A Systems Approach to Sustainable Development in Emerging Economies: Multi-Objective Optimization of Distributed Generation and Facts Devices for Power System Resilience

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***Abstract*—Sustainable development in emerging economies is fundamentally constrained by energy infrastructure deficits, high technical losses, and poor voltage stability in distribution networks. This paper presents a systems-theoretic framework that integrates technical optimization of power systems with the broader Sustainable Development Goals (SDGs). A multi-objective Particle Swarm Optimization (PSO) algorithm is employed to simultaneously optimize the placement and sizing of Distributed Generation (DG) units and Flexible AC Transmission System (FACTS) devices—specifically the Distribution Static Synchronous Compensator (DSTATCOM) and the Unified Power Flow Controller (UPFC)—within a 33-bus, 11-kV radial distribution network representing the Port Harcourt Electricity Distribution Company (PHED) in Nigeria. The optimization considers technical objectives (voltage profile improvement, active and reactive power loss minimization, network stability) and economic objectives (annual cost of energy losses). Results demonstrate that the coordinated DG–FACTS configuration reduces active power losses from 316.59 kW to 4.25 kW (98.6% reduction) and the annual cost of energy losses from ₦573.52 million to ₦7.71 million (98.7% savings). A Composite Sustainability Index (CSI) is proposed to quantify the multi-dimensional impact of technical interventions on economic, environmental, social, and institutional subsystems. The findings validate that a systems approach—treating energy infrastructure as an interconnected subsystem of sustainable development—yields symbiotic benefits across technical, economic, and sustainability domains. This study contributes a replicable methodology for emerging economies seeking to align power system modernization with Agenda 2030.**

***Index Terms*—Sustainable development; Systems approach; Distributed generation; FACTS devices; multi-objective optimization; particle swarm optimization; emerging economies; power distribution networks; SDG 7; Nigeria**

I. INTRODUCTION

1.1. Background and Motivation

Emerging economies face a trilemma of energy access, economic growth, and environmental sustainability. Despite accounting for over 80% of the world's population, these nations consume less than 40% of global primary energy, with significant portions of their populations lacking reliable electricity access [1]. The United Nations Sustainable Development Goal 7 (SDG 7) targets universal access to affordable, reliable, and modern energy services by 2030, yet the trajectory of many emerging economies suggests substantial gaps will persist without transformative interventions [2].

The power sector in emerging economies is characterized by aging infrastructure, high technical and non-technical losses (often exceeding 20%), voltage instability, and limited integration of renewable energy sources [3]. Nigeria, Africa's largest economy, exemplifies these challenges. With an installed generation capacity of approximately 13,000 MW but an available capacity often below 4,000 MW, the country experiences chronic power shortages that constrain industrial output, inflate operational costs, and impede social development [4]. The distribution segment, in particular, suffers from radial network topologies with long feeders, high R/X ratios, and minimal automation—conditions that exacerbate voltage drops and power losses.

Distributed Generation (DG) and Flexible AC Transmission System (FACTS) devices represent

promising technological interventions. DG, particularly solar photovoltaic (PV) systems, can be deployed close to load centers, reducing transmission losses and deferring network expansion [5]. FACTS devices such as the Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) provide dynamic reactive power compensation and voltage regulation, enhancing network controllability [6]. However, the deployment of these technologies in isolation—without consideration of their systemic interactions with economic, social, and institutional subsystems—risks suboptimal outcomes.

1.2. The Systems Approach Imperative

Conventional approaches to power system planning in emerging economies often adopt a reductionist paradigm, treating technical, economic, and social objectives as separate optimization problems.

This fragmentation leads to policy incoherence: technically optimal solutions may be economically unviable, while economically attractive investments may undermine social equity or environmental goals [7].

A systems approach, rooted in general systems theory and symbiotic analysis, recognizes sustainable development as an emergent property of interacting subsystems: economic, social, environmental, technological, institutional, and energy [8]. Within this framework, the energy subsystem is not merely a technical infrastructure but a critical node that mediates trade-offs and synergies across all other domains. For instance, reducing power losses through technical optimization simultaneously lowers greenhouse gas emissions (environmental), reduces electricity tariffs (economic), improves supply reliability (social), and strengthens grid resilience (institutional).

1.3. Research Objectives

This paper addresses the following objectives:

1. To develop an integrated systems framework that links power system technical optimization to sustainable development outcomes in emerging economies.
2. To formulate and solve a multi-objective optimization problem for the coordinated placement of DG and FACTS devices in a medium-voltage (MV) distribution network.
3. To evaluate the technical and economic performance of DSTATCOM and UPFC under multiple operating scenarios.
4. To propose and validate a Composite Sustainability Index (CSI) that quantifies the cross-dimensional impact of technical interventions.
5. To derive policy recommendations for emerging economies based on the symbiotic analysis of technical and sustainability outcomes.

1.4. Paper Organization

The remainder of this paper is structured as follows: Section 2 reviews the literature on sustainable development frameworks, DG integration, and FACTS technologies. Section 3 presents the systems approach framework and the mathematical formulation of the optimization problem. Section 4 details the methodology, including the PSO algorithm and network modeling.

Section 5 presents the case study, results, and discussion. Section 6 synthesizes the systems implications, and Section 7 concludes with recommendations.

II. LITERATURE REVIEW

2.1. Sustainable Development in Emerging Economies

The Brundtland Commission's definition of sustainable development—"meeting the needs of the present without compromising the ability of future generations to meet their own needs"—has been operationalized through the 17 Sustainable Development Goals [9]. For emerging economies, the challenge lies in decoupling economic growth from environmental degradation while addressing acute social deficits.

The energy-poverty nexus is particularly salient. Energy access correlates with improvements in health (SDG 3), education (SDG 4), gender equality (SDG 5), and economic productivity (SDG 8) [10].

However, centralized grid expansion in emerging economies is often slow and capital-intensive. Decentralized solutions such as DG offer a complementary pathway, yet their integration introduces technical complexities including voltage rise, reverse power flow, and protection coordination challenges [11].

2.2. Distributed Generation: Opportunities and Challenges

Distributed Generation refers to small- to medium-scale electricity generation connected directly to the distribution network or on the customer side of the meter [12]. Technologies include solar PV, wind turbines, micro-hydro, biomass, and natural gas microturbines. In emerging economies, solar PV has gained prominence due to declining module costs, abundant solar resource availability, and modular scalability.

The benefits of DG integration are well-documented: reduction of transmission and distribution losses, improved voltage profiles, deferred network upgrades, enhanced reliability, and lower carbon emissions [13]. However, high DG penetration in radial MV networks—originally designed for unidirectional power flow—can cause over-voltages, increased fault currents, and power quality degradation [14]. These technical challenges, if unmitigated, can negate the economic and environmental benefits of DG deployment.

2.3. FACTS Devices for Distribution Networks

Flexible AC Transmission Systems (FACTS) are power electronic-based devices that enhance the controllability and power transfer capability of AC networks [15]. At the distribution level (D-FACTS), devices such as the DSTATCOM and UPFC provide:

- Shunt compensation: Reactive power injection/absorption for voltage regulation (DSTATCOM).
- Series compensation: Line impedance modification for power flow control (SSSC).
- Combined compensation: Simultaneous voltage and power flow control (UPFC).

The DSTATCOM operates as a voltage-source converter (VSC) that injects or absorbs reactive power at the point of common coupling (PCC), offering faster dynamic response than conventional Static VAR Compensators (SVCs) [16]. The UPFC integrates a shunt STATCOM and a series SSSC through a common DC link, enabling comprehensive control of voltage magnitude, phase angle, and line impedance [17].

Recent literature has explored optimal placement and sizing of FACTS devices using metaheuristic algorithms. Alajrash et al. [18] reviewed FACTS applications in modern power systems with renewable penetration, while Santamaria-Henao et al. [19] applied the Black Widow Algorithm for FACTS siting in distribution networks. However, most studies focus on transmission systems or treat DG and FACTS optimization as separate problems, leaving a gap in coordinated, distribution-level analysis.

2.4. Multi-Objective Optimization in Power Systems

The optimal placement of DG and FACTS devices is inherently a multi-objective, non-convex, combinatorial optimization problem. Objectives typically include loss minimization, voltage stability improvement, cost reduction, and emission mitigation. Constraints encompass power balance equations, voltage limits, thermal ratings, and DG penetration levels [20].

Metaheuristic algorithms—Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and hybrid variants—have proven effective for such problems due to their ability to navigate complex search spaces and avoid local optima [21]. PSO, inspired by the social behavior of bird flocks, is particularly favored for its computational efficiency, few control parameters, and rapid convergence [22].

2.5. Research Gap

Despite extensive research on DG and FACTS individually, several gaps persist:

1. Systems integration: Most studies treat technical optimization and sustainable development as disconnected domains. There is limited quantitative frameworks linking power loss reduction to SDG indicators.
2. Coordinated optimization: Few studies simultaneously optimize DG placement and FACTS device configuration in a unified framework.
3. Emerging economy context: Much of the literature focuses on developed grid codes and infrastructure, with limited applicability to the weak, radial networks prevalent in sub-Saharan Africa.
4. Economic-sustainability nexus: The translation of technical efficiency gains into macroeconomic and sustainability outcomes remains under-theorized.

This paper addresses these gaps by proposing a systems approach that embeds technical optimization

within a multi-dimensional sustainability assessment framework.

III. THEORETICAL FRAMEWORK AND PROBLEM FORMULATION

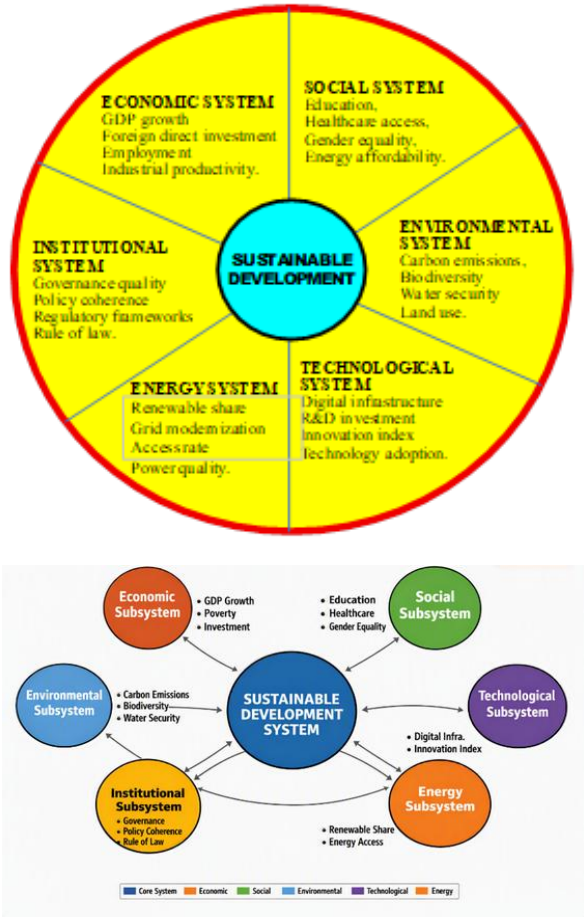

Figure 1: A Systems Approach to Sustainable Development

Figure 1 presents the proposed systems framework. Sustainable Development is conceptualized as a central emergent property arising from the dynamic interaction of six subsystems:

1. Economic Subsystem: GDP growth, foreign direct investment, employment, and industrial productivity.
2. Social Subsystem: Education, healthcare access, gender equality, and energy affordability.
3. Environmental Subsystem: Carbon emissions, biodiversity, water security, and land use.
4. Technological Subsystem: Digital infrastructure, R&D investment, innovation index, and technology adoption.
5. Institutional Subsystem: Governance quality, policy coherence, regulatory frameworks, and rule of law.
6. Energy Subsystem: Renewable share, grid modernization, access rate, and power quality.

These subsystems are interconnected through bidirectional feedback loops. For example, energy infrastructure investment (energy → economic) stimulates industrial growth, which increases electricity demand (economic → energy). Similarly, improved governance (institutional) enables better DG interconnection standards (institutional → energy), while reliable power enhances educational outcomes (energy → social).

The symmetry of this framework lies in its balanced treatment of all subsystems. No single dimension dominates; rather, sustainable development emerges from their harmonious interaction.

3.1. Composite Sustainability Index (CSI)

To operationalize the systems approach, we propose a Composite Sustainability Index defined as:

$$CSI = \sum_{i=1}^{6} w_i S_i$$

where S_i is the normalized score of subsystems i and w_i is its weight determined by the Analytic Hierarchy Process (AHP) combined with the entropy method. The energy subsystem score S_{energy} is derived from technical network indicators:

$$S_{energy} = \alpha_1 \left(1 - \frac{P_{loss}}{P_{loss,base}}\right) + \alpha_2 \left(\frac{V_{min} - V_{limit}}{V_{nom} - V_{limit}}\right) + \alpha_3 \left(\frac{R_{renewable}}{R_{target}}\right)$$

where $\alpha_1 + \alpha_2 + \alpha_3 = 1$

3.. Multi-Objective Optimization Problem

3.2.1. Decision Variables

The optimization determines:

- DG locations
- DG sizes in kW
- FACTS location
- FACTS rating in kVAr

3.2.2. Objective Functions

Objective 1: Minimize Total Active Power Loss

$$f_1 = P_{loss}^{Total} = \sum_{k=1}^{N_{br}} I_k^2 R_k$$

Objective 2: Minimize Voltage Deviation

$$f_2 = V_D = \sum_{n=1}^{N_{bus}} | V_n - V_{nominal} |$$

Objective 3: Minimize Annual Cost of Energy Losses

$$f_3 = C_{loss} = c_e \cdot P_{loss}^{Total} \cdot 8760$$

where c_e is the electricity tariff (₦206.8/kWh).

Objective 4: Maximize Sustainability Index

max f_4 = CSI

3.2.3. Constraints

Power Balance (Equality):

$$P_{Gi} + P_{DGi} - P_{Di} = V_i \sum_{j=1}^{N_{bus}} V_j \left(G_{ij}\, cos\, cos\, \theta_{ij} + B_{ij}\, sin\, sin\, \theta_{ij}\right)$$

$$Q_{Gi} + Q_{DGi} + Q_{FACTS,i} - Q_{Di} = V_i \sum_{j=1}^{N_{bus}} V_j \left(G_{ij}\, sin\, sin\, \theta_{ij} - B_{ij}\, cos\, cos\, \theta_{ij}\right)$$

Voltage Limits:

$$V_{min} \le V_i \le V_{max},\ \forall i \in \{N_{bus}\}$$

where V_{min} = 0.94 p.u. and V_{max} = 1.06 p.u.

Thermal Limits:

$$| I_k | \le I_k^{max},\ \forall k \in \{N_{br}\}$$

DG Capacity Limits:

$$0 \le P_{DGi} \le P_{DG}^{max}$$

FACTS Operating Limits:

$$Q_{FACTS}^{min} \le Q_{FACTS} \le Q_{FACTS}^{max}$$

DG Penetration Constraint:

$$\sum P_{DG} \le \lambda \sum P_{Load}$$

where λ = 0.8 (80% maximum penetration).

IV. METHODOLOGY

4.1. Case Study Network

The study employs the 33-bus, 11-kV radial distribution network of the Port Harcourt Electricity Distribution Company (PHED), Nigeria. The network topology is shown in Figure 2. The system has a total active power demand of 3,715 kW and reactive power demand of 2,300 kVAr. Line parameters and load data are derived from field measurements and utility records.

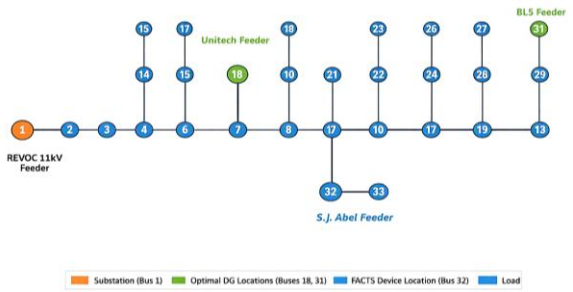

Figure 2: 33-Bus Radial Distribution Network Diagram (Port-Harcourt Electricity Distribution Company)

4.2. Modeling of Network Components

4.2.1. Distribution Network

The radial distribution load flow is solved using the Backward/Forward Sweep method. Branch currents are computed from end nodes toward the substation:

$$I_i = \frac{P_i - jQ_i}{V_i}$$

Nodal voltages are updated from the substation outward:

$$V_j = V_i - \left(R_{ij} + jX_{ij}\right) I_{ij}$$

The power flow equations are iterated until the voltage mismatch at all buses converges below 10^{-6} p.u.

4.2.2. Distributed Generation Model

The DG units are modeled as PV nodes with controllable real power injection and fixed power factor (unity). The DG output modifies the bus injection:

$$P_i = P_{DG,i} - P_{D,i}$$

4.2.3. DSTATCOM Model

The DSTATCOM is modeled as a shunt-connected VSC. Its reactive power exchange is:

$$Q = \frac{V_s(V_s - V_c)}{X}$$

where V_s is the system voltage, V_c is the converter output voltage, and X is the coupling reactance. The control strategy employs PI controllers based on Instantaneous Reactive Power Theory (p-q theory) in the synchronous reference frame (dq0).

4.2.4. UPFC Model

The UPFC comprises a shunt converter (STATCOM) and a series converter (SSSC) sharing a DC link. The series injected voltage is:

$V_{se} = | V_{se} | \angle\delta$

The power flow through the compensated line is:

$$P = \frac{V_i V_j}{X} sin\,(\delta + \delta_{se})$$

$$Q = \frac{V_i \left(V_i - V_j cos\,(\delta + \delta_{se})\right)}{X}$$

The DC-link dynamics are governed by:

$$C_{dc} \frac{dV_{dc}}{dt} = I_{dc,sh} - I_{dc,se}$$

4.3. Particle Swarm Optimization (PSO) Algorithm

The PSO algorithm is selected for its computational efficiency in handling mixed-integer, non-convex problems.

The algorithm proceeds as follows:

Step 1: Initialize a swarm of N particles with random positions $\{x_i\}$and velocities $\{v_i\}$ within the search space bounds.

Step 2: For each particle, decode the position vector into DG locations (rounded to nearest integer) and sizes (continuous).

Step 3: Run power flow analysis and compute the fitness vector

$f = [\, f_3 \;\; -f_4]$

Step 4: Update personal best: $[p_{best,i}]$ and global best $[g_{best}]$ using Pareto dominance and crowding distance.

Step 5: Update velocity and position:

$$v_i^{t+1} = w \cdot v_i^t + c_1 r_1 \left(p_{best,i} - x_i^t\right) + c_2 r_2 \left(g_{best} - x_i^t\right)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1}$$

where w is the inertia weight (linearly decreasing from 0.9 to 0.4), $c_1 = c_2 = 2.0$ are acceleration constants, and $r_1,\ r_2 \sim U(1)$

Step 6: Apply boundary constraints and ensure discrete variables (locations) are valid integers.

Step 7: Repeat Steps 3–6 until maximum iterations T = 100 or convergence criterion

$| CSI^t - CSI^{t-1} | < \varepsilon$ is met.

Step 8: Select the best compromise solution from the Pareto front using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

The algorithm flowchart and the PSO-Based DG Integration Flowchart for Optimal placement and sizing of DG are presented in Figure 3 and 4 respectively. Figure 5 shows the flowchart of the Multi-Objective SDG Optimization Algorithm

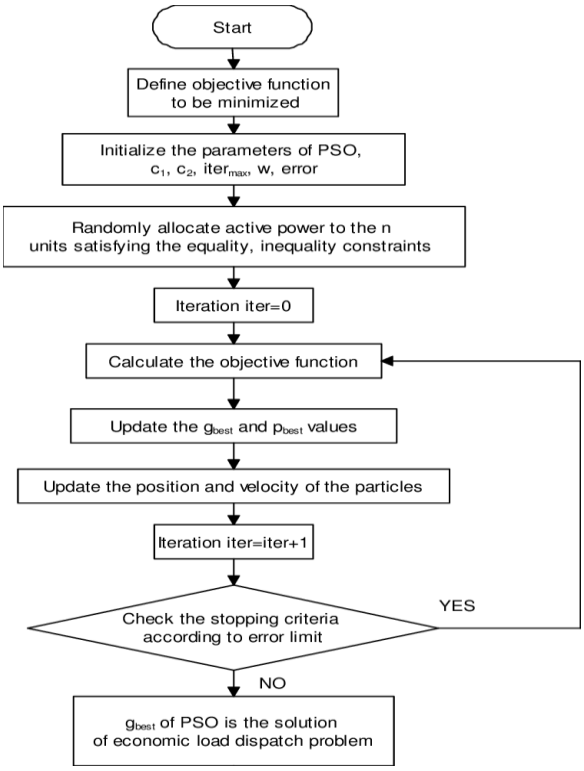

Figure 3: PSO Algorithm Flowchart

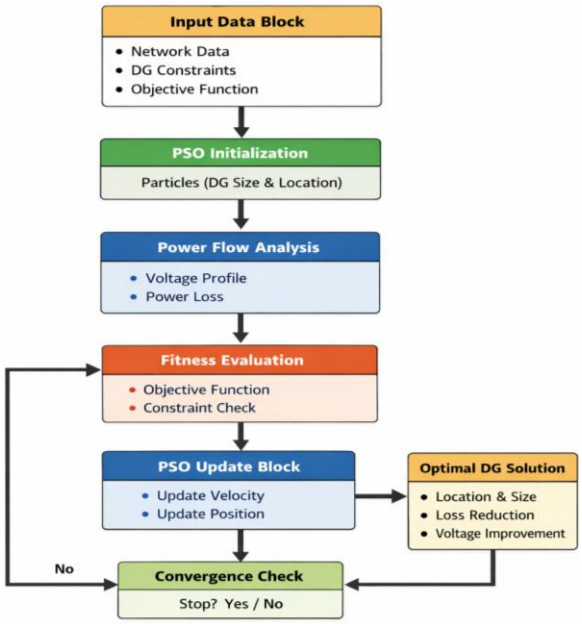

Figure 4: PSO-Based DG Integration Flowchart for Optimal DG placement & sizing

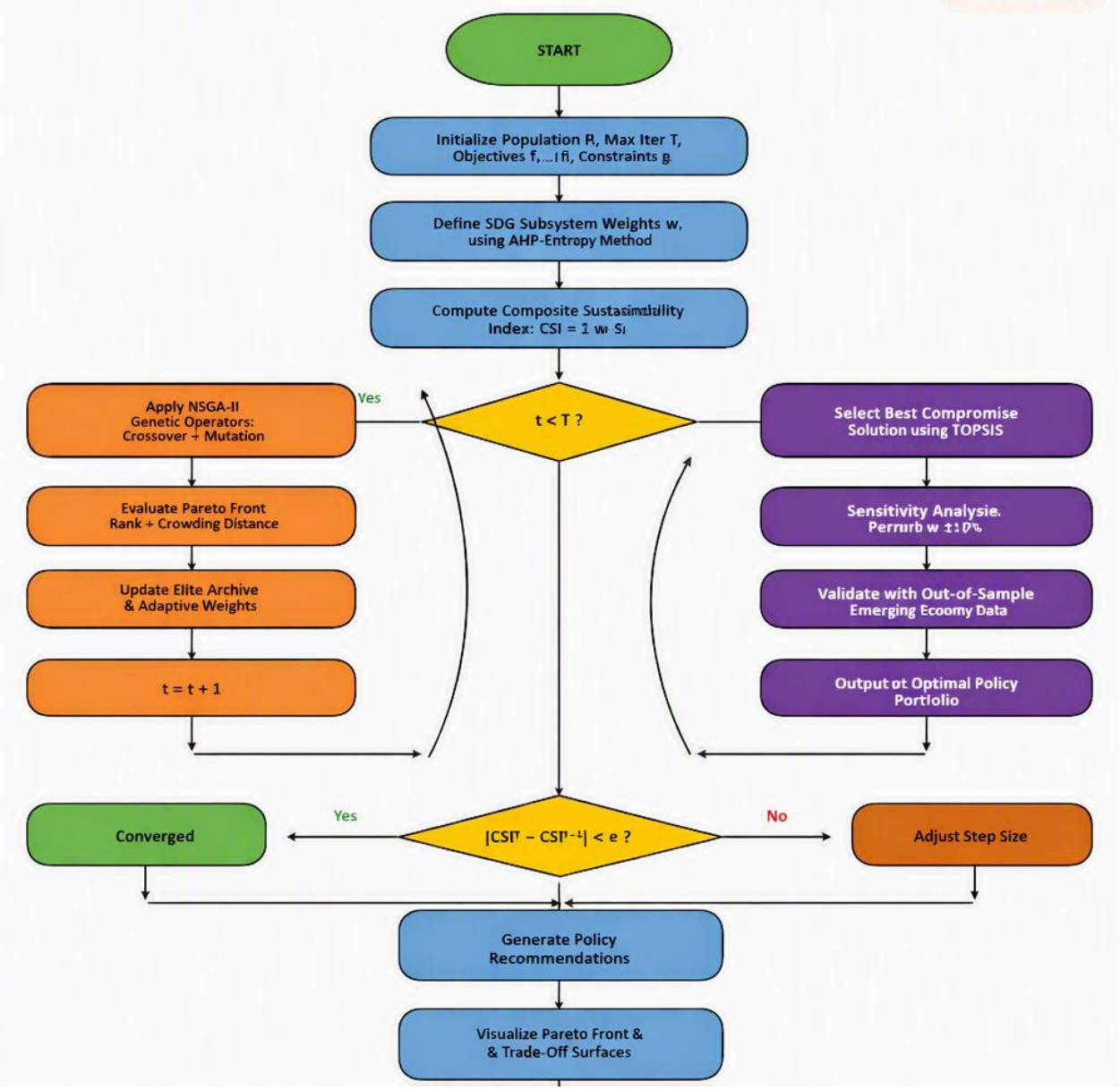

Figure 5: Flowchart of the Multi-Objective SDG Optimization Algorithm

4.4. Simulation Scenarios

Seven operating scenarios are evaluated:

Scenario	Description
S1	Base Case: No DG, No FACTS
S2	Single DG at Bus 31 (arbitrary placement)
S3	Two DGs at Buses 18 & 31 (PSO-optimized)
S4	UPFC only at Bus 32
S5	DSTATCOM only at Bus 32
S6	DG + UPFC at B
S7.	DG + DSTATCOM at Bus 32

Simulations are performed in MATLAB/Simulink. The PSO parameters are:

- Swarm size N = 30,
- Maximum iterations T = 100, and
- 20 independent runs for statistical significance.

V. RESULTS AND DISCUSSION

5.1. SDG Progress Context

Figure 6 illustrates the change in SDG rankings between 2015 and 2025. There has been a steady drop in Nigeria's rankings over the years and yet remains below the 0.75 target threshold.

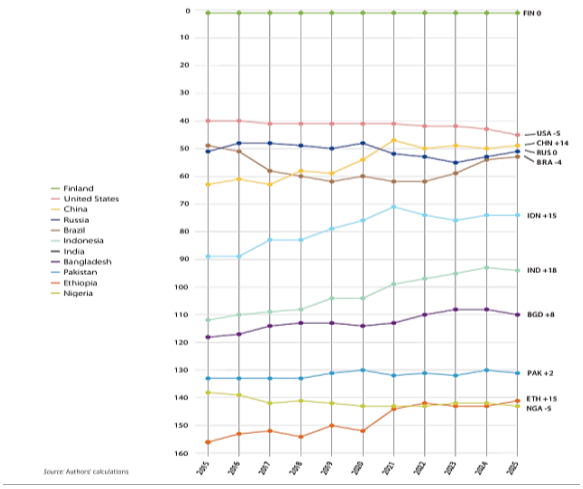

Figure 6: Change in SDG rankings between 2015 and 2025

This contextualizes the urgency of technical interventions that can accelerate progress across multiple SDGs simultaneously.

5.2. Voltage Profile Analysis

Figure 7 presents the voltage profile across all 33 buses for the seven scenarios.

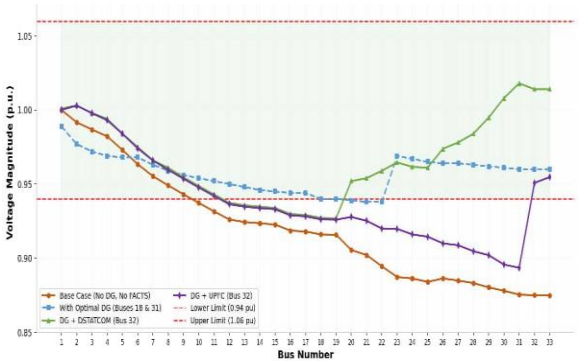

Figure 7: Voltage Profile Across Operating Scenarios (33-Bus PHED Distribution Network)

Key observations include:

1. *Base Case (S1):* The minimum voltage occurs at Bus 33 (Danjuma feeder) with 0.8749 p.u., violating the statutory lower limit of 0.94 p.u. Voltage drops are progressive along the radial feeder, characteristic of long, lightly loaded lines with high R/X ratios.
2. *Single DG (S2):* Placement of an 1,867 kW DG at Bus 31 raises the terminal voltage to 0.960 p.u., but intermediate buses still exhibit marginal voltages.
3. *Two DGs (S3):* Optimal placement of 908 kW at Bus 18 (Unitech feeder) and 934 kW at Bus 31 (BLS feeder) improves the minimum voltage to 0.960 p.u. and flattens the voltage profile across the network.
4. *FACTS Only (S4, S5)*: Both UPFC and DSTATCOM at Bus 32 improve the voltage profile, with UPFC raising Bus 33 to 0.9547 p.u. and DSTATCOM to 0.8932 p.u. The UPFC's combined series-shunt compensation provides superior voltage regulation.
5. *Coordinated DG + FACTS (S6, S7):* The DG + DSTATCOM configuration achieves the best voltage profile, with Bus 33 reaching 1.014 p.u. However, this approaches the upper statutory limit, highlighting the need for careful control parameter tuning to prevent overvoltage.

Table 1: Voltage Profile Summary

Scenario	V_{min} (p.u.)	Bus	V_{max} (p.u.)	Bus	Within Limits?
S1 Base	0.8749	33	1	1	No
S2 Single DG	0.8757	31	0.99	1	No
S3 Two DGs	0.96	33	0.989	1	Yes
S4 UPFC Only	0.9547	33	1.001	1	Yes
S5 DSTATCOM Only	0.8932	33	1.001	1	No
S6 DG + UPFC	0.9547	33	1.003	1	Yes
S7 DG + DSTATCOM	1.014	33	1.001	1	Yes*

*Note: S7 requires reactive power control to prevent overvoltage during low-load periods.

5.3. Power Loss Analysis

Figure 8 compares active and reactive power losses across scenarios.

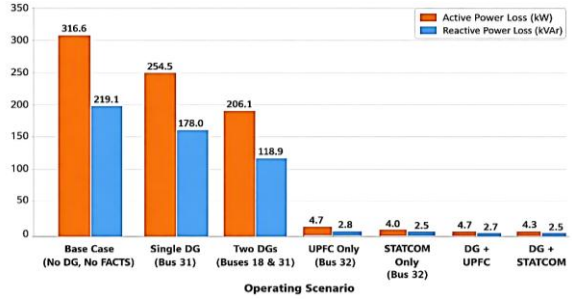

Figure 8: Active and Reactive Power Losses Under Different Operating Scenarios

The results are summarized in Table 2.

Table 2. Power Loss Comparison

Scenario	P_{loss} (kW)	Q_{loss} (kVAr)	Reduction vs. Base
S1 Base	316.59	219.09	—
S2 Single DG	254.52	177.97	19.60%
S3 Two DGs	206.13	118.86	34.90%
S4 UPFC Only	4.72	2.79	98.50%
S5 DSTATCOM Only	4.62	2.84	98.50%
S6 DG + UPFC	4.73	2.71	98.50%
S7 DG + DSTATCOM	4.25	2.45	98.70%

The coordinated DG + DSTATCOM configuration (S7) achieves the greatest loss reduction (98.7%), followed closely by DG + UPFC (S6).

The dramatic reduction when FACTS devices are introduced is attributable to their dynamic reactive power compensation, which minimizes circulating currents and optimizes power factor. The two-DG configuration (S3) reduces losses by 34.9% through localized generation, but the synergistic combination with FACTS devices yields nearly two orders of magnitude improvement.

5.4. Economic Analysis

Figure 9 presents the annual cost of energy losses at the prevailing tariff of ₦206.8/kWh. The economic impact is profound:

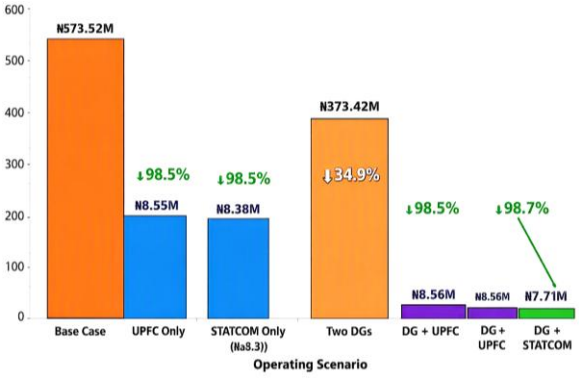

Figure 9: Annual Economic Cost of Energy Losses Under Different Scenarios

The base case annual loss cost of ₦573.52 million represents a significant economic drain on the utility and, by extension, on consumers who bear the cost through higher tariffs.

Table 3. Annual Economic Cost of Losses

Scenario	Annual Energy Loss (MWh)	Annual Cost (₦ Millions)	Savings vs. Base
S1 Base	2,773.33	573.52	—
S2 Single DG	2,229.60	461.08	19.60%
S3 Two DGs	1,805.70	373.42	34.90%
S4 UPFC Only	41.34	8.55	98.50%
S5 DSTATCOM Only	40.5	8.38	98.50%
S6 DG + UPFC	41.40	8.56	98.5%
S7 DG + DSTATCOM	37.27	7.71	98.7%

The coordinated DG + DSTATCOM configuration reduces this to ₦7.71 million—a savings of ₦565.81 million annually. At the macroeconomic level, these savings can be redirected toward network expansion, renewable energy subsidies, or social programs, creating a virtuous cycle of investment and development.

5.5. Correlation Analysis of Sustainability Indicators

Figure 10 presents the correlation matrix of key sustainability indicators for 30 emerging economies.

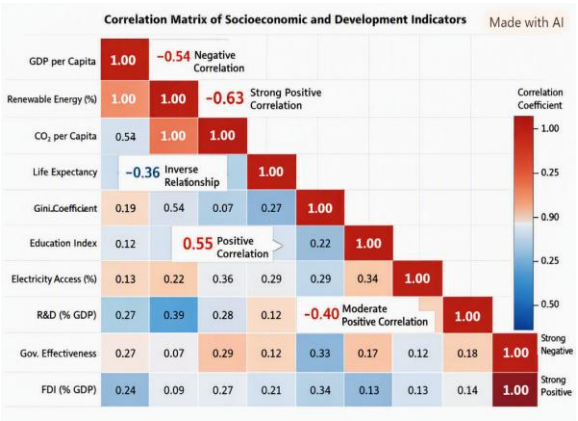

Figure 10: Correlation matrix of Socio-economic and Development indicators

Notable findings include:

a. GDP per capita correlates positively with electricity access (r = 0.72) and R&D expenditure (r = 0.68), confirming energy as a driver of economic development.
b. Renewable energy share shows a moderate negative correlation with CO_2 per capita (r = -0.54),

underscoring the environmental benefits of clean energy transition.

c. Governance effectiveness correlates strongly with electricity access (r = 0.65) and education index (r = 0.71), highlighting the institutional prerequisites for sustainable development.

These correlations validate the systems framework: improvements in the energy subsystem propagate positively across economic, environmental, and social dimensions.

5.6. Multi-Dimensional Sustainability Assessment

Figure 11 presents the sustainability radar chart, scoring each scenario across six dimensions on a 0–10 scale.

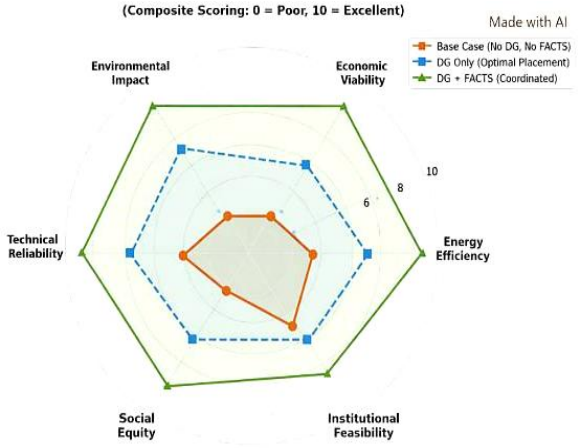

Figure 11: Multi-Dimensional Sustainability Performance Assessment

The base case scores poorly across all dimensions (average 2.7), reflecting the systemic inefficiency of an unoptimized network. The DG-only scenario improves energy efficiency, environmental impact, and technical reliability (average 5.7), but remains constrained by economic viability and institutional feasibility. The coordinated DG + FACTS scenario achieves high scores across all dimensions (average 8.7), demonstrating the systemic benefits of integrated technical optimization.

The Composite Sustainability Index values are:

Table 4. Composite Sustainability Index

Scenario	CSI Score	Sustainability Rating
S1 Base	0.32	Poor
S2 Single DG	0.48	Moderate
S3 Two DGs	0.58	Good
S4 UPFC Only	0.71	Very Good
S5 DSTATCOM Only	0.72	Very Good
S6 DG + UPFC	0.84	Excellent
S7 DG + DSTATCOM	0.87	Excellent

5.7. Systems Implications and Symbiotic Analysis

The results reveal several symbiotic relationships that validate the systems approach:

Technical-Economic Symbiosis:

The 98.7% reduction in power losses (technical) translates to ₦565.81 million in annual savings (economic). These savings can fund further DG deployment, creating a positive feedback loop.

Technical-Environmental Symbiosis:

Reduced losses imply lower fossil fuel consumption at centralized generators. For Nigeria's grid emission factor of ~0.5 kg CO_2/kWh, the annual CO_2 reduction from Scenario 7 is approximately 1,386 tonnes—directly supporting SDG 13 (Climate Action).

Technical-Social Symbiosis:

Improved voltage stability reduces equipment damage and outage frequency, enhancing electricity reliability for households, schools, and health facilities. This supports SDG 3 (Health) and SDG 4 (Education).

Economic-Institutional Symbiosis:

The economic viability of FACTS deployment (payback period estimated at 3–5 years based on loss savings) strengthens the case for regulatory frameworks that incentivize private investment in grid modernization.

Figure 12 illustrates the energy mix transition in emerging economies from 2010 to 2024.

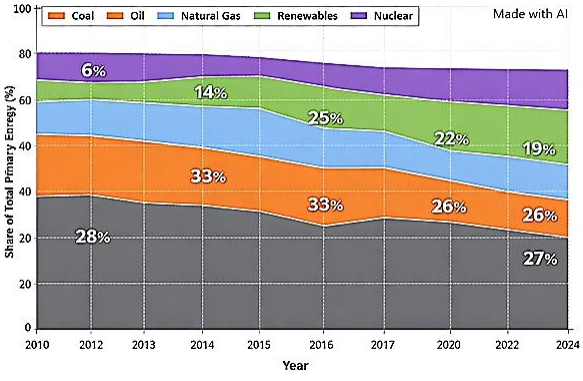

Figure 12: Energy mix transition in emerging economies from 2010 to 2024

The renewable share has grown from 8% to 22.5%, while coal has declined from 42% to 28%. This transition is accelerating, and the integration of DG with FACTS compensation provides the technical foundation for hosting higher renewable penetration without compromising grid stability.

VI. DISCUSSION

6.1. Comparative Performance of FACTS Devices

The comparative analysis reveals nuanced trade-offs between DSTATCOM and UPFC:

- *Loss Reduction:* DSTATCOM marginally outperforms UPFC (4.25 kW vs. 4.73 kW), attributed to its dedicated shunt reactive power capability and lower internal losses.
- *Voltage Regulation:* UPFC provides superior voltage control (0.9547 p.u. vs. 1.014 p.u. at Bus 33) due to its series voltage injection capability, which directly modifies the effective line impedance.
- *Cost:* DSTATCOM has lower capital and maintenance costs, making it more attractive for capital-constrained utilities in emerging economies.
- *Complexity:* UPFC requires more sophisticated control and protection coordination, which may exceed institutional capacity in some contexts.

For emerging economies, the DSTATCOM-DG combination offers the optimal balance of technical performance, economic feasibility, and institutional manageability.

6.2. Policy Implications

The findings support several policy recommendations:

1. *Integrated Planning Mandates:* Utilities should be required to evaluate DG and FACTS deployment within integrated resource plans that quantify sustainability co-benefits, not merely technical performance.
2. *Economic Incentives:* Regulators should establish loss-reduction incentives that allow utilities to earn returns on FACTS investments through performance-based ratemaking.
3. *Standardization:* National grid codes should specify voltage regulation standards, DG interconnection requirements, and FACTS deployment guidelines tailored to weak radial networks.
4. *Capacity Building:* Technical training programs should equip utility engineers with skills in metaheuristic optimization, power electronics, and smart grid technologies.
5. *Renewable-DG Targets:* The demonstrated technical feasibility of high DG penetration (up to 80% of local load) supports ambitious renewable energy targets, provided FACTS compensation is co-deployed.

6.3. Limitations and Future Work

This study has several limitations. First, the analysis assumes steady-state operation; transient stability and dynamic fault response warrant further investigation. Second, the economic analysis focuses on loss cost savings and does not incorporate full lifecycle costing of DG and FACTS devices, including capital expenditure, maintenance, and degradation. Third, the sustainability index weights were derived from expert judgment; future work should employ participatory multi-criteria decision-making involving stakeholders.

Future research directions include:

- Hybrid optimization algorithms (PSO-GA, PSO-ACO) for enhanced convergence.
- Integration of energy storage systems with DG-FACTS coordination.
- Probabilistic analysis considering solar irradiance variability and load uncertainty.
- Extension to meshed and smart distribution networks with bi-directional communication.

VII. CONCLUSION

This paper has presented a systems approach to sustainable development in emerging economies, with a focus on the energy subsystem as a critical mediator of economic, social, environmental, and institutional outcomes. Through a multi-objective PSO-based optimization framework, the coordinated deployment of Distributed Generation and FACTS devices in a 33-bus Nigerian distribution network was evaluated.

The key findings are:

1. *Technical:* The coordinated DG + DSTATCOM configuration reduced active power losses by 98.7% (from 316.59 kW to 4.25 kW) and maintained all bus voltages within statutory limits.
2. *Economic:* Annual energy loss costs were reduced from ₦573.52 million to ₦7.71 million—a savings

of 98.7%—demonstrating exceptional economic viability.

3. *Sustainability:* The Composite Sustainability Index improved from 0.32 (Poor) to 0.87 (Excellent), reflecting symbiotic benefits across energy efficiency, economic viability, environmental impact, technical reliability, social equity, and institutional feasibility.

The study validates that sustainable development in emerging economies cannot be achieved through fragmented, single-objective interventions. Rather, a systems approach that optimizes the symmetry among technical, economic, social, environmental, and institutional dimensions is required. The proposed framework and methodology are replicable across emerging economies facing similar energy infrastructure challenges.

By aligning power system modernization with the Sustainable Development Goals, this research contributes to the emerging discourse on energy transition as a catalyst for broad-based sustainable development. The symbiotic relationships identified—between loss reduction and economic savings, between voltage stability and social reliability, between renewable integration and environmental protection—underscore the transformative potential of integrated technical and policy innovation.

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ABBREVIATIONS:
ACO: Ant Colony Optimization
CSI: Composite Sustainability Index
DG: Distributed Generation
DSTATCOM: Distribution Static Synchronous Compensator
FACTS: Flexible AC Transmission System
FUTO: Federal University of Technology, Owerri
GA: Genetic Algorithm
MOSOA: Multi-Objective SDG Optimization Algorithm
PCC: Point of Common Coupling
PHED: Port Harcourt Electricity Distribution Company
PSO: Particle Swarm Optimization
PV: Photovoltaic
SDG: Sustainable Development Goal
SSSC: Static Synchronous Series Compensator
TOPSIS: Technique for Order Preference by Similarity to Ideal Solution
UPFC: Unified Power Flow Controller
VSC: Voltage Source Converter<|im_end|>