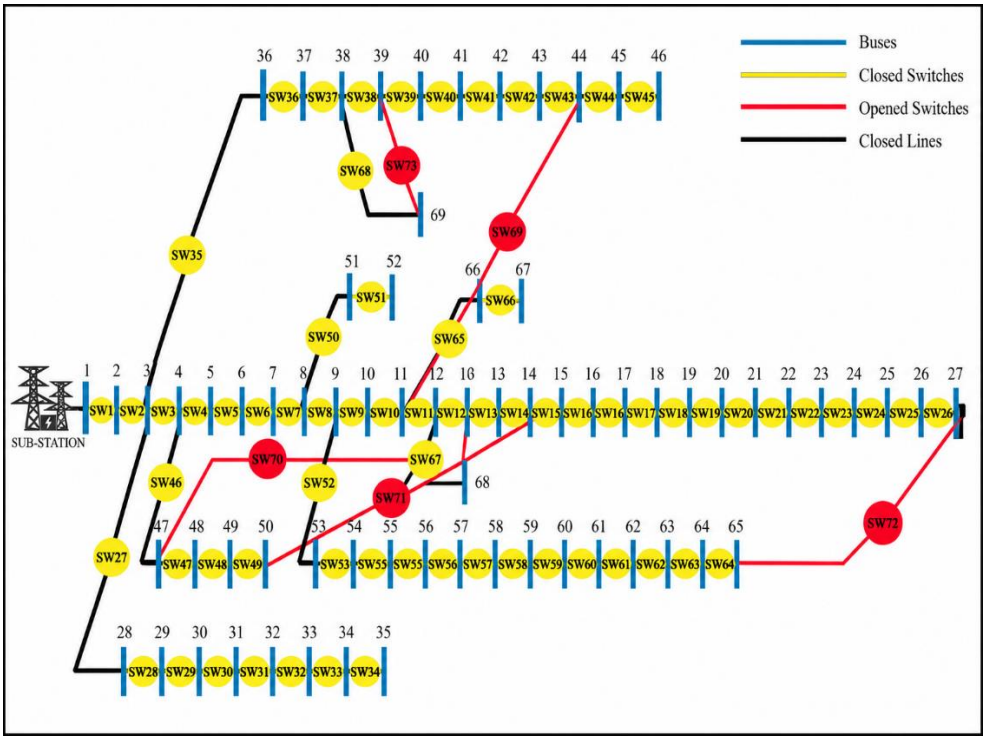


Fig. 2 Single-line diagram of IEEE 69-bus radial distribution system reconfiguration

Table 3. Test parameter comparison of both the 33-bus and 69-bus configuration systems

Parameter specifications	IEEE 33-bus system	IEEE 69-bus system
Number of buses	33	69
Number of branches	37	73
Sectionalizing switches	32	68
Tie switches	5	5
Base voltage	12.66 kV	12.66 kV
Total active load	3,715 Kw	3,802.19 kW
Total reactive load	2,300 kVAR	2,694.60 kVAR
Initial power loss	202.67 kW	224.98 kW
Initial minimum voltage	0.9338 p.u.	0.9078 p.u.
Initial ENS	51.53 kWh/year	462.30 kWh/year
Initial SAIFI	2.5966 int/cus/year	2.7654 int/cust/year
Initial CAIDI	5.5851 hrs/int	4.6791 hrs/int

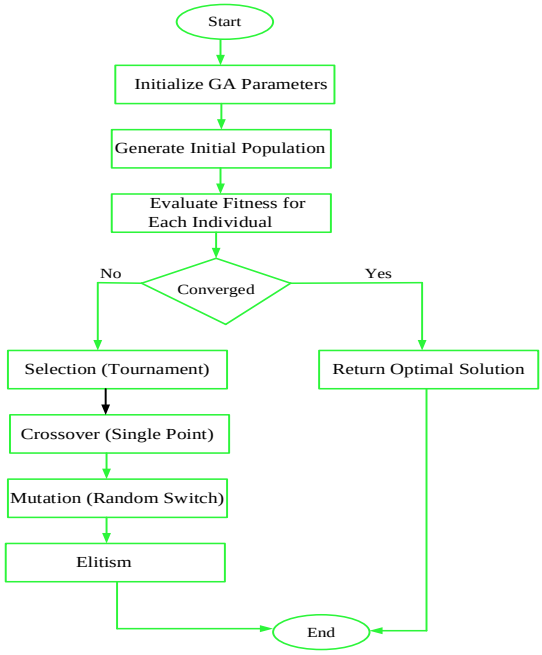


Fig. 3 Genetic algorithm optimization flow chart

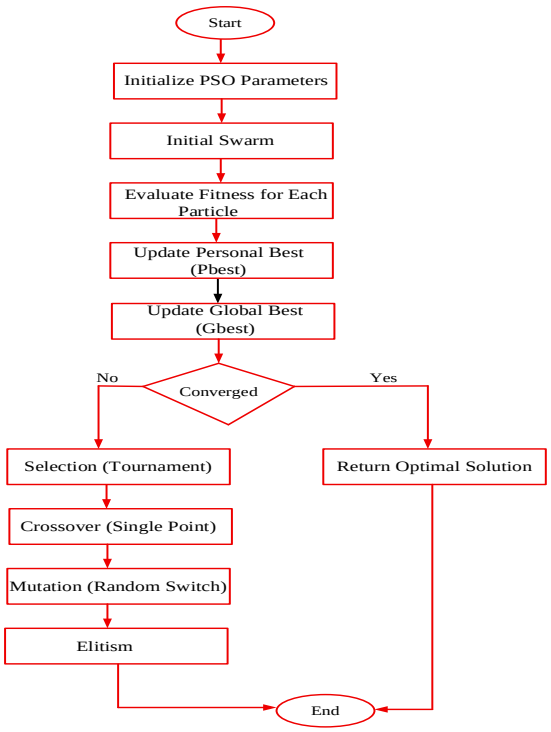


Fig. 4 Particle swarm optimization flow chart

3. Results and Discussion

Table 4 depicts the performance analysis of GA and PSO in the 33-bus system. The GA has its best open switches, S1, S15, S22, S24, and S37, with a computational system convergence time of 0.5 seconds. The GA effectively unveils a power loss reduction of 49.43% with a voltage improvement of 2.65% at the minimum bus. Moreover, the CAIDI exhibits a reduction of 24.71%, SAIFI reduces by 32.95%, and ENS reduction of 41.19%. Hence, minimizing the frequency and duration of system outages. Furthermore, with the best open switches S12, S18, S19, S20, and S25 and with a computational system convergence time of 0.24 seconds, the PSO demonstrated excellent performance in power loss reduction of 61.75%, with a corresponding voltage increase of 1.51%, although the system voltage is less than that exhibited by the GA, it still falls within the acceptable operating limit. Nonetheless, the PSO unearths a CAIDI reduction of 30.59%, SAIFI reduction of 26.22%, and ENS reduction of 48.08%. Hence, from the aforementioned analysis, the PSO demonstrates its capability of enhancing the system reliability by outperforming the GA in terms of reduction in ENS and CAIDI.

Meanwhile, Table 5 presents the performance analysis of GA and PSO in the 69-bus system. The GA, with the key opened, switches S1, S33, S48, and S73, and a corresponding computational system convergence time of 0.48 seconds, shows a power loss reduction of 49.91%. Besides, this performance reduction demonstrated that the GA is applicable to larger network configurations and is in line with or in agreement with the 33-bus system results. Moreover, a minimum voltage increase of 2.75% was observed. Nonetheless, the ENS exhibited a reduction of 41.59%, the SAIFI demonstrated a reduction of 33.27%, and a CAIDI reduction of 24.95%. Hence, demonstrating a significant reliability gain. Furthermore, with key or best-opened switches S22, SS33, 34, S35, and S51, and with a computational system convergence time of 0.24 seconds, the PSO unveiled a 61.75% power loss reduction, which matches or is in agreement with the 33-bus system's performance. Hence, the unveiled consistency demonstrates that the PSO maintains its cost-effectiveness across distinct distribution network capacities. Meanwhile, the minimum voltage improvement obtained was 1.75%, while this voltage is lower compared to the GA voltage improvement, it remains within the acceptable or allowable limits. Besides, the reduction of ENS is 47.19%, with a SAIFI reduction of 25.74%, and a corresponding CAIDI reduction of 30.03%, hence demonstrating the cost-effectiveness of the PSO in improving reliability of the system in large distribution network configurations.

Table 4. Algorithm design comparison of GA and PSO on the IEEE 33-bus System

Parameter specifications	GA	PSO	Superior Algorithm
Power Loss Reduction (%)	49.43	61.75	PSO
Voltage Improvement (%)	2.65	1.51	GA
ENS Reduction (%)	41.19	48.08	PSO
SAIFI Reduction (%)	32.95	26.22	GA
CAIDI Reduction (%)	24.71	30.59	PSO
Computation Time (Seconds)	0.51	0.24	PSO
Convergence Speed	Gen 51	Iter 47	PSO

Table 5. Algorithm design comparison of GA and PSO on the IEEE 69-bus System

Parameter specification	GA	PSO	Superior Algorithm
Power Loss Reduction (%)	49.91	61.75	PSO
Voltage Improvement (%)	2.75	1.75	GA
ENS Reduction (%)	41.59	47.19	PSO
SAIFI Reduction (%)	33.27	25.74	GA
CAIDI Reduction (%)	24.95	30.03	PSO
Computation Time (Seconds)	0.48	0.24	PSO
Convergence Speed	Gen 78	Iter 72	PSO

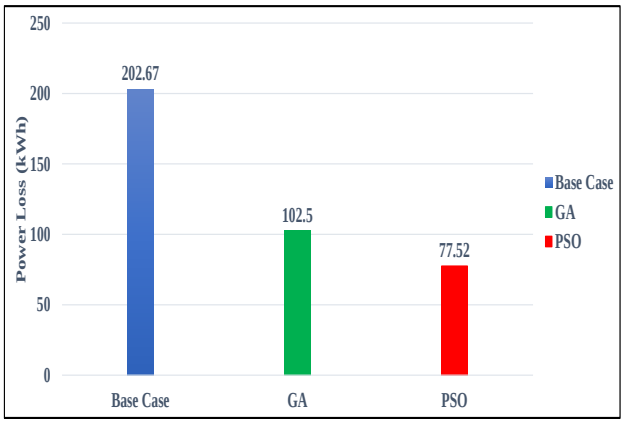


Fig. 5 Power loss analysis for both GA and PSO on the IEEE 33-bus system configuration

Furthermore, the performance analysis graph of the IEEE 33-bus configuration of the base case and the optimal system configuration unveiled via GA and PSO is illustrated in Figure 5. Besides, with the initial five-tie distinct switches, namely, 33,34,35,36, and 37, opened, the system unearthed an active power loss of 202.67 kW, due to the restriction of power flow redistribution, resulting in certain feeders overloaded and others underutilized, hence, resulting in a significant power loss and waste of energy owing to I^2 R losses on the loaded branch sides.

Moreover, after utilizing the GA with the corresponding switches such as 1, 15, 22, 24, and 37, the power losses were reduced to 102.50kW, depicting a reduction of 49.43%. Nonetheless, with the PSO using optimally selected open switches such as 12, 18, 19, 20, and 25, the power loss was reduced to 77.52, representing a 61.75% reduction and a 12.32% improvement over the GA. However, it can be established from the aforementioned analysis that the PSO is more cost-effective in terms of power loss minimization or reduction compared to the GA. Moreover, the active power losses can be derived or computed via Equation (1).

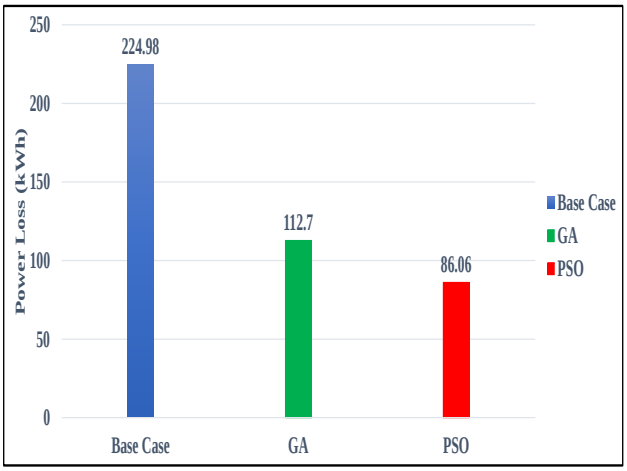


Fig. 6 Power loss analysis for both GA and PSO on the IEEE 69-bus system configuration

Moreover, Figure 6 presents the power loss analysis for the IEEE 69-bus system configuration using both GA and PSO techniques. Besides, the five distinct selected switches, namely 69, 70, 72, and 73, opened, resulted in an increase in power loss of 224.98 kW compared to that of the IEEE 33-bus configuration system. Meanwhile. The employment of the GA with the selected open switches, such as 1, 33, 41, 48, and 73, unveiled a power loss reduction of 112.70kW, representing 49.91% and depicting an enhancement in GA. Moreover, after the introduction of PSO with selected switches, namely 22, 33, 35, and 51, the power loss was reduced to 86.06kW, unveiling a reduction of 61.75%. Hence, it can be observed that the results obtained by the PSO in the IEEE 33-bus system are the same as the PSO power loss reduction in the IEEE 69-bus system, hence demonstrating the reliable performance of the PSO in various design networks. Meanwhile, the PSO exhibits superior performance over GA in terms of power loss reduction, which is in agreement with or consistent with the IEEE 33-bus system analysis.

Besides, to intuitively buttress the aforementioned analysis, Figure 7 illustrates the percentage power loss reductions for both GA and PSO in both IEEE 33-bus and IEEE 69-bus configuration systems.

$$P_{loss} = \sum_{i=1}^{nb} r_i \frac{P_i^2 + Q_i^2}{V_i^2} \quad (1)$$

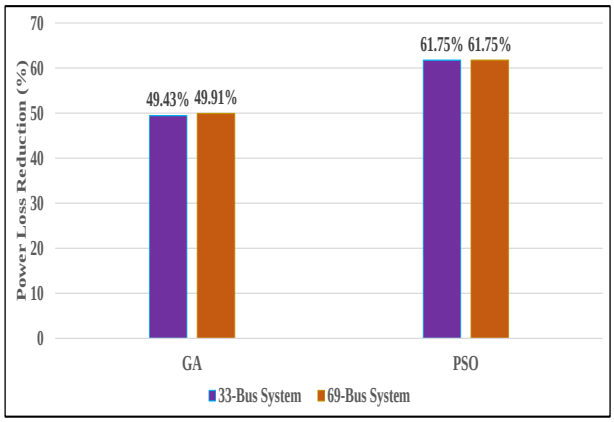


Fig. 7 The synergy analysis of both GA and PSO optimization for both IEEE 33-bus and IEEE 69-bus

The voltage profile analysis graph of the IEEE 33-bus configuration system involving both GA and PSO is illustrated in Figure 8. Besides, with open switches 33, 34, 35, and 37, the minimum level of voltage recorded at bus 18 is 0.9338 p.u., which is below the required or allowable minimum voltage level of 0.95 p.u., depicting 1.71% below the acceptable voltage limit. Furthermore, after the introduction

of GA with the selected open switches 1, 15, 22, 24, and 37, the obtained voltage increased to 0.9585 p.u., exceeding the acceptable voltage limit of 0.95 p.u., representing a 0.89% enhancement in voltage level. Nonetheless, when switch 37 is deliberately closed, the GA can regulate the load distribution via the flow of power away from the loaded system feeders by restoring the voltage at bus 18 to exceed 0.95 p.u and meeting the conventional power quality. Meanwhile, analysis of the PSO with optimally opened switches 12, 18, 19, 20, and 25, the voltage level maximized to 0.9479 p.u. with reference to bus 18, representing a 1.5% enhancement, which is approximately equal to the requirement of 0.95 p.u. Minimum voltage limit.

Also, the graph analysis for the voltage profile of the IEEE 69-bus configuration system incorporating both GA and PSO techniques is illustrated in Figure 9. Besides, the selected five distinct open switches 69, 70, 71, 72, and 73 are considered. Meanwhile, at bus 69, the minimum voltage level is 0.9078 p.u., which is approximately equal to 0.91 p.u., which is significantly lower and a threat or critical to the system. Nonetheless, this significant voltage drop may be due to the long feeder lengths, which lead to high current injection. Furthermore, with the implementation of GA with open switches 1, 33, 41, 48, and 73, the voltage level rose to 0.9328 p.u., representing 2.75% enhancement. Although it is more than 0.91 p.u., it still does not meet the minimum voltage level of 0.95 p.u. Nonetheless, after the implementation of the PSO with its optimal switches 22, 33, 34, 35, and 51, the voltage level rose to 0.9237 p.u., depicting a 1.75% enhancement, which is lower than the GA results. Hence, the PSO increased the voltage level above 0.91 p.u., depicting a slight safety margin compared to GA. Nevertheless, the voltage profile analysis can be computed in Equation (2). Moreover, to ensure an intuitive analysis, the percentage improvement of the synergy of GA and PSO optimization on both the IEEE 33-bus and IEEE 69-bus configuration systems on the voltage profile is presented in Figure 10.

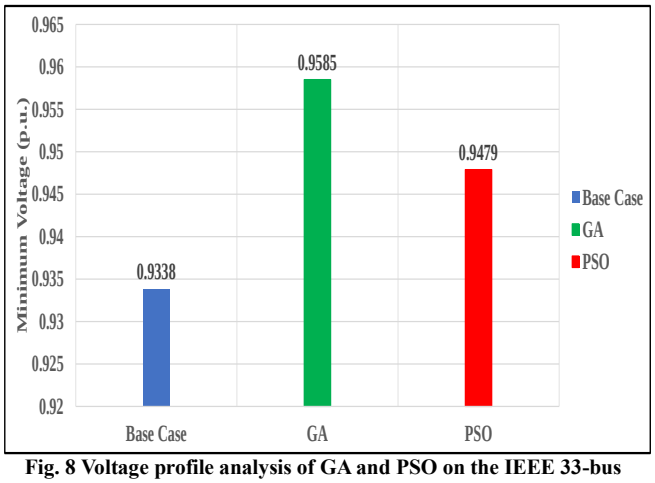


Fig. 8 Voltage profile analysis of GA and PSO on the IEEE 33-bus system

$$V_D = \sum_{i=1}^{nb} \frac{V_b - V_i}{V_b} \quad (2)$$

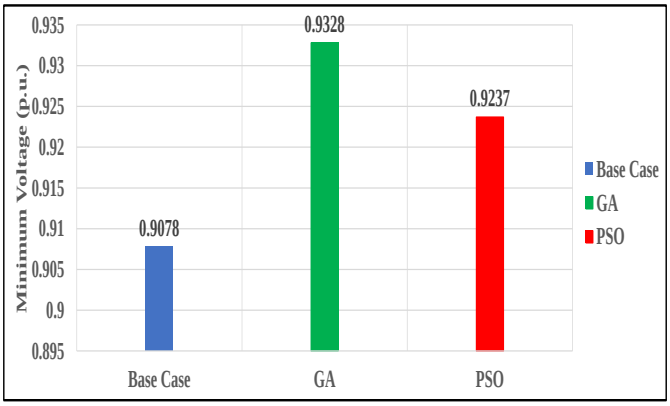


Fig. 9 Voltage profile analysis of GA and PSO on the IEEE 69-bus system

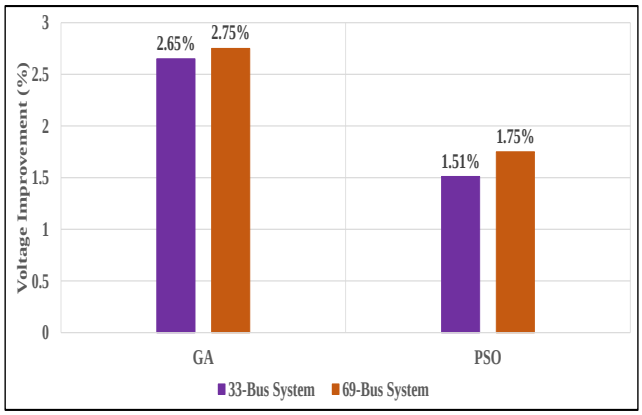


Fig. 10 Synergy analysis of both GA and PSO optimization on both IEEE 33-bus and IEEE 69-bus configuration systems on the voltage profile

Moreover, the ENS analysis of both GA and PSO techniques on the IEEE 33-bus is shown in Figure 11. Besides, the initially obtained ENS is 51.53 kWh/year. Nonetheless, this Energy Not Supplied (ENS) is due to the radially configured system not having an alternative supply path, with corresponding sustained customer outages due to faults. Meanwhile, with the implementation of GA optimization techniques, the ENS was reduced to 30.31 kW/year, depicting a reduction of 41.19% in the customer system outages. Nevertheless, after bringing the PSO optimization technique on board, the ENS was reduced to 26.76 kW/year, representing a 48.08% outage reduction. Besides, the superior or enhanced reduction in ENS of 48.08% compared to GA of 41.19% depicts reliability improvement with robust network configuration in terms of connectivity.

Nevertheless, ENS analysis of both GA and PSO methodologies on the IEEE 69-bus is illustrated in Figure 12. Besides, the base case system analysis unveiled an ENS of 462.30 kWh/year, which is significantly higher owing to the longer length of network reconfiguration with frequent or

more customer system outages. Also, applying the GA optimization method reduced the ENS to 270.03 kWh/year, unveiling a 41.59% reduction. Meanwhile, the PSO optimization method unearthed an ENS of 244.15kWh/year, corresponding to a reduction of 47.19%. Moreover, the pattern of optimization analyzed in the IEEE 33-bus with the PSO, unveiling a higher reduction, agrees with that of the IEEE 69-bus, depicting superior or higher performance of PSO. Besides, to buttress the analysis, the ENS reduction of 218.15kWh/year compared to the reference value in the IEEE 69-bus system for PSO is significant or higher than 244.15kWh/year compared to the reference value in the IEEE 33-bus system configuration, demonstrating its greater influence in large network reconfiguration. Hence, the network reconfiguration has a significant influence on the reliability of large or long networks. Nonetheless, the PSO consistency demonstrated an enhanced ENS reduction on both the IEEE 33-bus and 69-bus system configurations. Besides, the ENS estimation or computation can be expressed in Equation (3). Nonetheless, the ENS percentage reduction synergy analysis of both GA and PSO optimization on both IEEE 33-bus and IEEE 69-bus configurations is illustrated in Figure 13 to buttress the aforementioned analysis.

$$ENS = \sum_{i=1}^{nb} L_i^{avr} U_i \quad (3)$$

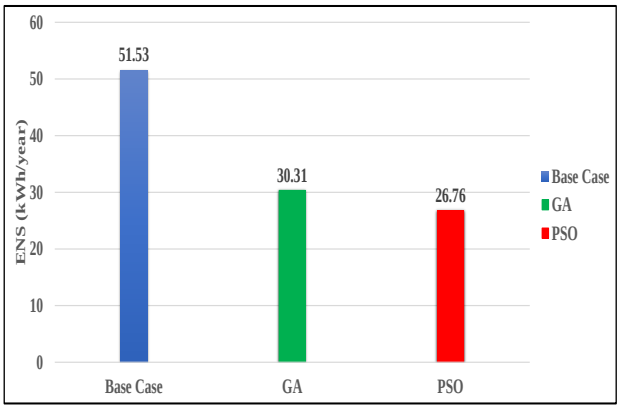


Fig. 11 ENS analysis of GA and PSO on IEEE 33-bus system configuration

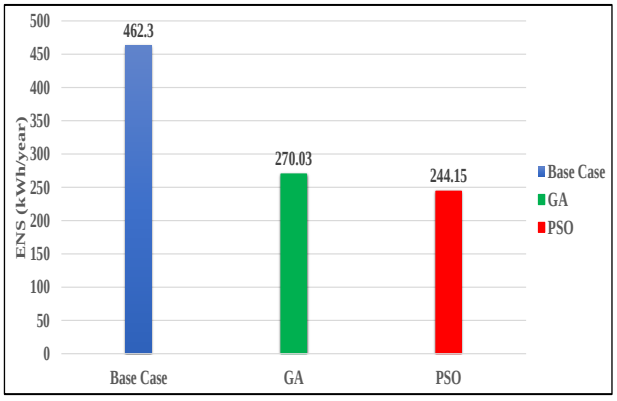


Fig. 12 ENS analysis of GA and PSO on IEEE 69-bus system configuration

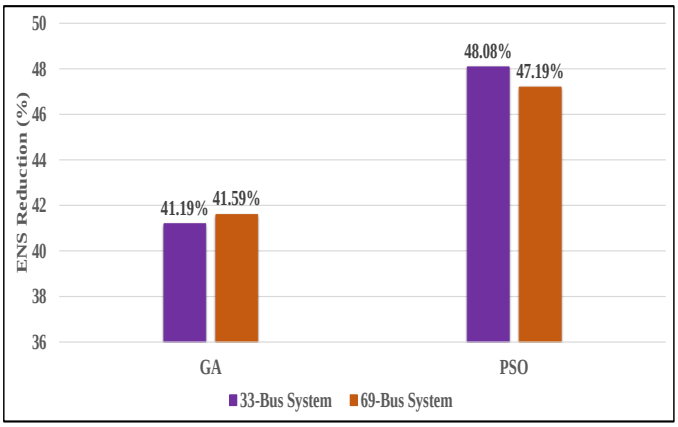


Fig. 13 ENS synergy analysis of both GA and PSO optimization on both IEEE 33-bus and IEEE 69-bus configuration systems

Furthermore, the base or initial SAIFI measured when analyzing GA and PSO on the IEEE 33-bus configuration system is 2.5966, depicting the average number of interruptions experienced by the involved customer per annum, as illustrated in Figure 14. Meanwhile, the SAIFI, when analyzed after GA optimization, was reduced to 1.7410, representing a reduction of 32.95%. Nonetheless, the SAIFI, when analyzed after PSO optimization, unveiled a reduction of 1.9157, representing a 26.22% interruption reduction. Nonetheless, the GA exhibits an enhanced reduction in interruption compared to the PSO optimization technique.

Moreover, the analysis of GA and PSO optimization methods on the IEEE 69-bus with an initial SAIFI of 2.7654, which is slightly higher compared to that of the IEEE 33-bus, is shown in Figure 15. Besides, after the introduction of GA optimization, unveil a reduced SAIFI of 1.8453, depicting a reduction of 33.27%. Meanwhile, the SAIFI reduced to 2.0536, indicating a reduction of 25.74% after the introduction of the PSO optimization method. Nevertheless, the GA depicts a consistent pattern by exhibiting higher SAIFI reduction compared to the PSO in both the IEEE 33-bus and IEEE 69-bus configuration systems. Nonetheless, the SAIFI can be analyzed using Equation (4).

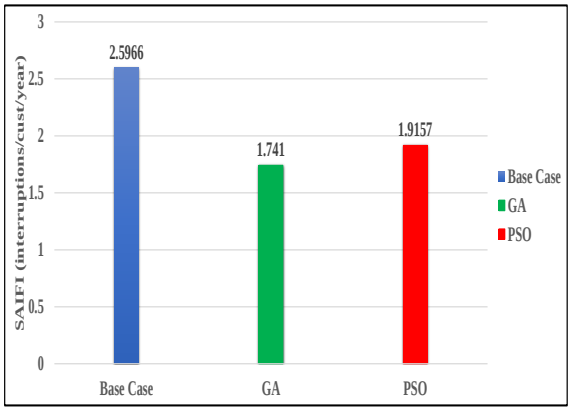


Fig. 14 SAIFI analysis of both GA and PSO on the IEEE 33-bus configuration system

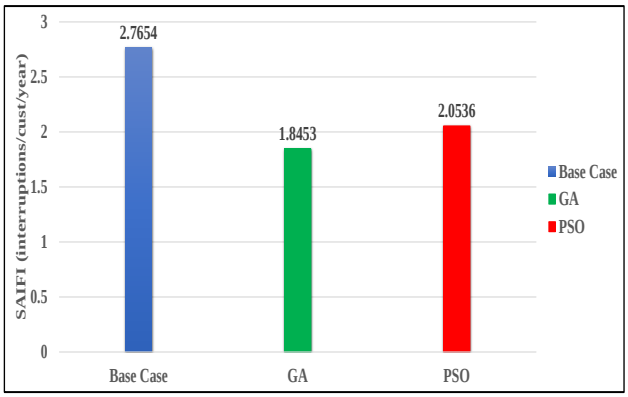


Fig. 15 SAIFI analysis of both GA and PSO on IEEE 69-bus configuration system

$$SAIFI = \frac{\sum ACIFI_i \times C_i}{\sum C_i} \quad (4)$$

Furthermore, CAIDI analysis of GA and PSO optimization with an initial CAIDI value of 5.5851 interruptions per hour on the IEEE 33-bus configuration system is illustrated in Figure 16. Meanwhile, the CAIDI unveiled after the analysis of GA optimization was reduced to 4.2048, depicting a 24.71% interruption reduction. Nonetheless, after the PSO optimization analysis, the unearthed CAIDI was reduced to 3.8764, representing a 30.59% reduction in hours per interruption, which demonstrates better performance compared to the GA method of optimization.

Meanwhile, analysis of GA and PSO optimization on the IEEE 69-bus system with a base or initial CAIDI value of 4.6791 is shown in Figure 17. Besides, after the introduction of the GA optimization technique, the CAIDI was reduced to 3.5115 hours per interruption, depicting a reduction of 24.95%. Moreover, after the analysis of the PSO optimization method, the obtained CAIDI was reduced to 3.2740, depicting a 30.03% reduction, which demonstrates that the PSO is superior to or outperforms the GA optimization method. Moreover, the computational analysis can be established via Equation (5).

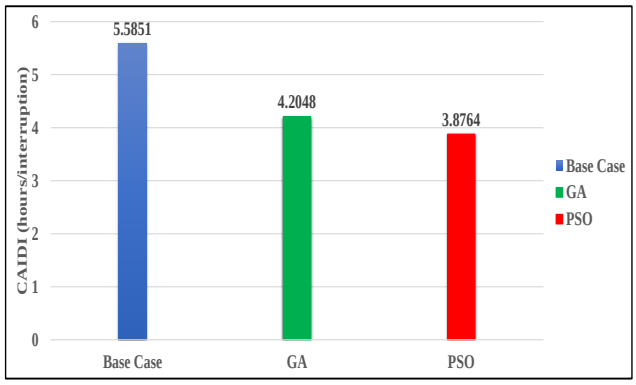


Fig. 16 CAIDI analysis of GA and PSO optimization on the IEEE 33-bus configuration system

$$CAIDI = \frac{SAIDI}{SAIFI} \quad (5)$$

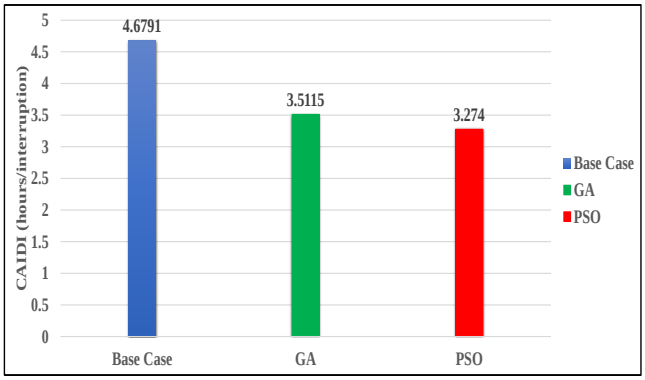


Fig. 17 CAIDI analysis of GA and PSO optimization on the IEEE 69-bus configuration system

Furthermore, the reliability enhancement analysis in terms of SAIFI and CAIDI reduction of both GA and PSO optimization on both IEEE 33-bus and IEEE 69-bus configuration systems is illustrated in Figure 18. Meanwhile, the GA consistently demonstrated better performance compared to the PSO optimization method in terms of SAIFI reduction. Moreover, PSO exhibits a reduced SAIFI of 26.22% and 25.74%, respectively, in IEEE 33-bus and IEEE 69-bus, while the GA optimization technique depicts a reduced SAIFI of 32.95% and 33.27%, respectively, on IEEE 33-bus and IEEE 69-bus. Hence, indicating better performance of GA compared to the PSO technique. Nonetheless, in the CAIDI reduction analysis, the PSO demonstrated consistently better performance compared to the GA optimization in both the IEEE 33-bus and the IEEE 69-bus. Thus, GA optimization unveiled a reduction of 24.71% and 24.95%, respectively, while the PSO unearthing a reduction of 30.59% and 30.03% in the IEEE 33-bus and IEEE 69-bus, respectively. Hence, exhibiting the merit of PSO, and indicating faster service or system restoration owing to its CAIDI reduction capacity.

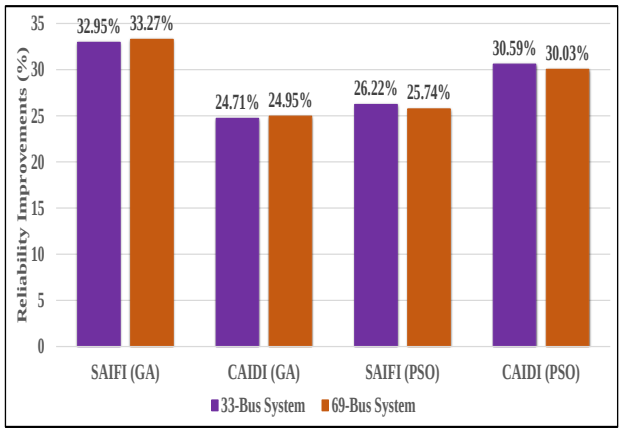


Fig. 18 Reliability improvement analysis of SAIFI and CAIDI on both IEEE 33-bus and IEEE 69-bus configuration systems

Moreover, the convergence analysis of the GA and PSO optimization methods on the IEEE 33-bus configuration system is presented in the graph depicted in Figure 19. Meanwhile, the convergence of the GA optimization technique was obtained at iteration 51, while the PSO optimization method converges quickly at iteration 47, hence indicating superior convergence compared to the GA optimization method. Nonetheless, Figure 20 depicts the convergence analysis graph of GA and PSO optimization techniques on the IEEE 69-bus configuration system.

Besides, the optimization pattern depicted on the IEEE 33-bus is repeated on the IEEE 69-bus system, in that the PSO optimization technique converges more quickly compared to the GA optimization technique. Thus, the GA optimization method converges at iteration 78, while the PSO obtains the ideal system solution at iteration 72, demonstrating the computational efficiency merit of the PSO implementation across various design networks compared to the GA optimization technique.

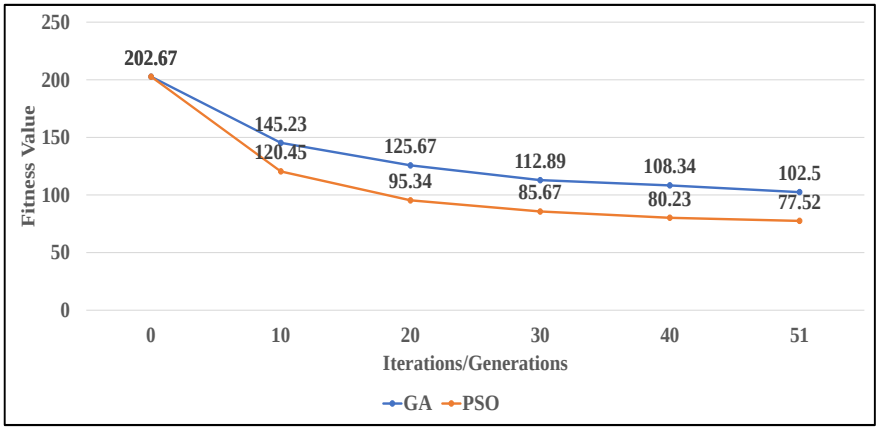


Fig. 19 Convergence analysis graph for GA and PSO on the IEEE 33-bus configuration system

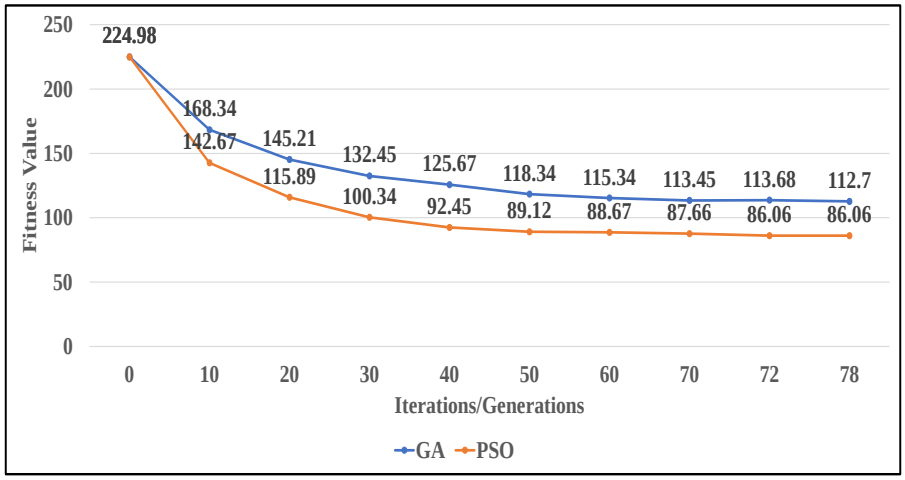


Fig. 20 Convergence analysis graph for GA and PSO on the IEEE 69-bus configuration system

5. Conclusion

The multi-objective distribution network using IEEE 33-bus and IEEE 69-bus configuration systems utilizing the synergy of Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) was effectively and extensively developed, analyzed, and compared in this research work. Meanwhile, the obtained results indicate that the GA exhibits a higher voltage level enhancement of 2.75% with a corresponding SAIFI reduction of 33%. Nonetheless, the PSO unveils superior or enhanced power loss reduction of 61.75%, ENS reduction of 48%, and CAIDI reduction of 30% with a corresponding computational speed of 0.24 seconds. Hence, from the aforementioned results analysis, it can be concluded that the selection of the optimization algorithm depends on or is subject to specific operational requirements of the network, in that no single optimization algorithm dominates or is capable of performing optimally in all parameter measurements. Besides, while the PSO performs excellently in terms of loss, ENS, and CAIDI reduction, the GA performs well in terms of voltage enhancement and SAIDI reduction. Additionally, while the GA is recommended for voltage quality and interruption frequency reduction, the PSO is recommended for loss reduction and quick computational analysis.

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