International Journal of Engineering & Technology, 10 (2) (2021) 108-115

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Optimal power flow-path determination for voltage control in electricity distribution using the modified dijkstra's algorithm

Ofem Ajah Ofem [1], Moses Adah Agana [1] *, Ejogobe Owai E. [1]

[1] Department of Computer Science, University of Calabar, Calabar, Nigeria
**Corresponding author E-mail: ganamos999@ahoo.com*

Abstract

This paper examines the electric power distribution network system of the Port Harcourt Electricity Distribution Company (PHEDC); its shortcomings, costs and voltage loss in distribution with a view to finding optimal solution through determination of optimal power flow path. The Modified Dijsktra's Algorithm was applied to generate optimal flow path model of the distribution network with seven (7) nodes from Afam Thermal Power Station (source) to the Calabar Distribution Centre (destination) via the interconnected substations. The structural design of the PHEDC distribution network and a review of relevant literatures on shortest path problems were adopted. The modified Dijkstra's algorithm was simulated using JavaScript and is able to run on any web browser (Google Chrome, Mozilla Firefox, etc). It was applied to a practical 330kV network using the relevant data obtained from the company and the result shows the negative effect of distance on voltage quality. It was observed that the Modified Dijkstra's Algorithm is suitable for determining optimal power flow path with up to 98 percent level of accuracy because of its suitability for determining the shortest route in both transportation and power energy distribution as well as its overall performance with minimal memory space and fast response time.

Keywords: *Graph; Optimal; Flow-Path; Node; Distribution.*

1. Introduction

In electric energy supply, the electricity distribution sub sector is pivotal in the electric power supply system, responsible for providing the final link between the power transmission sub-system and the electric power consumers. In the course of electric energy distribution, impedance by certain factors can cause consumers to experience low voltage supply. The ultimate goal of any electric power industry is to get optimal power transmission through a flow path so as to satisfy consumer's needs. There could be several transmission paths available to route voltage from a power generating station to the consumers. However, amongst such paths, there should be an optimal flow path that exists from the source to the destination node in such a network with a minimum weight at its constituent edges. An optimal flow path has the objective of establishing minimum losses in distribution when variations exist in the distance of interconnected substations, capacity of transmission line and voltage stability methods [1].

An optimal path is defined as the path with minimal explorations in a given network tree or graph from the source node to the destination node. Optimal path determination involves finding the distance between two nodes in a graph in such way that the sum of the lengths or weights of its the connections between the nodes is minimized, and approaches and algorithms exist to find solutions to shortest path problems [2]. Shortest path algorithms predominantly operate on graphs. A given input graph, G is made up of set of vertices, V, and edges, E, linking them. The link between nodes (edges) that have weight produce weighted graphs; and most times such edges are bidirectional, making the graph to be undirected [3].

The major aim of any electrical power system is to adequately supply electric power to all points of utilization with minimum cost and optimal and reliable voltage. A routing table is maintained to keep the measured distance based on cost of each path. There is always a need at every point in time to select the shortest path with minimum cost from a source node to the destination based on the data in the routing table. An electric power distribution system equally utilizes the same approach.

Electric energy is often generated in large centralized power stations (plants) and uses the network that both transmits and distributes to the loads that feed the consumers [4]. The assumption that power flows in one direction and that the connection between various components connected to distribution networks are passive is used to plan and control the distribution networks. The maximum voltage in the network can be lowered using voltage control measures [3]. There are varieties of algorithms to find the shortest path in a transportation network and can as well be applied in finding the optimal flow path in electric power distribution. In this study, the modified Dijkstra's algorithm using the network map of PHEDC was implemented.

The study aims at designing a model of a more efficient platform for power distribution and establishing optimal flow path as a determinant of voltage quality control in a typical grid network, with particular concern on the Port Harcourt Electricity Distribution Company

(PHEDC); ranging from the thermal power station in Afam to Calabar using the modified Dijkstra's algorithm. The figure below depicts the modeled graph structure of the PHEDC distribution network.

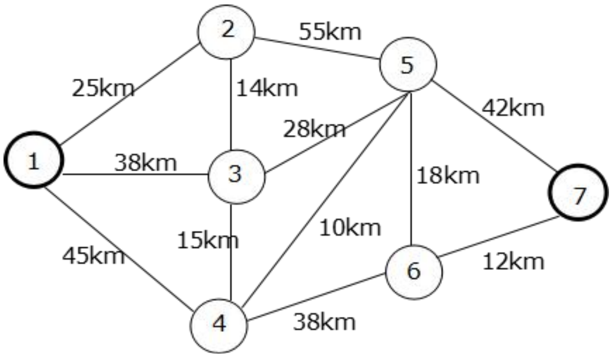

Fig. 1: A Power Distribution Network Modeled as A Graph Structure in the PHEDC Distribution System with Nodes and Edges (Amani, 2015).

Given a graph G = (V, E), where V and E are the set of vertices and edges, there may be need to determine the optimal flow path from a single starting node (v) also known as the source, to all other nodes in the graph. It is thus a shortest path problem involving a single-source. The optimal path tree covering every node in the graph is made up of the sum of all the optimal paths (the shortest path) starting with (v) to all other nodes. Dijkstra's algorithm is an algorithm that is suitable for solving shortest path problems with positive side values. It is used to determine the shortest path based on the least weight (distance) from one node to another. An n-by-n matrix is used in describing the weighted digraph G having n vertices. The matrix is represented as D=[d_{ij}], where, d_{ij} = length (or distance or weight) of the edge from vertex i to vertex j as shown below:

$$dij = \begin{cases} > 0, \text{ for } i \neq j \\ = 0, \text{ for } i = j \\ > \infty, \text{ (large number), if there is no edge linking } i \text{ to } j \text{ [6]} \end{cases} \quad (1)$$

The nodes of such graphs are labeled using the Dijkstra's algorithm. At each stage in the algorithm, some vertices have permanent labels while others are each assigned a temporary label. In the initialization of the algorithm a permanent label 0 is assigned to the originating node s, and a temporary label assigned continuously to each of the remaining n-1 nodes. From that point, another node in each iteration can be set as a permanent label based on the rules defined below [6]:

a) Each node j that is yet to be labeled as permanent is assigned a new temporary label with the value min[old label of j, (old label of i + dij)], where i is the latest node with the permanent label in the preceding iteration, and dij represents the distance from i to j. dij = infinity if i and j are not connected.
b) Amongst all the temporary labels, the least value is computed, and the corresponding vertex assumes this as the permanent label. If more than one shortest path is identified, any one of the candidates is selected and assigned a permanent label. The iteration of steps a and b continues until a permanent label is assigned to the destination node. The first node to be assigned a permanent label has zero distance from s while the second node to be labeled as permanent (from the remaining n-1 nodes) is the nearest node to s. The next node to be assigned a permanent label from the remaining n-2 nodes is the second nearest node to s, and so on. The permanent label of each node is the shortest length of the edge linking that node from s [6].

The need to minimize the distance and time in a network given some data motivated the application of Dijkstra's algorithm [7]. However, the major disadvantage of the algorithm is that it does a blind search and thus wastes much time and resources. It is not suitable for handling negative edges and the time complexity of the traditional Dijkstra's algorithm is given as $O(n^3)$; where n is the number of edges. The outcome is usually an acyclic graph that cannot yield the right shortest path, hence the need for its modification.

1.1. The modified Dijkstra's algorithm

It is possible to modify the traditional Dijkstra's algorithm used in computing shortest paths through several methods. One of such methods is the Modified Dijkstra's Shortest Path (MDSP) algorithm [7] [13]. In this algorithm, some better parameters exist for finding a valid shortest path other than the use of a single parameter. The outcome of the nodes being analyzed with the time complexity can be easily determined, so the Modified Dijkstra's Shortest Path algorithm is considered to be more efficient in determining the shortest path with up to 98% level of accuracy.

This study is based on the modification of the traditional Dijkstra's Algorithm so as to minimize the total number of iterations aimed at getting an optimum solution. In this approach, not only one node can satisfy the condition of the second step in the shortest path problem unlike the case with the traditional Dijkstra's algorithm [7]. Thus;

a) Each node j that is not yet designated as a permanent label is assigned a new temporary label with the value min[initial label of j, (initial label of i + dij)], where i is the most recent node with a permanent label in the previous iteration, and dij is the length of the path (edge) between nodes i and j. If i and j are not linked with an edge, then dij = infinity.
b) The least value amongst all the nodes with temporary labels is computed to get the permanent label of the associated node. If there is not just one shortest path, then all the shortest paths are selected and each is assigned a permanent label.
c) Steps (a) and (b) are iterated (maximum n-1 times) until the destination node t is assigned a permanent label.
d) Given that T=[tij] is the matrix depicting the shortest path, then its form t is given as follows:

$$t_{ij} = \begin{cases} 0, \text{ if } d_{ji} = 0 \text{ or } d_{ji} = \infty \\ d_{ji}, \text{ otherwise} \end{cases} \quad (2)$$

1.2. The modified Dijkstra's algorithm steps

Step 1: Initialization

- Make node s have distance value of zero, then designate it as Permanent [node s assumes the state of (0, p).]
- Allocate a distance value of ∞ to each node and designate each as Temporary [each of these other nodes assumes the state of (∞, t)]
- The node s is designated as the current node

Step 2: Update of Distance Value and Current Node Designation Update. Let the index of the current node be i.

1) Find the link (i, j) that connects the set J of nodes with temporary labels of the current node i and update the edges of such nodes.
- For each j Є J, let new dj = min{dj, di +cij} [this is an update of the distance value dj of node j], where cij is the cost of traversing the link (i, j).
2) Find a node j with the least edge dj among all other nodes j Є J and compute j* so that min dj = dj* j Є J
3) Label node j* as permanent and make it the current node.

Step 3: Criterion for termination

If all nodes the nodes accessible from node s have been assigned permanent labels, then end.

1.3. Benefits of the modified Dijkstra's algorithm

1) The number of iterations can be minimized with lesser number of nodes, thereby making it possible to overcome the problem of large memory space requirement.
2) When applied to electric power distribution system, power flow can take shortest paths to other nodes (substations) while minimizing losses even when faults occur on some transmission lines,,
3) It is easy to implement.

2. Related works

Shortest route from one point to another point (node) is termed as the shortest path and able to determine optimal route through the network [5].

The use of directed diffusion in a study on the analysis of energy routing for low energy sensor networks for wireless communications and networking indicated a potential path from data sources (source node) to the sink node [8]. A routing table is used to keep the measured distance based on the cost of traversing each path. A path with its associated cost is selected at each time based on the contents of the routing table. The selection criterion is to choose the path with the least cost/distance [9].

Also as observed by [5], Dijkstra's algorithm is suitable for determining the shortest distances that join nodes in a graph, representing for instance, road networks, air routes, electric energy distribution routes, etc. The algorithm exists in many variants; Dijkstra's algorithm was originally designed to find the shortest path between two adjacent nodes, but a more common one permanently makes one node the origin (source) node and then determines the shortest routes from the origin to all the other remaining nodes in the graph, thus creating a shortest path tree. It can as well be used for computing the least distance from just one vertex to a fixed destination vertex and the algorithm terminates once the least distance to the destination vertex is found.

In a related study by [9], an algorithm for optimal path selection was used to apply the concept of minimum spanning tree (MST) given some weight values. Road transportation network for shortest path query processing in networks was used to conduct an experimental study both theoretically and practically. The study revealed a simplified generic method of generating the least distance queries efficiently in undirected graphs with reduced query times and pre-processing overheads capable of competing against precision.

In a study by [3], [10] when determining voltage stability margins, the importance of system modeling was found to be critical since splitting half analysis significantly effects the behaviour of electric power systems. The effects of detailed generator models and several exponential load models were established.

In [1], while considering the Nigerian 330KV network of 30 bus systems, a sharp drop in Mega Volt Ampere Reactive (MVAR) was found to help electrical companies to transmit more voltage and serving more customers without increasing their power networks. Newton-Raphson's solution method was used to carry out the analysis [11]. Also, in wireless packet switch network system, the combination of Open Shortest Path First (OSPF) and modified Dijsktra's algorithm was found to provide useful methods for solving problems relating time determination and shortest path [6], [9]. Coding of the algorithm using networking approach as well as the ability to manage and control the network were found to be efficient with varying Quality of Service (QoS) requirements in time/delay-sensitive applications.

In a related study by [12], it was observed that the smart grid concept that is emerging and the distribution network of the future require repeated and fast load flow solutions that will be useful in optimization, automation, distribution planning and power restoration [12].

3. Methodology

Most researches that involve the application of Dijkstra's algorithm have been conducted to find the shortest path that exists between nodes in a network, and these have often yielded different results when various nodes are involved. Most of such results are often constrained to the specified nodes based on the size of the data structure.

In this research, the design is for an electric power distribution network of the Port Harcourt Electricity Distribution Company, Nigeria. The objective is to establish an optimal flow path from the source node at Afam station to the destination node at Calabar. The modified Dijkstra's algorithm involving an undirected network system has been used in achieving this. The attributes of the model as follows:

1) It is a problem that requires the determination of the shortest path from a network from one source to several others.
2) The size of each edge has a positive value
3) Each node is made up of a status label
4) It is an undirected graph
5) The comparison additional model is used in computing the shortest path.

A critical review of the existing PHEDC power distribution network in the study area was done to enable the application of the modified Dijkstra's algorithm to find the optimal path in the network. A solution platform in JAVASCRIPT was used to code the computation of

the optimal path in the PHED distribution network from Afam (Port Harcourt) to Calabar with 7 nodes (n = 7). Data relating the power distribution network and facilities was sourced from the company to enable the analysis of how to obtain an optimal path.
The data was abstracted and modeled as a graph represented as G = (V, E), where V represents the (V_0, V_1,……V_{n-1}) also referred to as the vertexes and E represents the edges (e_1, e_2,……e_n). Each edge is an arc or the link between two adjacent nodes. The mathematical model for the system is as shown in equations 3 - 5.

$$G = (V, E) \tag{3}$$

$$V(G) = (V_0, V_1, \ldots V_{n-1}) \text{ or set } \epsilon \text{ of vertices} \tag{4}$$

$$E(G) = (e_1, e_2 \ldots e_n) \text{ or set } \epsilon \text{ of edges} \tag{5}$$

In the model, the graph is made up of two main components which are the nodes and the edges. A data structure was designed to represent these components. Two ways exist in which the graph can be represented in the computer; this could be in a sequential or in a linked list form.
However, since it is a sparse graph that was used in representing the power flow path network, adjacency linked list was used. Information about adjacent nodes are kept in the adjacency matrix. In the system several instances require the determination of the shortest path from one node to another for optimum electric energy supply.

3.1. Network model

The network model for a power flow in Port Harcourt Electricity Distribution system was abstracted as a graph. The algorithm works efficiently for both directed and undirected network systems. Figure 2 below shows the different electric power substation locations within the network and their representations as nodes.

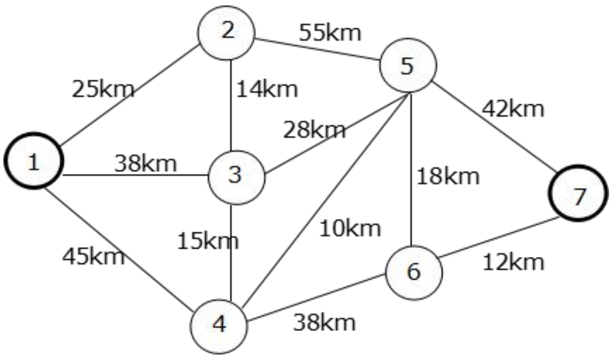

Fig. 2: Electric Power Substation Locations and Their Representations as Nodes.

Each node is identified with its edge length d_{ij}, a preceding node and status. The size of an edge represents the shortest distance of between the nodes that such an edge connects, and the predecessor of a node is the node before the given node in the shortest path from the originating node. A node can have a permanent or temporary label.
In the context of this research, the square sign □ is used for permanent label of a node and ○ for temporary label of a node. When a node is marked as permanent it means it has been included in the shortest path. A temporary node can assume a new label if required but once a node is made permanent; it cannot be changed to a temporary status again. The steps of the algorithm are as follows:

i). Start with the source node as the current working node, assign it a permanent label; leaving all other nodes with temporary labels.
ii). Check all the nodes with temporary labels and label the required nodes based on minimum weight criterion.
iii). Make the node with the least weight permanent and the current working node.
iv). If the nodes in steps ii and iii have equal values, choose any one of them.
v). Iterate ii, iii and iv until the destination node is made permanent

3.2. Network simulation

To have the optimum solution when the number of nodes increases, the research emphasis was placed on the data structure and its ability to store a given number of nodes with some constraints. The simulation was done in different stages ranging from 1-7.

Stage 1: Node 1 => 0 □
Nodes 2, 3 and 4 are accessible from node 1. Each of these nodes has a temporary label equal to the length of the edge joining it to node 1. At this point, no update is done on any temporary label the lower bound (Permanent label, PL) and upper bound (Temporary label, TL). Any nodes that cannot be directly accessed from node 1 has ∞ as its temporary label. Edges that can be directly accessed from the source are represented with full lines while dotted lines are used for edges that cannot be directly accessed from the source; i.e. initialize node 1 to 0 as its PL, while all other nodes in the network that are not directly reachable from node 1 are given TL of infinity (∞).
Thus, the node model at this stage is shown in figure 3 below:

PL = n_1 = 0; L(1) = {0, 25, 38, 45, ∞, ∞, ∞}
*

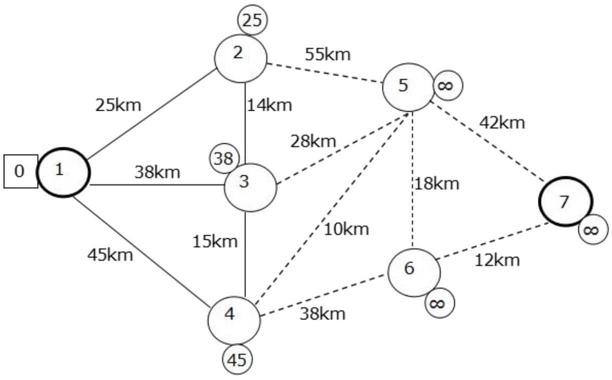

Fig. 3: Network Simulation at Stage 1, With Node 1 as the Permanent Label.

At Stage 2:
Node 2 => 25

Compare all TLs of all reachable nodes to node 1 and make the smallest a PL. If $TL(n_2) \leq TL(n_3)$ and $TL(n_2) \leq TL(n_4)$ then $PL = n_2$, otherwise $PL \neq n_2$; and it's subject to further comparison. (Note: If there is a tie, then take any path). i.e. Route 1 à 2 = min(0 + 25) = 25
Route 1 => 3 = min(0 + 38) = 38
Route 1 => 4 = min(0 + 45) = 45
Since $TL(n_2) \leq TL(n_3)$ and $TL(n_2) \leq TL(n_4)$, then $PL = n_2$ =25.
Thus, the node model at this stage is shown in figure 4 below:
L(2) = {0, 25, 38, 45, 80, ∞, ∞}
* *

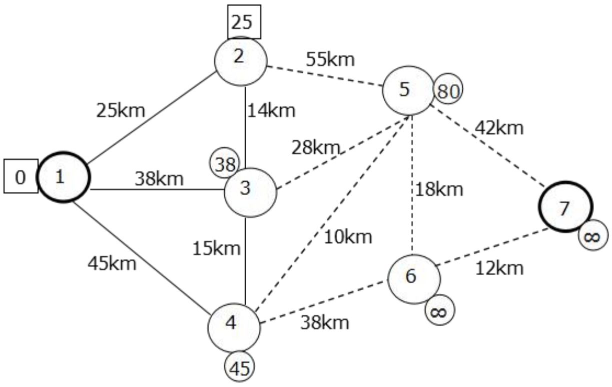

Fig. 4: Network Simulation at Stage 2, With Node 2 as the Permanent Label.

At Stage 3:
Node 3 => 38

Update all reachable nodes from the current PL and compare their weights to determine TLs then make the smallest a PL. If TL $(n_3) \leq TL(n_4)$ and $TL(n_3) \leq TL(n_5)$ then $PL = n_3$, otherwise $PL \neq n_3$; and it's subject to further comparison.
i.e. Route 1 => 2=> 3 = min(0 + 25 + 14) = 39
Route 1 => 3 = min(0 + 38) = 38 Since $TL(n_3) \leq TL(n_4)$ and $TL(n_3) \leq TL(n_5)$, then $PL = n_3$;
Hence , current $TL(n_3)$=38 ≤ updated $TL(n_3)$= 39; then $PL=n_3$ =38;
The node model at this stage is shown in figure 5 below:
L(3) = {0, 25, 38, 45, 66, ∞, ∞}
* * *

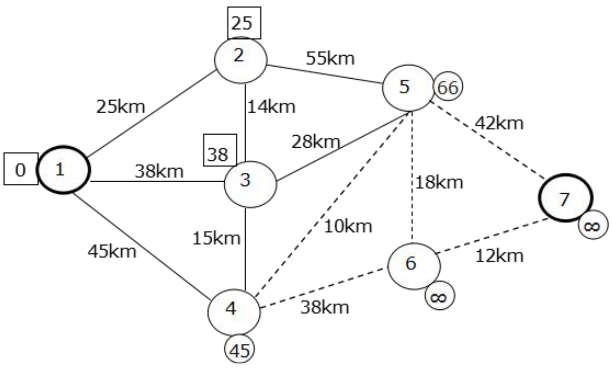

Fig. 5: Network Simulation at Stage 3, With Node 3 as the Permanent Label.

At Stage 4:
Node 4 => 45

Update all reachable nodes from current PL and compare their weights to determine TLs, then make the smallest a PL. If $TL(n_4) \leq TL(n_5)$ and $TL(n_4) \leq TL(n_6)$, then $PL = n_4$, otherwise $PL \neq n_4$; and its subject to further comparison.

i.e. Route 4 =>5 = min(0 + 45 + 10) = 55
Route 4 => 6 = min(0 + 45 + 38) = 83 Since $TL(n_4) \leq TL(n_5)$ and $TL(n_4) \leq TL(n_6)$, then PL = n_4;
Hence, current $TL(n_4)$= 45 ≤ updated $TL(n_4)$ = 55; then PL = n_4 =45.
The node model at this stage is shown in figure 6 below:
L(4) = {0, 25, 38, 45, 55, 83, ∞}
* * * *

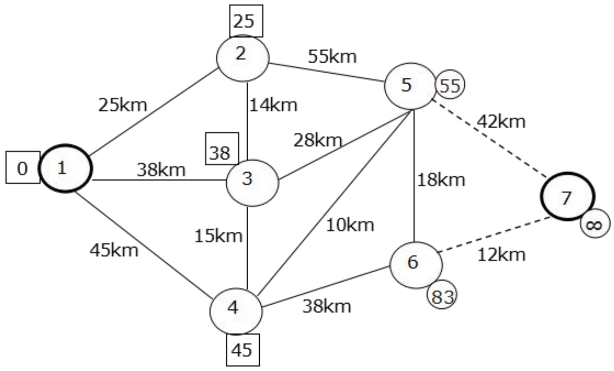

Fig. 6: Network Simulation at Stage 4, with Node 4 as the Permanent Label.

At Stage 5:
Update all reachable nodes from current PL and compare their weights to determine TLs, then make the smallest a PL. If $TL(n_5) \leq TL(n_6)$ and $TL(n_5) \leq TL(n_7)$, then PL=n_5, otherwise PL≠n_5; and it,s subject to further comparison.
i.e. Route 5 => 6 = min(0 + 55 + 18) = 73
Route 5 => 7 = min(0 + 55 + 42) = 97
Since $TL(n_5) \leq TL(n_6)$ and $TL(n_5) \leq TL(n_7)$, then PL = n_5; The node model at this stage is shown in figure 7 below:
L(5) = {0, 25, 38, 45, 55, 73, 97}
* * * * *

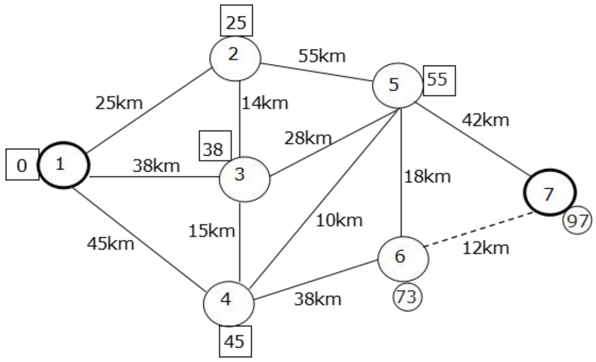

Fig. 7: Network Simulation at Stage 5, With Node 5 as the Permanent Label.

AT STAGE 6:
Update all reachable nodes from current PL and compare their weights to determine TLs, then make the smallest a PL. If $TL(n_6) \leq TL(n_7)$ then PL=n_6, otherwise PL≠n_6; and its subject to further comparison.
i.e. Route 6 => 7 = min(0 + 73 + 12) = 85 Since $TL(n_6) \leq TL(n_7)$, then PL = n_6;
Thus, the node model at this stage is shown in figure 8 below:
L(6) = {0, 25, 38, 45, 55, 73, 85}
* * * * * *

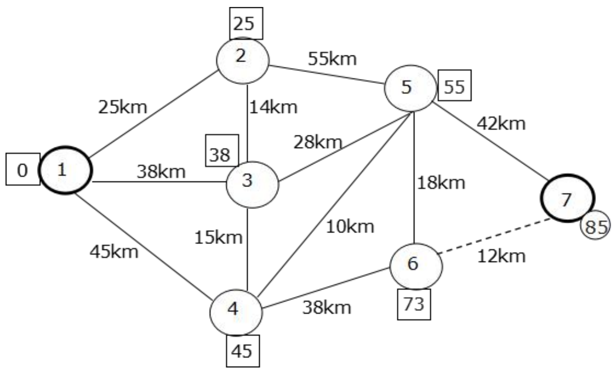

Fig. 8: Network Simulation at Stage 6, with Node 6 as the Permanent Label.

At Stage 7:
Update $TL(n_7)$ and make it a PL. Hence, PL = n_7 = 85. This is because n_7 is the last node in the network. The node model at this stage is shown in figure 9 below:
L(7) = {0, 25, 38, 45, 55, 73, 85}
* * * * * * *

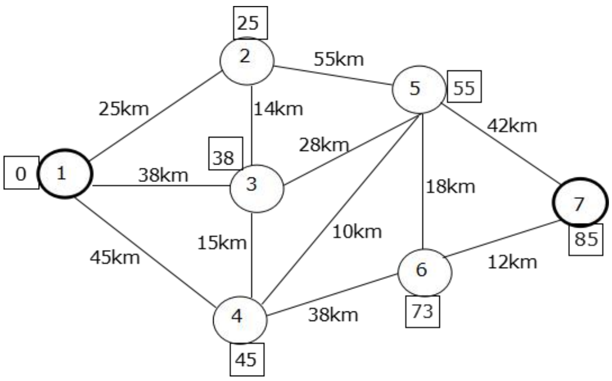

Fig. 9: Network Simulation at Stage 7, with Node 7 as the Permanent Label.

4. Results

The model network has 'N' nodes (where n = 7) and the Modified Dijkstra's algorithm was used to compute the least distance from the source (Afam) to the destination (Calabar). Accordingly, when a particular node is selected, the algorithm finds the overall distance considering all its possible reachable neighbours.
In the model, nodes and edges were the two main components used to represent the graph through adjacency link list. The matrix used in representing keeps the adjacent nodes is as shown below;
Node Cost (distance value)

1	0	∞	∞	∞	∞	∞	∞
2	0	25	38	45	80	∞	∞
3	0	25	38	45	66	∞	∞
4	0	25	38	45	55	83	∞
5	0	25	38	45	55	73	97
6	0	25	38	45	55	73	85

From the matrix above, the following routes are possible; R1: 1 => 2 => 5 => 7
0 + 25 + 55 + 42 = 122
R2: 1 => 3 => 5 > 7
0 + 38 + 28 + 42 = 108
R3: 1 => 4 => 5 => 7
0 + 45 + 10 + 42 = 97
R4: 1 => 4 => 5 => 6 => 7
0 + 45 + 10 + 18 + 12 = 85
R5: 1 => 4 => 6 => 7
0 + 45 + 38 + 12 = 95

The chart below shows the possible routes in the network and equivalent optimal flow path distances indicating the path with optimal flow cost as Route 4 (85km).

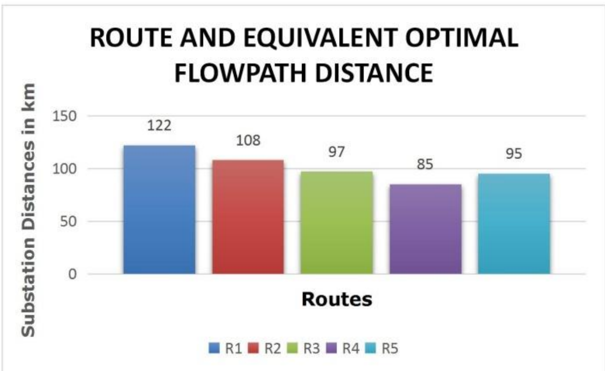

Fig. 10: Bar Chart Showing the Substation Distances and Route with Optimal Flow Cost.

Figure 10 above shows that voltage quality is a function of distance; also, the modified Dijkstra's algorithm essentially forms a dynamical loop system whereby the distance cost determines the voltage supply. Hence, the shortest weight cost is 85, and the path whose sum of edges is equal to 85 is the optimal route; i.e. R4: 1=>4=>5=>6=>7. The result confirmed that the shortest route in electric power distribution from Afam to Calabar is applicable, which covers a distance of 85km.
One of the most severe issues in a distribution system is the excessive voltage drop. Hence, voltage control in distribution systems needs to be properly formulated and rigorously solved. Figure 11 below shows the negative effect of distance on voltage quality.

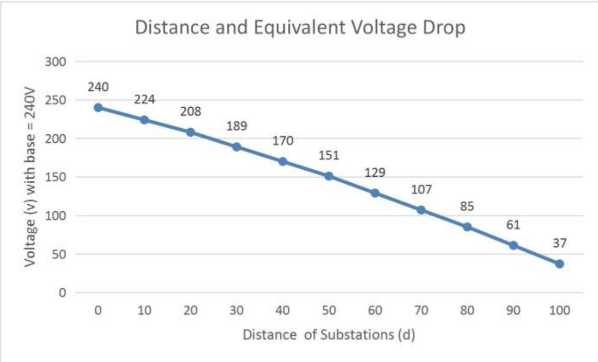

Fig. 11: Negative Effect of Distance on Voltage Profile of A Power Distribution System.

The overall losses between the power plant and consumers are in the range between 8% and 15% as shown in figure 11 above. In a power system network, there is no phase angle for any voltage and similarly, there is no imaginary part for the transmission line impedance. As a result, only the amplitudes of current and voltage are the variables left for power flow control. Electricity distribution companies use transformers for stepping down the voltage generated at a permissible range (from 11/33kv to 415v) before transmission.

5. Conclusion

A distribution system is cardinal in an electric power system. This is because it serves as bridge linking the bulk power supply and the consumers who share units from it. To cope with the ever increasing need for electric power supply, a well planned and effective distribution network is a compendium. As a result, the effectiveness of a distribution system is measured by its ability to ensure that the voltage variations are within allowable limits at consumer terminals.

As an Open Shortest Path First (OSPF) approach, the modified Dijkstra's Algorithm is suitable for allowing the application of linguistic knowledge to explain the rudiments of probability functions that are not linear, utilizing several input values to depict the changing state of the network with more accuracy. It is suitable for providing qualitative service as well as good utilization of links, keeping losses minimal.

The simulated model is proved to have desirable attributes, for instance, it is robust, has and fast response time, capable of adjusting in tone with changes and uncertainties in networks. It was observed that the Modified Dijkstra's Algorithm is suitable for determining optimal power flow path with up to 98 percent level of accuracy because of its suitability for determining the shortest route in transportation and power energy distribution as well as its overall performance with minimal memory space and fast response time.

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