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RESEARCH ARTICLE

Selecting Communication Technologies for an Electrical Substation Based on the AHP

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ABSTRACT Traditional communication technologies for distribution substations will soon have difficulties meeting the needs of emerging applications. This is due to exponential population growth and future energy demands, necessitating a reliable and fast response from the grid. Moreover, to the best of our knowledge, academic work regarding selecting appropriate communication technologies within electrical distribution substations is scarce. Thus, this research aims to aid decision-makers in selecting the best communication technology for an electrical distribution substation. This study uses the Analytical Hierarchy Process (AHP) to shortlist, rank, and decide the most suitable communication technologies for an electrical substation based on its geographical location. Technical, economic, infrastructure, and service standards are the main criteria used for the selection. The weight obtained from the pairwise comparison for each criterion is based on the literature review and expert opinions. The results comprise rankings of communication technologies tailored to different demographic settings, including urban, suburban, and rural areas. These rankings are generated through a comprehensive pairwise comparison process, building upon the earlier comparative analysis. Additionally, a structured framework has been developed to select the most appropriate communication technology for electrical substations in urban, suburban, and rural areas. According to our study, fiber optics, Narrowband Power Line Communication (NBPLC), and Long Range (LoRa) technology are the most prominent communication solutions for urban and suburban regions. Meanwhile, satellite communication (SATCOM), NBPLC, and fiber optics are prominent in rural areas.

INDEX TERMS Analytical hierarchy process (AHP), communication technologies, energy, multicriteria decision-making (MCDM), smart grid, substations.

I. INTRODUCTION

Communication network in substations is critical for information technology (IT) data transfer and operational technology (OT) data, such as billing and supervisory control and data acquisition (SCADA). Currently, at the electrical distribution substation level, the most used communication technologies are cellular and pilot cables. However, more applications are emerging in the future, such as electric vehicle (EV), Advanced Metering Infrastructure (AMI), as well as building and home automation. The current communication technologies used will no longer support these evolving applications.

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Issues and challenges experienced in active distribution networks for current communication solutions are discussed in [1], including but not limited to, evolving communication requirements and demands, stringent dependability, security issues and interoperability problems. Hence, reassessing the existing communication technology is crucial in the substation; upgrade it if necessary. An inaccurate decision on the appropriate communication technology for an electrical distribution substation would have remarkable technical and financial consequences. Thus, further research is required to determine potentially suitable communication technologies for the electrical distribution substation.

The current communication infrastructure in the distribution grid will be further stressed by the expected exponential growth in population, the anticipated increase in distributed energy resources, and the rise in end-user applications connected to the networks. The increase in power consumption, bandwidth, and data rate may cause the distribution grid to experience network congestion, latency, jitter, and network failure. Thus, to meet these future demands, viable future communications technologies must be investigated, particularly for electrical distribution substation communication [2].

The operational communication networks used by power utility companies use various communication media. Copper, fiber optics, and wireless-based media are the three main media that transmit data in smart grid systems [3]. The use of the existing electrical grid for data communication is made possible by Power Line Communication (PLC). Narrowband PLC is suitable for transmitting small or low-speed data over long-distance high voltage (HV) power transmission lines, and a dedicated infrastructure integrated into the substation provides a signal path, connecting substations over long distances (>500 km) without repeaters. Fiber optics media, a sophisticated cable, are gaining popularity due to their infinite bandwidth and resilience to external elements like electromagnetic interference [3].

Sen and Bakka examine the use of wireless networks in substation automation [4]. The most common wireless technologies have been outlined in the international communication standard IEC 61850, such as ZigBee, WiMAX, WLAN, Wireless HART, etc. Wired technology has drawbacks, including the need for trenches and manual labor for assembling and testing. Meanwhile, wireless technology presents numerous advantages over wired technologies, such as ease of installation, low cost, and extensive range. Another study proposes an intelligence inspection at a 750kV substation using a 5G wireless communication [5]. The overall advantages of 5G include ensuring data stability, timeliness, and reliability, as well as improving the economics of 750kV substation intelligent inspection to meet its objective.

This paper aims to indicate the selection process of finding the most suitable communication technologies for an electrical distribution substation according to demographics. We have chosen the Analytical Hierarchy Process (AHP) as it provides a structured and systematic framework for evaluating and ranking complex alternatives, which is especially relevant in decision-making processes concerning communication technology selection for electrical substations. Throughout the pairwise comparison phase, subject matter experts actively engage by providing their informed opinions, contributing to the final results derived exclusively from the AHP methodology. The AHP was employed because of its capacity to strike a balanced approach, avoiding excessive rigidity while not entirely relying on quantitative data. Expert engagement is integral to ensure decisions are adaptive and evidence-based, rendering this research highly applicable for practical implementation. We believe that AHP is a suitable tool to address the multicriteria decision-making challenges in this context.

Our current study shows that the AHP method is well-suited for providing effective solutions to the decision-makers involved. AHP was deliberately chosen as we aimed to create a decision-making process that incorporates dynamic human input aligned with real-world practicality. While we acknowledge that there may exist simple and potentially accurate methods that lack human intervention, we aim to bridge the gap between academic research and practical implementation.

Furthermore, to the best of our knowledge, there is a notable absence of research papers focusing on selecting suitable communication technologies, specifically within electrical distribution substations. Thus, our research aims to offer a pragmatic approach that can be readily implemented in real-world scenarios.

To the best of our knowledge, this study pioneers the use of AHP in finding suitable communication technologies in electrical distribution substations.

The contributions of this paper are as follows:

1) Identifying and characterizing the important criteria and alternatives for selecting the communication technology in an electrical distribution substation
2) Developing an AHP structure involving the scaling, weighting, and ranking of the alternatives based on urban, suburban, and rural demographics
3) Providing a ranking of communication technologies for electrical distribution substations in urban, suburban, and rural areas

The remainder of the paper is structured as follows. Section II examines the recent application of AHP. Section III discusses the methodology of the AHP structure. Section IV discusses the overall results; Section V is the discussion part, and Section VI provides the conclusion.

II. LITERATURE REVIEW

The conventional power distribution network is designed to distribute electricity and information in a one-way flow from the transmission network to consumers via electrical distribution substations. Supply and demand trends for electricity have changed since the introduction of distributed energy resources (DERs) and other end-user applications, such as EVs, AMIs, and smart appliances. Meanwhile, the traditional distribution communication networks are unsuitable for adding these connections [6]. This may require a suitable communication in the distribution substation to accommodate the rapid response required for supply and demand from consumers to ensure effective power distribution.

Thus, this research mainly focuses on planning communication technology for electrical distribution substations. This study proposes a method to find suitable communication technologies in various demographics (urban, suburban, and rural areas) by integrating the machine learning (ML) model and one of the Multicriteria Decision-Making (MCDM) techniques, the Analytical Hierarchy Process (AHP). The integration aids decision-makers in identifying the possible suitable communication technologies for electrical distribution substations, along with the list of potential criteria concerning the decision-making.

MCDM is particularly useful in this communication field because each problem requires a unique decision. MCDM deals with complex problems that depend on the solution methods selected by decision-makers (DMs). One of the MCDM methods, AHP, has been widely used in multiple important sectors, including medicine and healthcare [7], [8], business [9], [10] transportation [11], [12] and renewable energy [13], [14]. This method is used for various purposes, such as selection, cost-benefit analysis, forecasting, evaluation, decision-making, priority and ranking, and planning and development. The standard terms used in AHP are shown in Table 1 [15].

TABLE 1. Common term used in AHP.

Term	Definition
Decision-makers (DM)	Experts to weigh tasks given
Goal	What DM want to accomplish
Criteria	The options to be compared to and assessed
Alternatives	Option or decisions to choose orrank
Weights	Representing the relative importance of the criteria

AHP is used as a guideline to determine the weight of each criterion input data. It is appropriate for most goals (plan, identify, select, and assess) with a minimal number of criteria. It can function independently based on the criteria and their hierarchical relationships. In general, the AHP is demographic-driven, with each demographic influencing design and performance parameters.

In maintenance planning, AHP is useful for integrating multiple criteria for equipment conditions, such as determining the state of a substation's health. This technique has proven effective in evaluating the condition of 74 substations within the Tokyo Electric Power service areas [16]. Within five years, the effectiveness and practicability of AHP were assessed using the developed procedure. The condition indices were compared across three regions: urban, suburban, and remote areas, with the urban region having the lowest indices, followed by suburban and remote (a smaller index is generally preferred). These results were then validated by maintenance engineers. Using the AHP method, decision-makers can also foresee how their substations will fare in their overall health. In [17], a method is proposed for the environmental evaluation of a substation using fuzzy AHP. A model's goal is evaluated through its capacity to reduce the substation's pollution emissions and optimize its layout design. Based on the outcome, waste and environmental management levels should be highly considered. The authors also listed several suggestions for improving waste and environmental management.

Another difficult decision-making problem is evaluating, selecting, or planning the site or location for various projects, such as smart grids, power plants, and transportation. For example, Arief et al. [18] presented an AHP method for comparing the suitability of renewable power plants to conventional power plants. This method involves six criteria: safety and security, resources, public acceptance, energy cost, construction time, and carbon dioxide emission. The alternatives considered in the research were nuclear, thermal, and hydropower plants. The hydropower plant, with a priority value of 0.46, is shown to be the best, followed by the thermal power plant (0.29) and the nuclear power plant (0.24) [18]. The same concept was applied in [19], where the authors evaluated the suitability of renewable power plants as compared to conventional energy power plants in Pakistan. The process involved three main criteria: technical, economic, and environmental, along with eight sub-criteria. The results indicate that renewable power plants are preferable over conventional power plants due to their low cost and sustainability.

To locate promising sites for solar farms, this paper employs a decision analysis based on the AHP and Fuzzy AHP [20]. To reduce the subjectivity of the factor notation and enhance the outcome of the models, the AHP and Fuzzy AHP were employed. Climate, topography, geographic location, and environmental factors were used to create these broad categories for this research. A total of 15 factors, such as solar radiation, slope, distance from substations, and distance from lakes, were selected, and each criterion was divided into five classes. Sensitivity analysis was used to compare theoretical and effective factor weights to assess their influence. The results of AHP and Fuzzy AHP show that areas suitable for hosting solar farms account for more than 35% (1300 Ha) of the total area of the region. There was no significant difference in decision-making between the two methods for selecting the five highest priorities of attributes for solar power plants. Further, the performed similarity analysis revealed that 32% of the observed gap between AHP and Fuzzy AHP could be explained by factor weights and differences in approach.

Also, the AHP method can be integrated with Geographic Information System (GIS), which creates, edits, visualizes, analyzes, and publishes geospatial information. For example, Sun [21] presented an integrated GIS and AHP methodology to find optimal locations of electric vehicle charging stations in Nanshan District, Shenzhen City, China. The author also proposed Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to rank the alternative stations. The model uses the AHP method to calculate the weights for the selected element sets. The TOPSIS method was utilized to determine the final ranking of the closest alternative to the optimal solution. A total of four criteria and 18 sub-criteria were considered for society, transportation, environment, and technology. Another example of AHP-GIS system is proposed by Jong et al. [22], who presented a case study of AHP-GIS system in Sarawak, Malaysia, to identify potential renewable energy sites.

Another study on solar farm site selection has been initiated in [23] by implementing AHP and GIS. Study criteria for selecting solar photovoltaic (PV) panels are modified to account for the PV plant's installed capacity. In addition, a new technique called optimality-based site growing (OBSG) is proposed to further examine the eligible sites acquired from GIS simulations and find the best locations of PV farms. Since it considers the suitability of neighboring pixels and the distance from the geometric center of the most recent site, the OBSG method and resulting optimality maps provide an all-encompassing way of site selection. The proposed method is tested in Türkiye and found effective in locating large-scale PV plants. Large-scale PV farms of varied capacities (250 MW, 500 MW, and 1000 MW) were evaluated to determine the differences in their applicability. In sum, the proposed approaches yield useful information for locating optimal sites for massive PV farms.

The AHP approach can also be used in the communication network. In [24], the authors proposed two hybrid methods of AHP and back-propagation (BP) neural networks for an operational evaluation of satellite communication networks. The integration of AHP-BP accommodates the BP limitations on requiring a large amount of training data, and labeling sample data is a time-consuming and tedious process. Therefore, the authors proposed using the AHP method to label the sample data instead of it being labeled by the experts, then fine-tuning the label using a combination of the AHP method and the expertise of the experts. The evaluation is compared with Zhang's method, [25] as mentioned in the paper. Benefiting from the advantages provided by the proposed method, the evaluation result can reflect the effectiveness of the satellite communication system [24].

In this paper, authors modified a Fuzzy Logic and AHP-based multicriteria decision-making model in choosing the technology [26]. It is also the first work that attempts to capture the added value of adopting similar and interconnected technologies by referencing an existing hierarchical classification found in the literature. To reflect the multiplicative effect of adopting related and interconnected technologies, the model is paired with a structured taxonomy of Industry 4.0 technologies gleaned from the literature. A panel of decision-makers evaluates the positive impact that each alternative has on each KPI criterion, represented by 27 digital technologies. According to the Defuzzified Scores of the individual digital technologies, Remote Operation of Production ($DS_a = 0.4493$) is the most promising option for enhancing the three KPIs characterizing the sub-process's performance. With a DS_g of 0.3468, Automation is the most promising among all candidate technology groups. Automation outperforms Smart Working, the group with the single best-performing technology. Decision-makers were given three options regarding the outcome of the results.

With the increases in electric vehicle (EV) usage globally, it is necessary to accommodate sufficient charging stations. However, using renewable energy to power charging stations is still in its infancy. This research integrated solar-based electric charging station (EVCS) and solar farm site selection studies utilizing GIS and AHP to provide a methodology for selecting sites for solar-powered EV charging stations [27]. Precedent solar and EVCS site selection studies and expert opinions determined the most important site selection criteria: availability of power, number of EVs, solar energy potential, and land cost. The survey revealed that under economic criteria, power availability is the most crucial factor in choosing a solar EVCS location. However, solar energy potentially ranks the highest when environmental factors are considered. According to social criteria, the distance to high population density centers, social acceptance, and proximity to residential areas were highly rated. Finally, the most significant transportation criteria are the number of EVs, distance from roads/highways, and distance from current EVCS points. Urban planners, decision-makers, and researchers developing solar-supplied EV charging infrastructure stand to gain from the study's findings.

The highlights of AHP are its ease of use and scalability [15]. The overall hierarchy structures of AHP clarify the importance of each element, making it a convenient and straightforward approach. The next section discusses the methodology of the AHP method.

III. METHODOLOGY OF AHP

Due to its flexibility, ease of use, and quick implementation, AHP has been extensively studied and used in various fields to solve complex decision issues. DMs frequently struggle with deciding what is best for achieving their objectives. To overcome this problem, Saaty [28] in 1986 proposed the AHP method, whose broad framework involves the problem of decision-making, the elements or criteria related to the goals, and the alternative solutions. To develop the priorities accordingly, decisions should be made in the following manner [29]:

1) Define the problem and targets properly.
2) Derive several criteria and alternatives from the specified problem.
3) Structure the problem hierarchically, as shown in Figure 1, where the goal of the decisions is placed at the top, followed by the objectives and problem criteria

at the mid-level and the hierarchy structure, usually comprising a set of alternatives, at the lowest level.
4) Pairwise comparison matrices can be built by comparing the elements from the top level with those at the mid and bottom levels. The fundamental scale of importance is then used to evaluate the weightage of the criteria in pairwise comparisons. The scale of importance is summarized in Table 2.
5) Calculate the weightage and consistency ratio (CR).
6) The alternatives were ranked in accordance with their respective weightages.

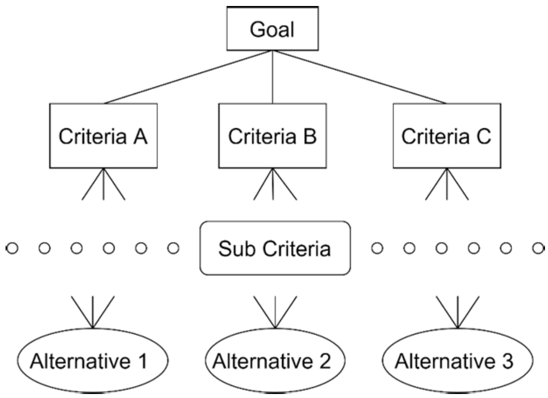

FIGURE 1. Overall view of AHP hierarchy structure.

TABLE 2. The fundamental scale of importance.

Scale of Importance	Definitions	Explanations
1	Equal significance	Equality of two values
2, 3	Slight significance	The value is slightly more important than others
4 ,5	Moderate significance	The value is preferable to the other
6, 7	High significance	The value is strongly preferable to the other
8, 9	Very high significance	The value is highly preferable to the other

In this study, the application of the AHP relies on existing literature reviews conducted by other researchers and the invaluable insights and expertise contributed by subject matter experts. Through extensive discussions and collaborative meetings involving academicians and field experts, a wealth of ideas and perspectives were exchanged to arrive at precise and appropriate solutions.

The criteria selection process involved a collaborative effort between academicians and industry experts from Universiti Tenaga Nasional (UNITEN) and Tenaga Nasional Berhad (TNB). This collective approach ensured a comprehensive and well-rounded set of criteria encompassing academic rigor and practical industry relevance.

The engineers from TNB come from various departments: Asset Management (AM), Supervisory Control and Automation Data Acquisition (SCADA), distribution network (DN), advanced metering (AM), Information and communications technology (ICT), and Energy Service (ES). Meanwhile, the academicians come different backgrounds: fiber optics, photonics, and wireless communication, and they have worked with TNB in the past.

For this research, the criteria and alternatives were meticulously selected, drawing from a comprehensive examination of literature, expert insights, and our prior work [2]. The alternatives were chosen based on their current utilization or suitability for distribution substations, as intricately discussed in our previously published paper. Our research process involved a multifaceted approach that incorporated machine learning techniques for the technical criteria selection. The criteria were derived from machine learning outputs, specifically the 'support prediction' and 'contradict prediction' values. This approach allowed us to identify and exclude certain technical criteria with minimal impact on selecting communication technologies for electrical distribution substations.

The criteria are based on [30], [31], and [32], where studies on telecommunication selection for rural areas as well as insights from experts. While the primary references may be old, the selection criteria remain pertinent. Moreover, we expanded our scope to include rural, urban, and suburban areas. The involvement of experts from various fields played a pivotal role in determining the most suitable criteria for our research.

AHP is heavily involved in pairwise comparison. Pairwise comparison matrices can be built by comparing the elements from the top level with those at the middle and bottom levels. The fundamental scale of importance is then used to evaluate the weightage of the criteria in pairwise comparisons. In this study, the pairwise comparison was performed using Microsoft Excel. There are six steps involved in AHP, as described in the previous paragraph. Each step is thoroughly explained as follows.

A. DEFINE THE PROBLEM

To begin, the decision problem must be specified, and the appropriate criteria and sub-criteria must be assessed. The AHP evaluation criteria and sub-criteria must be verified by interviewing decision-makers working in the communication field. For this study, the main problem is to find suitable communication technologies for the electrical distribution substation.

B. DEFINE THE CRITERIA AND ALTERNATIVES

The next step is to define the criteria, sub-criteria, and the alternatives used in this research. In this study, ten communication technologies are proposed: narrowband power line communication (NPLC), fiber optics, ZigBee, Wireless Fidelity (WiFi), RF Mesh, cellular networks, Narrowband-IoT (NB IoT), Long Range (LoRa), Ultra-high frequency (UHF), and satellite communication (SATCOM).

The demographics to be evaluated for this study are urban, suburban, and rural areas. For this study, the data has been classified to urban, suburban, and rural, including the resident density (Table 3). Thus, each area has appropriate and distinct technology. The alternatives proposed for each area are listed in Table 4. The following step defines the main and sub-criteria of the study. In this work, four main criteria and 12 sub-criteria are included, where the technical criteria comes from the ML algorithm. The main criteria selected are technical, infrastructure, economic, and service standard. Each main criterion is divided into sub-criteria under the same cluster. The listed main criteria and sub-criteria alongside with the definition are tabulated in Table 5.

TABLE 3. Demographic classifications and the residence density.

New Demographic Classifications	Residence Density/km²
Urban	More than 1,500 per km²
Suburban	300–1,500 per km²
Rural	less than 300 per km²

TABLE 4. The proposed are for each alternative.

Alternatives Proposed for Each Area		
Urban	**Suburban**	**Rural**
NBPLC	NBPLC	NBPLC
Fiber optics	UHF	UHF
ZigBee	Fiber optics	Fiber optics
2.4GHz RF Mesh	ZigBee	ZigBee
4G	2.4GHz RF Mesh	2.4GHz RF Mesh
5G	4G	4G
Private LTE + NB IoT	Private LTE + NB IoT	Private LTE + NB IoT
LoRa	LoRa	LoRa
	SATCOM	SATCOM

C. CREATE THE AHP HIERARCHY MODEL

This step creates a model of the problem. According to the AHP methodology, a problem is a related set of sub-problems. Therefore, the AHP method relies on breaking the problem into a hierarchy of smaller problems. Once the goal, criteria, sub-criteria, and alternatives have been identified and defined, these elements are arranged hierarchically, starting with the goal of the problem, followed by level 1 (criteria), level 2 (sub-criteria), and finally, level 3, the alternatives proposed for this problem. The overall view of the AHP hierarchy structure for this study is shown in Figure 2.

D. ESTABLISH PRIORITY AMONGST CRITERIA USING PAIRWISE COMPARISON

The AHP method uses pairwise comparison to create a matrix. These pairwise comparison is based on the Saaty's fundamental scale of importance of 1-9. In this study, the relative importance of the main criteria (example: technical versus economic) is first weighed. This is demonstrated in Level 1, where the scale is the same for all demographics. Then, at the next level, the sub-criteria (example: mobility versus distance) of each main criterion are weighed and done at Level 2. Finally, the alternatives (example: NBPLC versus fiber) for each sub-criteria are weighed. This is done in Level 3, where the rank is specified for each demographic.

TABLE 5. List of main criteria and sub-criteria used in this research.

Main Criteria	Sub-Criteria	Definition
Technical	Mobility	Can specific technologies be mobile
	Distance	Coverage offered by a communication technology
	Scalability	Can the communication technology be scaled
	Data Rate	Amount of data transmitted over a network in a certain period of time
	Line of Sight (LoS)	Refers to the setting when the transmit and receive nodes are not in view of each other due to the presence of obstacles between them
Economic	Capital Expenditure (CAPEX)	Fixed, initial expenditure spent at the beginning of the business
	Operational Expenditure (OPEX)	Ongoing or month-to-month expenditure used to run the business
Infrastructure	Existing Infrastructure	Infrastructure that is already in place at a given location
	Technology Maturity	Technology that has existed and stable in a long period of time
Service Standard	Installation Complexity	The complexity to install the selected communication technology infrastructure in a specific area
	Maintenance Complexity	The complexity to maintain that technology
	Vulnerability	The security of communication technology

E. CALCULATE THE WEIGHTAGE AND THE CR

Following pairwise comparisons, a weighted value is assigned to the element in the pair with the most significant value. The pair's least significant element will be assigned with the reciprocal of the value. The weights are then normalized and averaged to obtain the relative weight for each element in the hierarchical model [33].

A CR is calculated to verify the credibility of the decision-makers' evaluation, knowing that the subjective judgments are frequently clouded by bias [33]. If the CR is less than or equal to 0.1, the pairwise comparison is regarded as consistent. If CR is greater than 0.1, the comparison is inconsistent, and the result is considered unreliable.

For such in [34], William C. Wedley commented that although it has been claimed by Saaty that a consistency ratio of less than 0.10 is preferable, a ratio of less than 0.20 is still regarded as acceptable. For CR less than 0.1, it is considered a rule of thumb. However, in some occasions where there is a large number of criteria, it is possible that CR will be greater than 0.1. For these cases, the greater the matrix size, the more CR with values > 0.1, but < 0.20 are still acceptable as stated in [34]. However, for this research, we deem that the CR less than 0.1 is acceptable, as the matrix size is considerable. Most research papers consider the CR less than 0.1 as a rule of

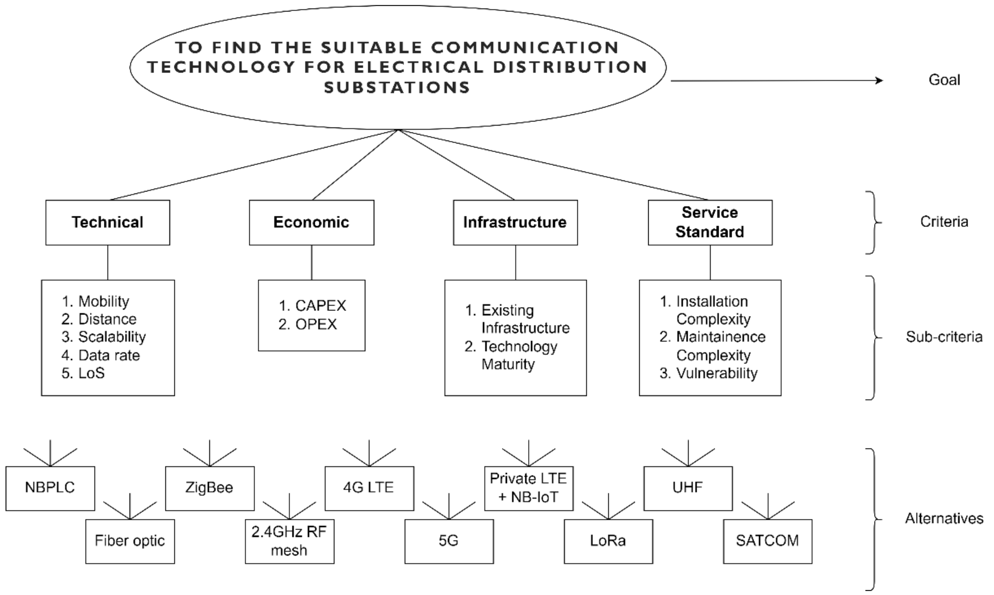

FIGURE 2. Overall view of the AHP hierarchy structure for this study.

thumb, for example in [35], if the number is 0.1 or less, the system will be consistent, but may revisit the verdict. In [36] it is recommended that the value of CR should not exceed 0.1.

F. RANK AND SELECT THE BEST ALTERNATIVE

The final step of AHP is the ranking and selecting the best alternatives for all demographics. This step involves the aggregation by considering the weight of each element in the hierarchy obtained from the pairwise comparison [33]. The process of weighing and adding is repeated until the final priorities of the alternatives at the lowest level are determined. The final weights are then used to rank the alternatives, and the best one is chosen. The next section will analyze the results obtained.

IV. RESULTS

This section discusses the overall results and performance of AHP in finding suitable technologies for electrical distribution substations in each demographic. Pairwise comparisons are used to determine the weightages of each criterion. The pairwise comparison compares the sub-criteria with another sub-criteria within the same group (example: Distance versus Mobility) given by the fundamental scale 1 to 9. This section also includes a final ranking of various alternatives for each demographic. It also discusses the overall analysis and discussion in depth.

Another term used in the AHP process is the Global Priorities (GP). The GP influences the final outcome and ranking, as it is used to find the evaluation score of each technology. The GP is assigned to criteria and sub-criteria. The GP for the sub-criteria is calculated by multiplying the values of, for example, the technical criteria by the mobility criteria. Each summated global priority must equal one, and the value is utilized in the subsequent step.

TABLE 6. Composite priority weights for the criteria and sub-criteria.

Criteria	Level 1	Sub-criteria	Level 2	Global Priorities (%)
Technical (A)	0.3679	Mobility (A1)	0.0645	2.37
		Distance (A2)	0.2781	10.23
		Scalability (A3)	0.2781	10.23
		Data Rate (A4)	0.1013	3.73
		LoS (A5)	0.2781	10.23
Economical (B)	0.1686	CAPEX (B1)	0.7500	12.65
		OPEX (B2)	0.2500	4.22
Infrastructure (C)	0.0956	Existing Infrastructure (C1)	0.7500	7.17
		Technology Maturity (C2)	0.2500	2.39
Service Standard (D)	0.3679	Installation Complexity (D1)	0.0718	2.64
		Maintenance Complexity (D2)	0.1140	4.19
		Vulnerability (D3)	0.8142	29.95

The demographic in this study is defined as resident density per km^2, where, urban has more than 1,500 per km^2, suburban 300–1,500 per km^2, and rural less than 300 per km^2. Table 6 summarizes the composite global priorities assigned to criteria and sub-criteria in the composite priority weighting scheme, whereas Levels 1 and 2 values are obtained from the weightage of pairwise comparisons.

From Table 6, technical and service standard criteria have the greatest priority of 36.79% (refer to Level 1 column: 0.3679), suggesting that both criteria are more important than the others. This is followed by economic criteria with 16.86% and the lowest priority, infrastructure criteria, with only 9.56%. Technical criteria are considered critical because the implementation of suggested communication technologies is contingent upon their functional and useful capabilities. This implies that the technical criteria are important as the functionality and capabilities of each communication technology are dependent on the applications at the end-user's side. Each application has their own applicability and can only be operated at a certain functionality. The main concern is the vulnerability of each communication technology. This is to ensure that any connection is secured. Moreover, the complexity of installation and maintenance is crucial because they have a remarkable financial impact. The next crucial criterion is economic, as this determines the cost to deploy and maintain each technology. The infrastructure criteria are given the lowest priority because they are used to assess the maturity of the proposed technology and its existing infrastructure.

TABLE 7. Global priorities for each sub-criterion.

Rank	Sub-criteria	Global priorities (%)
1	Vulnerability	29.95
2	CAPEX	12.65
3	Distance	10.23
4	Scalability	10.23
5	LoS	10.23
6	Existing Infrastructure	7.17
7	OPEX	4.22
8	Maintenance Complexity	4.19
9	Data Rate	3.73
10	Installation Complexity	2.64
11	Technology Maturity	2.39
12	Mobility	2.37

In Table 7, the sub-criteria are ranked according to their global priorities in descending order. The top-ranked sub-criteria among all is 'Vulnerability,' which has a priority of 29.95%. This is followed by 'CAPEX,' which has a priority of 12.65%, and 'Distance,' 'Scalability,' and 'LoS,' which all have the same priority of 10.23%. The top five factors comprised various sub-criteria that belong to all criteria except the infrastructure criterion. The 'Vulnerability' is deemed the most crucial since the proposed communication technology must be secured against cyber assaults and other threats. Data or information leakage is prevented with this measure. The least important sub-criteria, having global priorities of less than 3%, are 'Installation Complexity,' 'Technology Maturity,' and 'Mobility' with 2.64%, 2.39%, and 2.37%, respectively. The proposed communication technologies must only be installed once, and thus do not require high priority. In addition, this includes the maturity and mobility of communication technologies considered less important than others.

In urban areas, fiber optics, NBPLC, LoRa, Private LTE + NB IoT, 2.4GHz RF Mesh, 5G, 4G, and ZigBee are the technologies that can be integrated into a dense area. The Private LTE is merged with NB IoT as NB IoT works on the communication that operates in the existing cellular network, and Private LTE has a potential if the utility company is keen

TABLE 8. Final ranking for alternatives in urban area.

Alternatives (Urban)	Priorities	
	Normalized	Idealized
Fiber optics	0.210	1.0000
NBPLC	0.203	0.9676
LoRa	0.111	0.5274
Private LTE + NB IoT	0.106	0.5029
2.4GHz RF Mesh	0.101	0.4799
5G	0.096	0.4581
4G	0.095	0.4540
ZigBee	0.077	0.3672

to adapt private networks. For suburban and rural areas, 5G is not considered as it is a new technology and since it has a high data rate. Such a high data rate is not necessary in both areas. Moreover, new infrastructures of 5G may require high cost.

UHF and SATCOM are technologies considered in suburban and rural areas. They are not considered in urban areas due to other wireless communications that are already sufficient to cater the demand in urban areas. Moreover, both technologies are mainly implemented in an area that are not dense or an area where other technologies cannot be implemented due to factors, such as installation and maintenance complexity. Additionally, this will eventually cause cost surges.

From Table 8, the top three communication technologies in urban areas are fiber optics, NBPLC, and LoRa. The idealized column employs normalization by dividing each alternative score in the normalized column by the highest alternative score (0.210). The idealized value is to show the performance of NBPLC to be 96% as good as one with fiber optics and so on. While 4G and 5G rankings are almost identical, with minimal decimal differences. Overall, ZigBee has low weightages for almost all criteria.

TABLE 9. Final ranking for alternatives in a suburban area.

Alternatives (Suburban)	Priorities	
	Normalized	Idealized
Fiber Optics	0.191	1.000
NBPLC	0.174	0.910
LoRa	0.107	0.560
Private LTE + NB IoT	0.101	0.527
4G	0.095	0.495
2.4GHz RF Mesh	0.093	0.486
UHF	0.092	0.479
ZigBee	0.075	0.393
SATCOM	0.073	0.381

For suburban, the top three communication technologies are the same as urban as shown in Table 9. For fiber optics, the top three criteria contributing to the high weightages are the existing infrastructure, data rate, and distance.

TABLE 10. Final ranking for alternatives in a rural area.

Alternatives (Rural)	Priorities	
	Normalized	Idealized
SATCOM	0.190	1.000
NBPLC	0.149	0.788
Fiber Optics	0.146	0.768
UHF	0.110	0.581
Private LTE + NB IoT	0.091	0.480
4G	0.086	0.453
LoRa	0.084	0.444
2.4GHz RF Mesh	0.080	0.424
ZigBee	0.063	0.333

In suburban, fiber optics has the same low weightage criteria as in urban areas. As for LoRa, the top three criteria are CAPEX, maintenance complexity, and scalability. The lowest three technologies for suburban are UHF, ZigBee, and SATCOM.

Unlike in urban and suburban areas where wired technologies rank first and second, SATCOM is decided to be the most suitable communication technology in rural areas as shown in Table 10. As seen in the table, the bottom three are LoRa, 2.4 GHz RF Mesh, and ZigBee with a score of 0.084, 0.080, and 0.063, respectively.

V. DISCUSSION

This section discusses in detail on the results obtained from Table 8 until Table 10.

In Table 8, fiber optics ranked the highest for urban areas by considering laying the fiber optics with power cable. Besides, fiber optics covers longer distances as compared to other communication technologies. It is also not affected by LoS interference. NBPLC ranks second as it has high weightage in the vulnerability criteria. It is more secure because it is a closed system with a secure backbone (a private network). Also, it is not affected by LoS interference, and it scores high in the OPEX criteria because of its lifespan, without needing to change batteries as frequently as wireless technology.

Meanwhile, LoRa has high weightages on maintenance complexity, installation complexity, and CAPEX. This is because LoRa has high coverage areas. Hence, it requires a few equipment. Additionally, LoRa is equipped with a long battery life and is also low-powered. This substantially reduces the complexity and maintenance cost. LoRa's maintenance is also less complex than that of cellular networks since cellular maintenance requires a representative internet service provider. Installing LoRa is easy because it simply requires installing gateways and modules rather than excavation. LoRa has a lower CAPEX than wired systems, as there is no need for excavation, backfill work, and cable laying. LoRa is cheaper than other wireless technologies as some might require a new infrastructure (5G) and an equipment rack for each unit (2.4GHz RF Mesh).

Meanwhile, 4G has a low weightage on distance and OPEX, whereas 5G's weightage is low in LoS and OPEX. 5G has a higher frequency than other wireless communication technologies. This lowers the LoS. The OPEX is also high as 5G is a new technology. Besides, 5G is yet to mature, so It has low weightage in technology maturity and existing infrastructure. ZigBee is demerited due to its shorter distance, smaller data rate, more vulnerability to LoS, and less security than other communication technologies. Maintaining security with wireless networks is far more demanding than with wired networks. Other wireless networks, such as the cellular network, are known to be more secure than ZigBee.

In suburban, as demonstrated in Table 9, fiber optics has the same low weightage criteria as in urban areas. Meanwhile, NBPLC has high weightages on vulnerability, distance, and LoS. NBPLC has longer distance coverages compared to other wireless technologies. Since it is a wired technology, it has higher LoS than wireless technologies. This leads to minimal effect on signal transmission toward the receiver.

As for LoRa, the top three criteria are CAPEX, maintenance complexity, and scalability. The justifications for CAPEX and maintenance complexity are the same as in the urban area, where LoRa requires less CAPEX, and the maintenance is less complex than other technologies. As for scalability, LoRa has high weightage due to the star and mesh topology, making it highly scalable. In contrast, LoRa is considered an immature technology with less security and a low data rate, thus having low weightage on these aspects. The low data rate characteristic of LoRa is also less preferable as some applications only work at a high data rate. Although LoRa is considered an immature technology, it still ranks first among wireless technologies due to its high weightage in other criteria.

UHF has a lower data rate than other technologies. In terms of vulnerability, these technologies have almost the same security level. Similar to urban, ZigBee has low weightages for all criteria. SATCOM usage initially received high weightage in some criteria, such as ease of installation and maintenance. However, compared to other technologies, SATCOM has less weightage in all criteria; hence, it ranks last. Overall, SATCOM is usually used in rural areas as the last resort, making it less important.

SATCOM is known to have more coverage in rural areas than other technologies, as obtained in Table 10. Thus, it has higher mobility than other technologies. Also, the maintenance complexity is low since only the SATCOM dish at the ground needs maintenance. The SMEs also agree that SATCOM is the best technology for rural areas. Both wired technologies have the same top three criteria on existing infrastructure, LoS, and vulnerability. In rural areas, wired technology can be considered, but it is more expensive to construct and operate than SATCOM in terms of CAPEX and OPEX. As a result, when compared to wired technology, SATCOM is the better option.

For LoRa, 2.4 GHz RF Mesh, and ZigBee, some reasons contributing to the ranks are the vulnerability and existing infrastructure criteria. Wireless technologies are vulnerable to attacks and threats. Consequently, connections with low security are susceptible to data leakage, hacker hijacking, malware attacks, and other forms of attacks. Moreover, wireless infrastructure is unlikely to exist in rural areas, thus, making them have less weightage. Other criteria contributing to low scores are technology, maturity, distance, LoS, and mobility.

The analysis shows that AHP can structure problems and provide a systematic method for decision-making. It enables the examination of various qualitative elements in a mathematical model, which could help shorten the time required to analyze the alternatives. Using the standard selection procedure in these cases can take months to attain a conclusion. Since the criteria are established and the problem is constructed methodically, the AHP allows decision-makers to compare the scores of each technology choice to see their strengths and limitations.

VI. CONCLUSION

The current traditional communication technology for the electrical distribution substation cannot attend to the emerging and future applications in the distribution network. Suitable communication technology in an electrical distribution substation is crucial for transferring IT and OT data. An incorrect decision on the appropriate communication technology for an electrical distribution substation would have significant technical and financial consequences in the long run. Thus, this paper proposes the MCDM algorithm to identify suitable communication technology options for electrical distribution substations. AHP is used to determine the weight of each criterion. The performance parameters for this method are the weightage, CR, and evaluation score. The results obtained from the AHP show that the top three communication technologies for urban and suburban areas are fiber optics, NBPLC, and LoRa, with a priority of 0.210, 0.203, and 0.111 for urban areas and 0.191, 0.174, and 0.107 for suburban, respectively. Whereas for rural areas are SATCOM, NBPLC, and fiber optics with a priority of 0.190, 0.149, and 0.146, respectively. The results are verified by field experts, successfully identifying the most appropriate communication technology for urban, suburban, and rural areas. It can be concluded that incorporating AHP into the selection of communication technologies is beneficial, and the same developed model can be used to propose appropriate solutions for other fields and demographic areas.

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