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Design and Planning of a Smart Distribution Network for Power System Reliability: Case Study of Nigerian University Campuses

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ABSTRACT: Power system reliability is essential for ensuring consistent and efficient energy delivery in modern distribution networks of Nigerian Universities. This study focuses on designing and planning a smart distribution network to improve the reliability and sustainability of the power system in Nigerian Universities taking Ajayi Crowther University as a case study. The paper addresses existing challenges such as frequent outages, load imbalances, and inefficiencies by integrating renewable energy sources such as solar photovoltaic systems and wind turbines, along with automated fault detection and load management technologies. Intelligent algorithms and real-time energy monitoring enable predictive maintenance, dynamic load optimization, and targeted conservation strategies, such as automated lighting and temperature adjustments. A comprehensive assessment of the University's current energy infrastructure guides the optimization of load distribution, fault tolerance, and energy flow within the network. The design reduces dependence on external grid supply and diesel generators, lowering environmental impact while ensuring seamless power supply for students, staff, and faculty. Reliability measurements, such as the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI), evaluate the system's performance, demonstrating significant improvements in reliability, cost savings, and energy efficiency. This paper provides a roadmap for sustainable energy management and connectivity, establishing a model for similar institutions to address energy challenges and promote sustainable development goals.

KEYWORDS: Smart distribution network, Renewable energy sources, Fault detection, load management technologies, Power system reliability

1.0 INTRODUCTION

The key for the effective transmission of electricity to the load center necessitates the design and implementation of a dependable and consistent delivery network, together with efficient power provision to certain premises, which may be optimized via a well-structured electrical power distribution system. Balancing demand and supply in the economics of power systems planning and operation has been a moving target for decades [1]. Ajayi Crowther University is a renowned institution committed to academic excellence and technological innovation. With the growing student population and expanding campus facilities, there is a pressing need to modernize the University's network infrastructure. Typically, a distribution network generally comprises substations, primary feeders, transformers, and distributor and service mains, while renewable energy sources are widely being used to meet the energy demand [2]. The current network setup, while functional, lacks the agility, security, and scalability required to support the institution's evolving needs. The design of a smart network system can make Ajayi Crowther University's campus more efficient, sustainable, and user-friendly. This involves using various technologies like renewable energy sources, and smart distribution network devices. To start with, it is mandatory to conduct an analysis of the institution's energy consumption patterns and network infrastructure. This will help identify areas for improvement and determine the best strategies to implement. Gathering data on energy usage and network performance will be crucial in making informed decisions. The many advancements in renewable energy sources and their incorporation into distribution networks render the network susceptible. The extent of vulnerability is contingent upon the control and architecture of networks, whereas management is crucial for maintaining network functionality during standard operations. Energy generating at the distribution level offers advantages for both the consumer and the energy supplier, since it can diminish transmission losses and lower power generation costs. The primary elements of a conventional power system consist of power generating, transmission networks, and distribution networks. Generators are accountable for generating the necessary power from various sources like fossil fuels, nuclear energy, and renewable resources. The transmission systems are created to function effectively. Transporting substantial energy from centralized power plants to key energy use sites. The distribution systems then ensure that the energy is delivered to all electricity consumers in the system at the correct voltage and frequency [3]. Distribution denotes the processes involved in transporting and storing a product from the supplier phase to the customer phase within the supply chain. Distribution is a crucial determinant of a firm's total profitability as it directly influences both supply chain expenses and customer satisfaction. Effective distribution can facilitate the attainment of diverse supply chain objectives, encompassing both cost efficiency and heightened responsiveness. Consequently, firms within the same sector frequently opt for markedly distinct distribution networks [4-6]. The design of a distribution network seeks to organize and configure the network, establishing the number of echelons and specifying the kind, size, quantity, and placement of facilities for temporary product storage enroute to end customers. The design and planning of distribution networks are regarded as critical components in the establishment and operation of a distribution system [7]. The design of the distribution network aims to ensure that distribution systems can accommodate demand growth in the most timely, cost-effective, dependable, and safe manner possible [8]. Designing a distribution network generally necessitates comprehensive planning that commences a decade or more prior to construction. Two essential elements of this procedure are precise forecasting of future power consumption and proactive planning for system upgrades and expansions. This entails choosing suitable facilities and equipment to substitute obsolete assets that have surpassed their functional lifespan. This standard method of network design is typically utilized in traditional one-way distribution systems, where energy flows unidirectionally from high-voltage transmission networks to low-voltage distribution feeders. Traditional distribution planning seeks to ensure a dependable and cost-effective energy supply with minimal expenditure. by predicting peak load demands and developing optimal network schemes. As the share of steam-turbine-based thermoelectric power generation declines, the function of distributed generation (DG), including renewable sources like photovoltaic and wind plants, becomes more prominent in fulfilling increasing electricity demand. This shift reduces the need for extensive transmission system development while necessitating upgrades to distribution networks for better operation efficiency [9]. The high penetration of DGs introduces challenges such as bi-directional power flow, uncertainty in power output, and complications for network protection strategies. Additionally, distribution network operators (DSOs) must adopt advanced information and communication technologies to accommodate these changes. The rise of active distributed networks (ADNs) integrating distributed energy resources (DERs) like energy storage and demand-side management marks a significant evolution from traditional passive networks, previously focused on centralized power generation and one-way transmission. This shift reflects a growing focus on distributed energy systems, which require careful planning and management to ensure efficiency and reliability [10,11].

2.1 Materials and Methods

2.1Network reconfiguration in the distribution system

Distribution network reconfiguration (DNR) was employed due to its capacity to reduce power losses (primary objective) and achieve load balancing (secondary effect) among the main distribution feeders.

2.2 Definition of distribution network reconfiguration technique

The study evaluates the effectiveness of distribution network reconstruction methods using the IEEE 10-bus system, comparing three approaches and highlighting the State of Equilibrium (SOE) method as the most efficient for solving reconfiguration problems. The research incorporates Genetic Algorithm (GA) technology, widely used in network reconfiguration, and integrates it with OpenDSS, a distribution simulation software, through its Common Object Model (COM) features, with MATLAB facilitating the coordination of GA and simulation outputs. A daily load profile with 1-hour resolution is used to predict load demand and distributed generation (DG) output, generating optimal time-series reconfiguration strategies for real-time network adjustments. The study compares the GA-based approach to a conventional binary traversal search algorithm, providing a performance benchmark.

2.3 Distribution network reconfiguration methodology using hybrid heuristic-genetic algorithm

A hybrid heuristic-genetic algorithm-based approach was developed for optimal distribution network reconfiguration, enabling the identification of the optimal network topology for each hour based on predicted load demand and distributed generation output. The methodology combines heuristic methods and genetic algorithms to minimize network losses and optimize loading conditions while adhering to voltage and power rating limits.

The objective is to minimize network losses and maximise network loading framework. The two objective functions are given as follows:

1. Minimization of total network active power losses:

$$\min \sum P_{Totalloss} = min \sum k \in Nb_r; k = (i,j) g_k (V_i^2 + V_j^2 - 2V_iV_j cos\theta_{ij} \dots\dots\dots\dots (1)$$

where:

- $P_{Totalloss}$ - the total active power losses in the network
- N_{br} —set of online branches in the distribution network,
- g_k —conductance of k^{th} branch that connects bus i and bus j,

- V_i —voltage magnitude of bus i,
- δ_{ij}—voltage angle difference between bus i and bus j.

2. **Optimal element load balancing:**

$$\min \sum L_{index} = min \sum k \in Nb_r; k = (i,j) w_k (P_k^2 + Q_k^2 S_{nk} \dots\dots\dots\dots\dots\dots\dots\dots . (2)$$

where:

- L_{index}—network loading index,
- P_k—active power flow through branch k (connecting bus i and bus j),
- Q_k—reactive power flow through branch k (connecting bus i and bus j),
- S_{nk}—rated power of branch k,
- w_k—weight factor assigned to branch k.

Equation (1) defines expression for total network power losses based on full AC power flow equation. The full non-linear AC power flow is calculated for each evaluation of fitness function. Equation (2) defines the total network loading (balancing) index, in which the branch loading is weighted by the factor w_k. This equation is used in cases when the objective function of network reconfiguration is to balance the network element loading and distribute the load in a similar way across different network feeders. The weighting factor is introduced to allow the user to balance element loading in specific areas of the distribution network, while neglecting loading levels in other network parts. Using different values of weighting factors w_k, for example, balance the loading of the first few sections of all feeders, while neglecting other network parts.

In addition to the different objective functions, the optimal radial topology has to satisfy operational constraints such as:

$$V_{imin} \le V_i \le V_{imax}\ \forall i \in N_{bus} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . .3$$

$$S_k \le S_{nk}\ \forall k \in N_{bus} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4$$

where N_{bus} is a set of the network busses and $V_{imin} \le V_i \le V_{imax}\ \forall i \in N_{bus}$ is minimum/maximum voltage magnitude limit for the bus i. In each step of the proposed algorithm, the voltage and power rating limits are examined and switching operation is not allowed if these limits are violated. In cases when limits are violated, the processes, such as the initialization of candidate solution, crossover or mutation, are repeated until a feasible network solution is obtained.

During the algorithm's execution, switching operations are restricted when these limits are exceeded, prompting iterative processes such as solution initialization, crossover, or mutation until a feasible solution is achieved. This innovative approach demonstrates the potential of hybrid heuristic-genetic algorithms in enhancing power distribution network performance through effective topology optimization as shown in Figure 1.

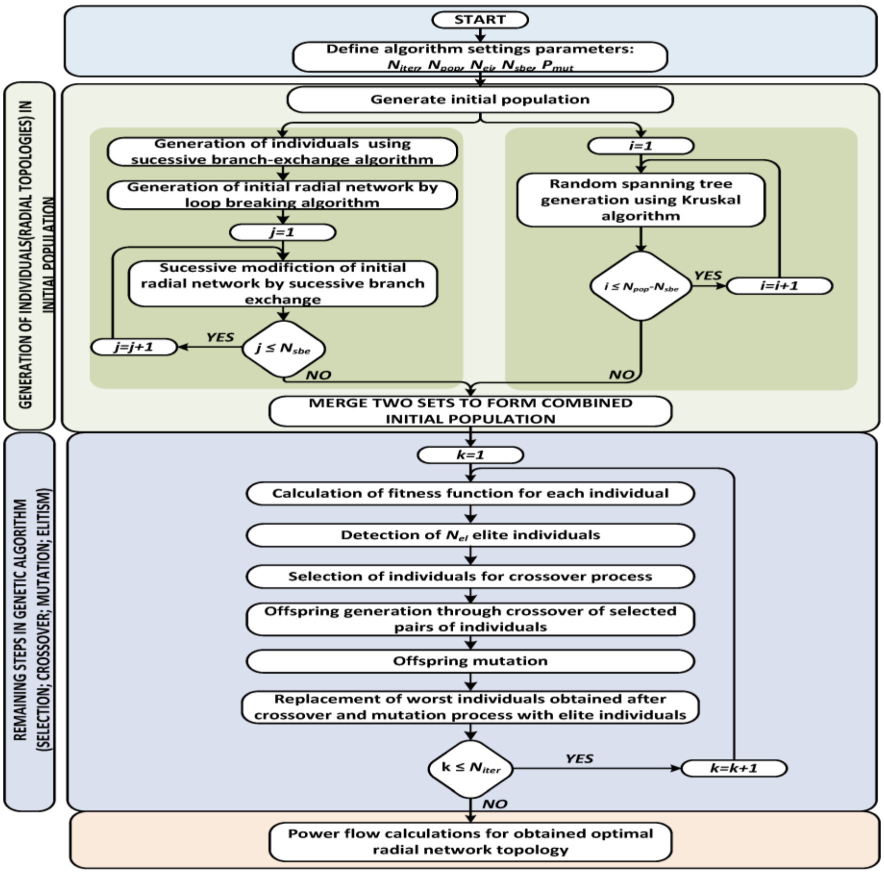

Figure 1: Flowchart of the Hybrid Heuristic-Genetic Algorithm employed to address the Optimal Reconfiguration Problem.

- N_{iter}—number of evolution cycles
- N_{pop}—population size
- N_{ei}—number of elite individuals in each population
- N_{sbe}—number of individuals generated by successive branch exchange algorithm
- P_{mut}—mutation probability.

3.0 RESULTS AND DISCUSSIONS

3.1Data preparation results

The model was validated with an IEEE 10-bus network, incorporating comprehensive data to ensure accurate simulations. Detailed branch and cable specifications provided precise parameters for the network model. Hourly load profiles, representing demand variations at each node, were graphically illustrated, highlighting fluctuations over time. Additionally, predicted renewable generation data such as PV and wind farm outputs sourced from the CREST Domestic Electricity Demand Model, were integrated to model renewable contributions. Figure 2 depicting load and renewable generation outputs showcased the variability and potential of incorporating renewable energy into the distribution network, validating the framework's ability to simulate realistic operational conditions.

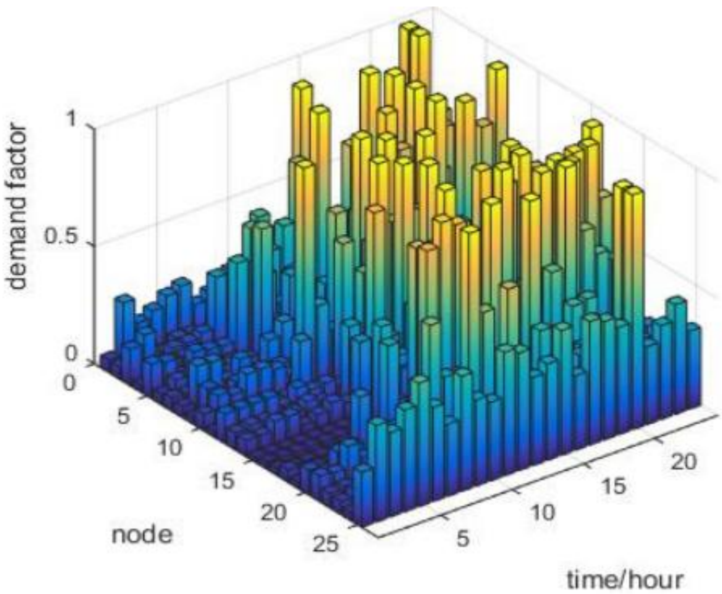

Figure 2: Nodes load profiles for IEEE-10 bus network

The input data for renewable generation, considering photovoltaic and wind farms, is presented in Figures 3 and 4. The data are derived from the CREST Domestic Electricity Demand Model. Table 1 presents the comprehensive data on photovoltaic and wind generations.

Table 1: Predicted Photovoltaic and Wind Energy Generations for a 10-Bus Distribution Network

S/No	Time (h)	PV Predictive hourly generation (Capacity Factor)	Wind Predictive hourly generation (Capacity Factor)
1	0:00	0.00	0.90
2	1:00	0.00	0.90
3	2:00	0.00	0.88
4	3:00	0.00	0.96
5	4:00	0.00	1.00
6	5:00	0.02	0.93
7	6:00	0.18	0.94
8	7:00	0.34	0.82
9	8:00	0.39	0.56
10	9:00	0.61	0.60
11	10:00	0.85	0.57
12	11:00	0.83	0.62
13	12:00	0.72	0.68

14	13:00	0.60	0.80
15	14:00	0.56	0.92
16	15:00	1:00	0.97
17	16:00	0.84	1.00
18	17:00	0.63	1.00
19	18:00	0.64	1.00
20	19:00	0.61	0.81
21	20:00	0.16	0.37
22	21:00	0.03	0.32
23	22:00	0.00	0.30
24	23:00	0.00	0.34

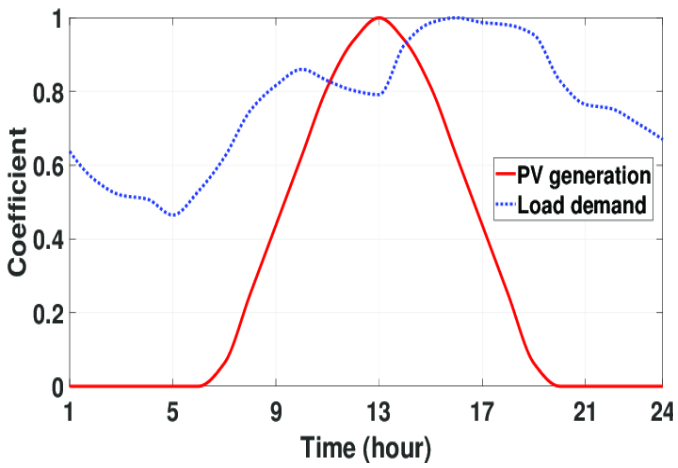

Figure 3: Predicted PV generation for the 10 bus system with the load management

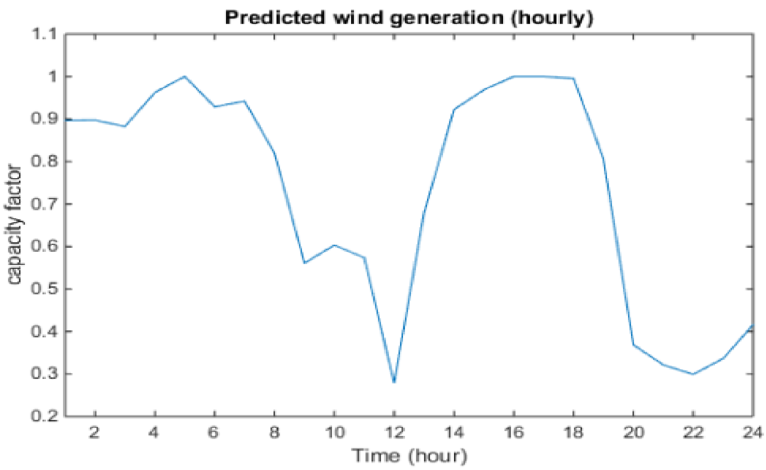

Figure 4: Predicted wind generation for the 10 bus system

3.2 Case Analysis

The traversal approach may examine the potential reconfiguration topologies during a specified timeframe and compute the associated power losses. The technique yields critical information, including the simulations durations and the most effective reconfiguration strategy for the simulations. The identical load profiles and binary encoding techniques utilized in the subsequent genetic algorithms are initially executed in a binary traversal fashion to maintain comparability. The results of the simulation are presented in Table 2. Network reconfiguration technology has been demonstrated to diminish power losses at every time interval. The reduction in power losses ranges from 0.1% to 0.2% during daylight hours, contingent upon the associated power delivery.

Table 2: Quantitative outcomes of binary traversal method

S/No	Time (h)	Optimal String	Optimised Power Losses (MW)	Actual Power Losses (MW)
1	1	10000	0.094	0.096
2	2	01111	0.068	0.070
3	3	10000	0.073	0.075
4	4	01111	0.071	0.073
5	5	01111	0.072	0.074
6	6	10000	0.061	0.063
7	7	10000	0.050	0.051
8	8	10000	0.033	0.034
9	9	10000	0.038	0.039
10	10	10000	0.027	0.028
11	11	10000	0.026	0.027
12	12	01111	0.026	0.027
13	13	10000	0.025	0.026
14	14	10000	0.033	0.034
15	15	10000	0.028	0.029
16	16	01100	0.027	0.028
17	17	10000	0.026	0.027
18	18	01011	0.024	0.025
19	19	10000	0.026	0.027
20	20	01111	0.030	0.031
21	21	01111	0.031	0.032
22	22	01111	0.030	0.031
23	23	10000	0.032	0.033
24	24	10000	0.044	0.045

Case Study Implementation

The case study applied a traversal approach and a hybrid heuristic-genetic algorithm to optimize network reconfiguration and enhance performance. The traversal method explored all possible topologies within a specific timeframe, calculating power losses and benchmarking metrics such as simulation time and optimal reconfiguration strategies. Results showed that reconfiguration reduced power losses by 0.1% to 0.2% during daytime hours, highlighting the potential for efficiency gains. The hybrid heuristic-genetic algorithm, combining heuristic methods for quick solutions with genetic algorithms for robust optimization, dynamically adjusted the network topology based on hourly load demands and renewable energy outputs. This approach minimized power losses, maintained voltage stability, and demonstrated superior efficiency and reliability by continuously adapting to changing network conditions.

4.0 CONCLUSIONS

This study focused on designing and planning a smart distribution network to augment the dependability, flexibility, and sustainability of the power system at Ajayi Crowther University. Addressing the limitations of the existing radial network, a robust ring network system was proposed, incorporating smart technology and renewable energy integration. A thorough assessment of the university's energy usage and infrastructure identified inefficiencies and informed the system design. The ring network structure, chosen for its redundancy and fault tolerance, featured IoT-enabled devices for real-time monitoring, control, and efficient energy management. Solar panels and wind turbines were strategically integrated to reduce reliance on external power and promote clean energy usage. Collaboration with the university's works unit ensured the design addressed practical challenges, such as budget constraints and infrastructure limitations. Additionally, a comprehensive data management system was developed to process and analyze the data generated by smart devices, enabling continuous optimization of the network. The project establishes a sustainable and adaptable power distribution framework, providing a foundation for future advancements.

5.0 RECOMMENDATIONS

The implementation of a smart distribution network at Ajayi Crowther University highlights numerous opportunities for future advancements in power system reliability and sustainability. Recommendations include expanding the integration of diverse renewable energy sources like geothermal and biomass, optimizing energy storage solutions through advanced and hybrid systems, and incorporating smart building technologies to enhance energy efficiency at the facility level. Emphasis should also be placed on strengthening cybersecurity measures to protect against digital threats, leveraging machine learning and artificial intelligence for predictive maintenance and real-time optimization, and exploring supportive policy and regulatory frameworks to promote adoption. Community engagement, collaboration with industry partners, and cross-institutional learning are critical for fostering innovation, ensuring social acceptance, and setting a global standard for sustainable energy practices. These recommendations provide a roadmap for future research and implementation, driving further innovation and resilience in smart grid systems.

CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

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