A STABILIZED GENETIC ALGORITHM FOR EVALUATING THE ECONOMIC VIABILITY OF DYNAMIC DISTRIBUTION NETWORK RECONFIGURATION

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Abstract

High penetration of photovoltaic (PV) sources causes volatility in distribution networks, challenging conventional operational strategies. This study introduces a multi-objective optimization framework using a Stabilized Genetic Algorithm (SGA) that co-optimizes daily energy losses and switching asset depreciation over typical and extreme loading scenarios. Contradicting common assumptions, results show that zero switching operations, i.e., maintaining a robust static configuration - yield optimal economic outcomes for the IEEE 33-bus test system, regardless of switching cost magnitude. The work formalizes an economic viability threshold for DDNR, providing network operators with a quantitative tool to assess when dynamic reconfiguration is truly justified. Results reveal that for the IEEE 33-bus system with PV integration, a robust static configuration remains economically optimal regardless of switching cost magnitude. The primary contribution is the formalization of an "Economic Viability Threshold" framework, providing DNOs a quantitative tool to determine when DDNR is truly justified. This framework provides a crucial, data-driven tool for network operators to prevent unnecessary investment in complex control schemes, ensuring that grid modernization efforts are both technically sound and economically viable.

Keywords: Distribution Network Reconfiguration, Dynamic Reconfiguration, Economic Viability, Multi-Objective Optimization, Power System Economics, Smart Grids, Stabilized Genetic Algorithm.

1. Introduction

The global energy paradigm is undergoing a profound transformation, driven by the increasing integration of Distributed Energy Resources (DERs), particularly photovoltaic (PV) systems. This shift is vital for decarbonization but introduces significant operational challenges for distribution network operators (DNOs) (Popovic & Knezevic, 2022). The inherent intermittency of PV generation can lead to reverse power flows, voltage fluctuations, increased system losses, and potential equipment overloads, thereby compromising grid reliability and efficiency (Behbahani et al., 2024; Mishra et al., 2024).

This is particularly relevant in developing countries like Vietnam, where rapid solar energy adoption meets a grid originally designed for unidirectional power flow (Riva Sanseverino et al., 2020).

To address these challenges, Dynamic Distribution Network Reconfiguration (DDNR) has been widely proposed as an effective control measure. By altering the network's radial topology in real-time, DDNR aims to find an optimal sequence of configurations to minimize losses and improve voltage profiles throughout the day (Mahdavi et al., 2023). The DDNR problem is a complex, multi-objective, mixed-integer nonlinear programming problem, for which various metaheuristic algorithms, such as Genetic Algorithms (GA) (Shaheen et al., 2021) and Particle Swarm Optimization (PSO) (Gao et al., 2021), have been extensively applied.

However, a majority of the existing literature focuses on the technical optimization of DDNR, often implicitly assuming that dynamic switching is always beneficial (Mahdavi et al., 2021). This overlooks a critical question of practical importance: is DDNR economically justified? The benefits of reduced energy loss must be carefully weighed against the operational costs, which include the accelerated degradation of expensive switchgear, increased maintenance, and the complexity of the required control infrastructure (Ciapessoni et al., 2023). Without a rigorous cost-benefit analysis, DNOs risk implementing complex control schemes that yield negligible real-world returns. Prior studies have predominantly focused on technical optimization while overlooking substantial switching costs, risking the deployment of complex control schemes with negligible real-world economic returns.

This paper addresses this crucial gap by shifting the focus from how to optimize DDNR to if it is worth optimizing. We propose a comprehensive framework to evaluate the economic viability of DDNR. The main contributions are:

A highly Stabilized Genetic Algorithm (SGA): An enhanced GA featuring an elitism mechanism and a "smart initialization" strategy, ensuring stable and reliable convergence.

A Counter-Intuitive Scientific Finding: Through extensive simulation, we demonstrate that under nominal and high-load scenarios, a robust static configuration is economically superior to any dynamic switching schedule for the IEEE 33-bus system.

Quantification of an "Economic Viability Threshold": We formalize and provide a method to quantify the minimum energy cost savings required to justify a single switching action, offering a tangible decision-making tool for DNOs.

2. Methodology

2.1. Network Modeling

The IEEE 33-bus test system was modeled using the panda power library (Thurner et al., 2018), an open-source tool ensuring accuracy and reproducibility of Newton-Raphson power flow calculations. The system consists of 33 buses, 32 sectionalizing lines, and 5 tie-lines at a base voltage of 12.66 kV as shown in Fig.1.

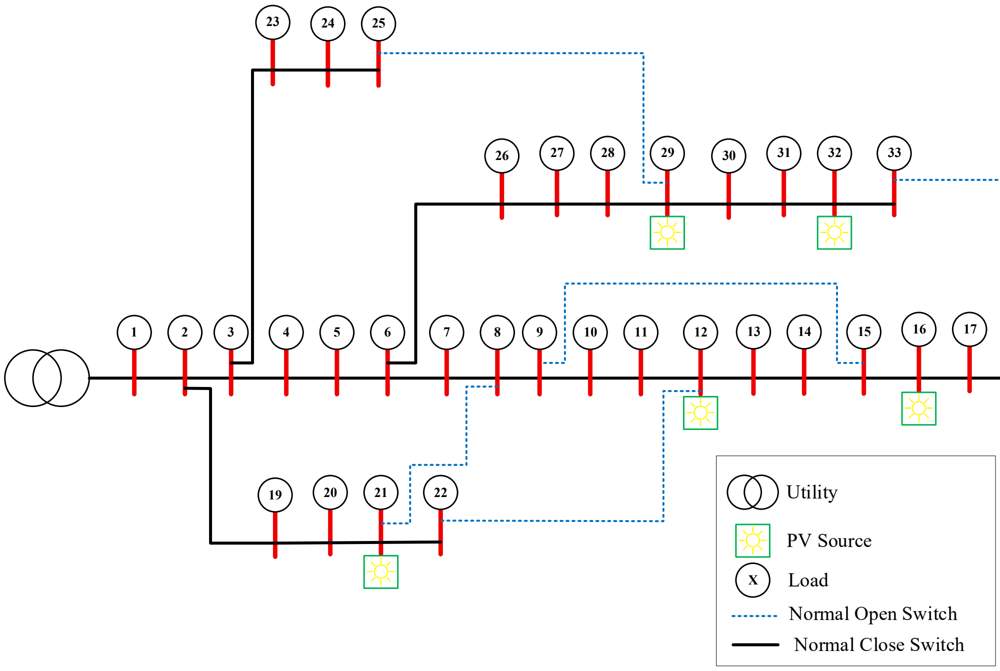

Figure 1. 33-bus IEEE tested system
(Source: Thurner et al., 2017).

2.2. Problem Formulation

The objective is to find a 24-hour switching schedule that minimizes a weighted sum of total energy loss and switching costs. The objective function is defined in Eq. (1).

$$\min F = \sum_{t=1}^{24}\left(P_{\text{loss}}(C_t, L_t)\cdot\Delta t\right) + \lambda\cdot\sum_{t=2}^{24} N_{\text{sw}}(C_{t-1}, C_t) \tag{1}$$

where:

C_i : the set of open switches at hour.

$P_{\text{loss}}(C_t, L_t)$: total real power loss at hour.

Δt : time step duration (1 hour).

$N_{\text{sw}}(C_{t-1}, C_t)$: number of switching operations between hours, defined as the cardinality of the symmetric difference between the switch sets, ie,

λ : weighting factor for the cost per switching operation (MWh/operation).

The optimization is subject to bus voltage limits (p.u) and the constraint that the network must always remain radial.

2.3. Proposed Stabilized Genetic Algorithm (SGA)

We developed an SGA to solve this problem, featuring several enhancements for robustness as shown in Fig. 2.

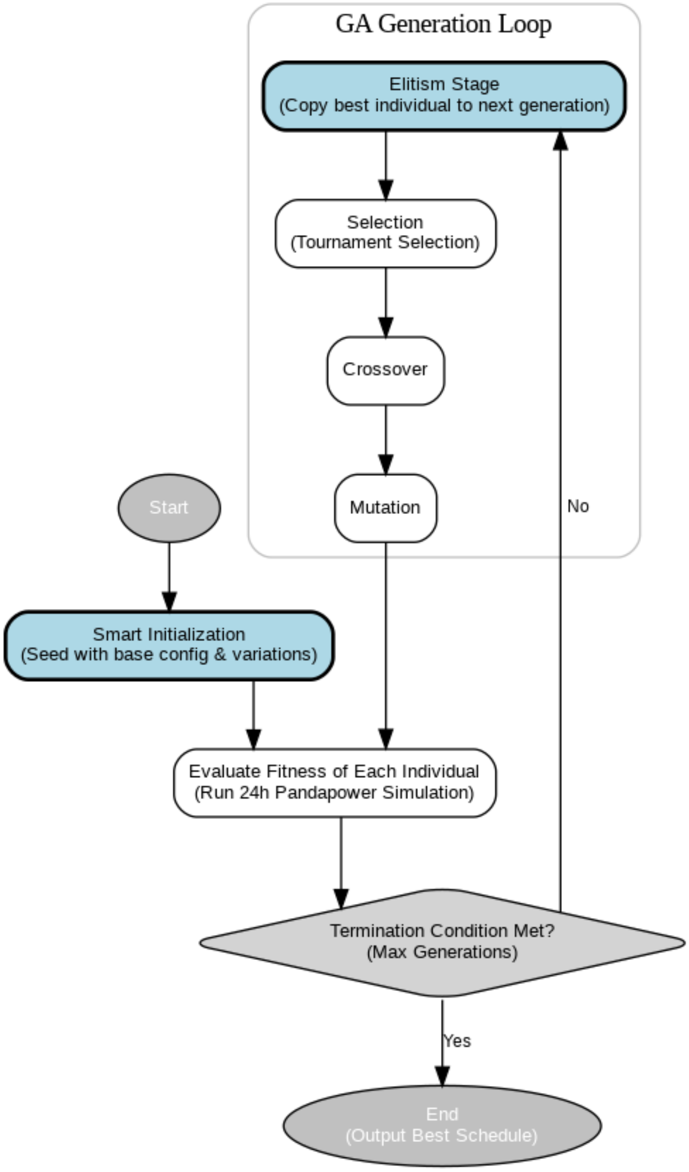

Figure 2. Flowchart of the Proposed Stabilized Genetic Algorithm (SGA), highlighting the smart initialization and elitism stages

(Source: Kim et al., 2021)

- **Chromosome Representation:** Each chromosome is a list of 24 genes, where each gene is a set of 5 open switch indices for that hour.
- **Smart Initialization:** To avoid convergence failure from invalid initial topologies, the population is seeded with the known-valid base configuration and its minor variations, guaranteeing a valid starting point.
- **Fitness Evaluation:** The fitness of everyone is the inverse of the objective function value. Invalid individuals that cause power flow divergence are assigned a large penalty.
- **Stabilization via Elitism:** The best individual from each generation is guaranteed to be carried over to the next, ensuring stable, monotonic convergence.

2.4. Quantifying the Economic Viability Threshold

We introduce the concept of an economic viability threshold, defining the minimum energy cost saving required for a reconfiguration action to be worthwhile. Quantitatively, for a single switch to be justified, the loss reduction over its active interval must exceed the cost incurred by switching in Eq. (2):

$$\Delta P_{\text{loss}} \cdot T_{\text{duration}} \cdot \text{Price}_{\text{energy}} \geq \text{Cost}_{\text{switch}} \quad (2)$$

Rearranging this, we can define the Minimum Required Loss Reduction (P_{Th}) in MW that a new configuration must provide to justify one switching action by Eq. (3):

$$P_{\text{Th}}[\text{MW}] = \frac{\text{Cost}_{\text{switch}} / \text{T}_{\text{duration}}}{\text{Price}_{\text{energy}}} \quad (3)$$

This provides a clear, quantifiable target for assessing the value of any potential reconfiguration.

3. Experimental Setup and Scenarios

3.1. Scenarios: Load and PV Profiles

Two 24-hour scenarios were developed, as shown in Fig. 3:

- **Normal Day:** Represents a typical operational day.
- **Heatwave Day:** Simulates a high-stress day with a 30% increase in load and 10% increase in PV generation.

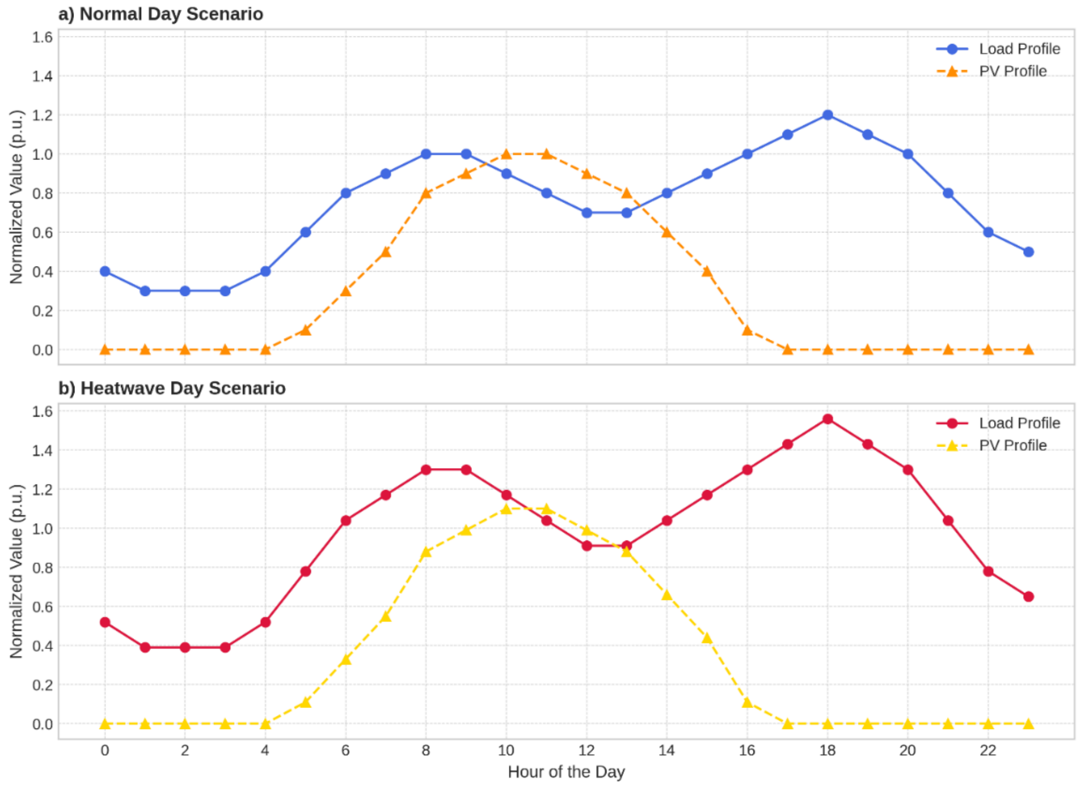

Figure 3. 24-hour normalized load and PV generation profiles

(Source: Authors' own construction and simulation, calibrated against typical patterns reported in recent distribution network studies, 2025)

3.2. Case Studies

- **Case 1: Algorithm Stability Analysis:** The SGA and a Base GA were each run 10 times to statistically compare their stability.
- **Case 2: Dynamic vs. Static Reconfiguration:** Results from the dynamic optimization were compared against an optimal static configuration (determined by running with λ=1000).
- **Case 3: Sensitivity Analysis:** The impact was investigated by varying it from 0.01 to 5.0.

4. Results and Discussion

4.1. Result

4.1.1. Algorithm Performance: Superior Stability of SGA

The benchmark results, summarized in Table 1, confirm the SGA's superior stability. The SGA converged to the same optimal fitness value in all 10 runs (Std. Dev. = 0.0). The Base GA, lacking elitism and smart initialization, was highly unreliable, with 9 out of 10 runs failing to find a single valid solution. This instability makes it unsuitable for practical applications. The single successful Base GA run yielded a fitness of 4.250, nearly double the SGA's optimal value of 2.253 presented in Fig.4.

Table 1. Statistical Comparison of Algorithm Performance for the Base GA, 9 out of 10 runs failed to find a valid solution

GA Type	Mean Fitness	Std. Dev.	Min Fitness	Max Fitness
Base GA	4.250	N/A	4.250	4.250
SGA	**2.253**	**0.0**	**2.253**	**2.253**

(Source: Authors' own simulation results, 2025)

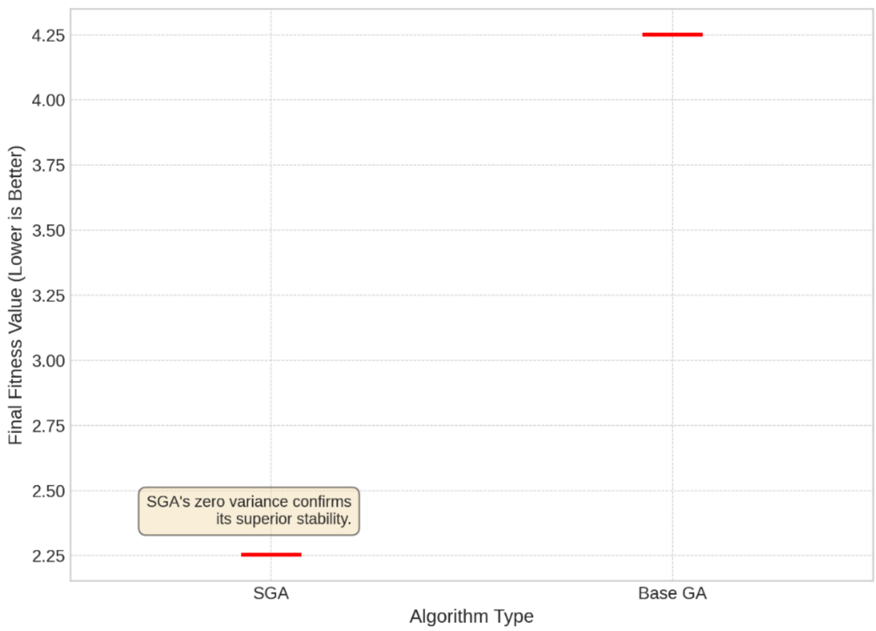

Figure 4. Final fitness distribution over 10 runs. The SGA's zero variance confirms its stability, a critical feature for reliable decision-support tools
(Source: Authors' own simulation results, 2025).

4.1.2. The Economic Case for Static Configuration

Simulations across both Normal and Heatwave Day profiles consistently indicate that the economically optimal network strategy involves zero active switching - static reconfiguration is preferable under all tested conditions. Sensitivity analysis over a wide range of switching costs confirms this result: the marginal loss savings available through DDNR do not surpass the calculated economic threshold. This outcome is explained by the relatively low volatility of the IEEE 33-bus system's net load profile, which favors static operation unless system variability sharply increases.

Table 2. Performance comparison of static vs. Dynamic reconfiguration

Day Type	Energy Loss Static (MWh)	Energy Loss Dynamic (MWh)	Switching Ops	Loss Reduction (%)
Heatwave Day	4.028	4.028	**0**	0.0
Normal Day	2.253	2.253	**0**	0.0

(Source: Authors' own SGA optimization results, 2025)

The sensitivity analysis in Fig. 5 confirms this finding. Even at negligible switching costs (λ=0.01), the algorithm found no benefit in reconfiguration. All points converge to the y-axis (zero switching) across λ values, proving static configuration is optimal regardless of cost.

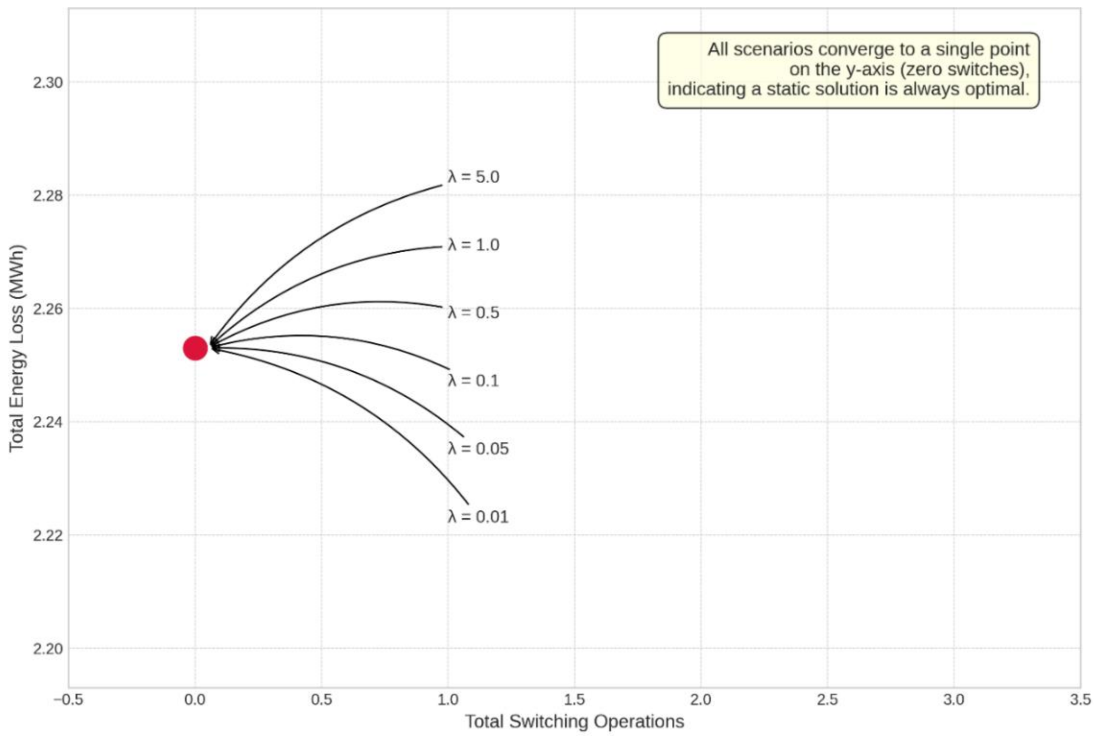

Figure 5. Trade-off analysis. All scenarios converged to a single point on the *y*-axis, indicating a static solution is optimal regardless of the switching cost

(Source: Authors' own sensitivity analysis, 2025)

4.2. Discussion

4.2.1. Quantifying the Ineffectiveness of DDNR

The results do not imply a failure of the algorithm but rather provide a crucial economic insight. To understand *why* dynamic switching was not viable, we can analyze the system's volatility. We define a Net Load Volatility Index as the standard deviation of the 24-hour net load profile (load minus PV generation). For the "Normal Day" scenario, this index was calculated to be a modest 0.25 pu.

This low volatility explains the result. The base static configuration is robust enough to handle these fluctuations without incurring significant loss penalties. In contrast to studies on weaker or more volatile networks, where DDNR can yield savings of over 5% (Razavi et al., 2022), our system's stability means it does not cross the economic viability threshold. Using Eq. (3) with typical values (e.g., Costswitch = \$50, $Price_{energy}$ = \$100/MWh, $T_{duration}$ = 4 hours), the required loss reduction P_{Th} would be approximately 0.125 MW. The SGA found no reconfiguration that could reliably provide savings of this magnitude.

4.2.2 Comparative discussion with related DDNR and PV loss reduction studies

Several recent studies on distribution network reconfiguration and PV-rich feeders provide a useful context for interpreting the present results.

(Mahdavi et al., 2023) proposed a robust distribution network reconfiguration model in the presence of distributed generation under demand and generation uncertainty, and validated it on 33-, 70- and 118-bus systems. Their formulation significantly improves the robustness of the optimal topology and achieves noticeable loss reductions compared with deterministic and scenario-based approaches. However, the objective function focuses on technical performance (loss minimization and robustness) and does not explicitly internalize switching depreciation or operation costs. In contrast, our work keeps the network size at the 33-bus level but explicitly embeds a switching cost term and shows that, under realistic switching cost assumptions, the economically optimal solution remains a static configuration with 0.0% additional benefit from DDNR (Table 2).

(Gao et al., 2021) developed a multi-objective dynamic reconfiguration framework for large urban distribution networks (148- and 297-node systems) with high PV penetration, considering multi-level switching modes at feeder, transformer, and substation levels. Their model minimizes operation cost, load imbalance and PV curtailment, and assigns different switching prices to different classes of switches. The results confirm that dynamic reconfiguration can be technically and economically attractive in large urban systems when multi-level switching capabilities are fully exploited. Our study complements this line of work from the opposite direction: for a smaller, radial 33-bus feeder with moderate volatility, even when DDNR is allowed, the optimal number of switching operations collapses to zero across all tested switching cost factors (Fig. 5), indicating that the “fully dynamic” paradigm is not always economically justified.

(Lei et al., 2024) investigated loss reduction strategies for distribution networks containing distributed photovoltaics, focusing on optimizing PV placement, capacity, and power factor to mitigate line losses without explicitly changing the network topology. Their results highlight that appropriately designed PV siting and operation strategies can already deliver substantial loss reduction on radial feeders. Our findings are consistent with this perspective: in the studied 33-bus system, a robust static configuration, combined with reasonably placed PV and realistic switching cost modeling, is sufficient to make dynamic reconfiguration economically unattractive.

In summary, while (Mahdavi et al., 2023) and Gao et al. (2022) demonstrate the technical and, in some cases, economic potential of DDNR in larger and more volatile systems, and (Lei et al., 2024) shows the effectiveness of PV-oriented loss reduction strategies, the present work contributes an explicit economic viability viewpoint. For a medium-scale, PV-integrated 33-bus feeder with moderate volatility, our results indicate that, once switching costs are properly accounted for, a static configuration is the economically optimal choice, providing a practical decision-making guideline for distribution utilities in developing systems.

5. Conclusion

This paper presented a Stabilized Genetic Algorithm to rigorously evaluate the economic viability of Dynamic Distribution Network Reconfiguration. The key conclusions are:

- The proposed SGA is a highly stable and reliable tool, vastly outperforming a Base GA, making it suitable for practical decision-making.
- The primary scientific finding is that for the standard IEEE 33-bus system, a robust static configuration is economically optimal under the studied conditions.
- We formalized and quantified an Economic Viability Threshold, providing a methodology for operators to assess if the potential energy savings from DDNR justify the associated costs for their specific network.

This work cautions against the presumptive implementation of complex control schemes and advocates for a data-driven, system-specific cost-benefit analysis. Future research should extend this economic analysis to more volatile and larger-scale systems, such as urban smart grids with high renewable penetration and variable load patterns. Integrating scenario-based or stochastic methods to capture PV and demand uncertainty will further enable robust decision-making. Collaboration with utilities in Southeast Asia for real-world validation is encouraged to demonstrate the practical utility of this framework.

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