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Planning For Medium Voltage Distribution Systems Considering Economic And Reliability Aspects

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Abstract: *Most medium voltage (MV) distribution systems are structured in mesh and radially operated to distribute electric power from distribution substations to consumers (distribution transformers). The difficult decision of building a new radial MV topology is which branch should be connected to others and could save cost in constructing for the operator in the first stage of designing and bidding for the new topology. Due to that problem which always occurs during the primary stage of designing proposals for the system, many heuristic algorithms have been implemented to make a convenient to build up distribution systems and analyze costs for the new system. This paper proposes to study from scratch buildup for the new radial topology to the final stage of the project by using and comparing two methods, called Minimum Spanning Tree (MST) Algorithm and Shortest Path (SP) Algorithm to find the shortest routing connection for structuring the topology with the shortest length of conductor and the better voltage profile by using backward forward load flow to modify. In addition, after the new radial topology is built up, the reliability indicator is proposed by identifying the optimal line among the possible connections within the topology. In the final stage, the economy is estimated by considering the cost of conductors, protective devices, labor, and operational expenses over a planning study of 30 years. To validate the proposed method, the standard test distribution system (9-bus test and 25-bus test) and the real distribution system, which is located in Khsach Kandal, Kandal, Cambodia with 47-bus is selected. The result of this paper demonstrates that the radial Medium Voltage (MV) topology is constructed using the Minimum Spanning Tree (MST) algorithm. This approach results in a reduced length of conductor and a faster payback period, despite the fact that the power loss of the SP algorithm is more favorable. However, the capital expenditure (CAPEX) of the SP system remains a significant concern for many investors. In the reliability index tie line connections are selected based on their highest probability of serving as tie lines within the system.*

Keywords: Medium Voltage Distribution, Radial Topology, Minimum Spanning Tree, Shortest Path, Tie-Line, Economic Analysis

1. INTRODUCTION

Electricity is an essential necessity for human life in the 21st century, as it powers nearly every aspect of our daily existence. From providing light in the darkness to enabling various forms of livelihood, society's dependence on electricity is undeniable. Therefore, ensuring all people have access to electricity is of great importance. With the rapid growth in population and the changing lifestyles of individuals, the demand for electricity distribution continues to rise. Consequently, it is crucial to study and optimize the distribution of power to adequately meet the residential and commercial needs of consumers. The regulatory authorities overseeing the electricity market have offered distribution companies incentives such as tax breaks and modifications to the energy price formula to promote the provision of electrical services in rural areas [1]. The primary goal is to enhance the standard of living in rural communities like the policy of electricity authority of Cambodia [2].

In paper [3] addresses the issues of inefficiency, redundancy, and management challenges associated with the two separate medium-voltage (MV) distribution systems. They emphasize the need for integration to enhance reliability and flexibility. To tackle this problem, a mixed-integer programming (MIP) approach was proposed, which was applied to a real site

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in Milan, Italy. Additionally, another study [4] proposes a step-by-step building algorithm aimed at minimizing the total planning cost of the system. Their approach incorporates reliability assessments to identify a reliable feeder, thereby achieving a network structure that minimizes interruptions while accommodating various configurations. Moreover, in the discussed paper [5], the study encompasses the optimal selection of distribution line routes, conductor sizes, and the location and sizing of protective devices, as well as the operational costs of the grid throughout the planning horizon. The mixed integer nonlinear programming (MINLP) problem is mentioned in the paper [6] for optimal planning of electrical distribution expansion. This type of mathematical modeling involves both integer and continuous variables, which allows for the representation of various operational constraints and decision-making parameters. To design distribution networks in medium-voltage applications, the authors of [7] developed a methodology that merges a genetic algorithm with an ant colony optimization approach. This method was assessed using a small test feeder made up of 10 nodes while evaluating various conductor sizes. Reference [8] details the use of a genetic algorithm for expanding medium-voltage distribution networks. This study specifically aims to create a software tool utilizing genetic algorithms for distribution network expansion planning. The methodology was applied to a small-scale test power system, showcasing its effectiveness in optimizing network design and planning procedures. The authors of [9] introduced an optimization methodology for planning distribution networks that employs a three-phase network representation along with a hybrid approach combining a genetic algorithm and a tabu search algorithm. After establishing the grid topology with a heuristic graph generator, the numerical results revealed the effectiveness of the tabu search algorithm (TSA) in determining the suitable set of conductor sizes needed for the network. There are various types of algorithms that have been proposed for optimal expansion planning of electrical distribution systems, including the Minimum Spanning Tree (MST), Shortest Path (SP), and Mixed Integer Nonlinear Programming (MINLP).

To contribute to this pilot study, three stages will be considered. The first stage involves routing the distribution network by comparing two algorithms, (MST) and (ST), with the objective of minimizing the total length of conductors. The second stage focuses on the sizing of conductors using BFWF analyses, and the integration of protective devices. This stage will also estimate the economic factors, including the costs of conductors, protective devices, and expenditures related to construction and maintenance over a 30-year period. In the final stage, the system's reliability will be examined by optimizing the tie-switch configuration through the selection of lines that allow for potential connections.

2. METHODOLOGY

To reach the objectives of the pilot study, the flowchart in Fig. 1 outlines the project's key stages that are going to be studied. Initially, essential input data is gathered, including coordinates (X, Y), load demand, line impedance, and other parameters. Next, the radial topology is optimized using MST and SP algorithms to find the most efficient cable routing while minimizing length. Following this, the BWFW method is applied, accompanied by an economic analysis to assess the configuration's financial viability. The project then focuses on identifying the four tie-lines with the highest potential for optimal performance, ensuring system connectivity and reliability. Finally, a comprehensive economic analysis evaluates the project's payback period, shedding light on its financial feasibility.

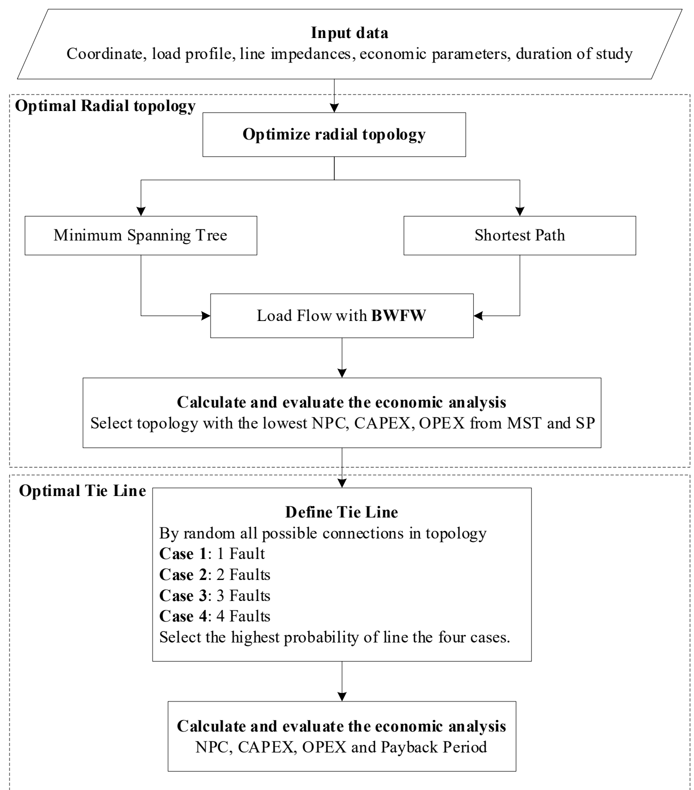

Fig. 1. Flow chart of the proposed method

2.1 Minimum Spanning Tree Algorithm (Kruskal)

A spanning tree for a connected graph G is defined as the tree that contains all the vertices of graph G. There are many spanning trees for a single graph. A minimum spanning tree of a weight-connected graph G (V, E) is the spanning tree that contains all the vertices with no cycles and the total weight of the edges of a tree is minimum. There can be multiple MST for a single graph, but all these MSTs have a unique same weight [10]. The algorithm is processed as follows:

1. Sort all the edges in the increasing order of their cost.

2. Choose the edge that has the smallest cost and check for the cycle. If the edge forms the cycle with the spanning tree discard that edge else include the edge in the spanning tree.
3. Repeat step 2 until all the vertices are included in the spanning tree [10].

2.2 Shortest Path Algorithm

Dijkstra's algorithm constructs minimal paths from a source node s to the remaining nodes, exploring adjacent nodes following a proximity criterion until the shortest path to goal node t is found. The exploring process is known as edge relaxation. When an edge (u,v) is relaxed from a node u, it is said that node v has been reached. Therefore, there is a path from source through u to reach v with a tentative shortest distance. Node v will be considered settled when the algorithm has found the shortest path from source node s to v. The algorithm finishes when t is settled [11]. The algorithm is processed as follows:

1. (Initialization) It starts on the source node s, initializing distance array $D[i]=\infty$ for all nodes i and $D[s]=0$. Node s is settled and considered as the current node c ($c \leftarrow s$).
2. (Edge relaxation) For every node v adjacent to c that has not been settled, a new distance from the source is found using the path through c, with the value $D[c]+w(c,v)$. If this distance is lower than the previous value $D[v]$, then $D[v] \leftarrow D[c]+w(c,v)$.
3. (Settlement) The node u with the lowest value in D is taken as the new current node ($c \leftarrow u$). After this, current node c is now considered as settled.
4. (Termination criteria) If u is the target node the algorithm is finished since the tentative path to u is now considered the minimum one. Otherwise, the algorithm proceeds to step 2.

To recover the path, every reached node stores its predecessor, so at the end of the query phase the algorithm just runs back from the target through stored predecessors till the source is reached. The "shortest-path tree" of a graph from source node s is the composition of every shortest path from s to the remaining nodes [12].

2.3 Backward Forward Load Flow

The backward/forward sweep (BFS) is among the most successful power flow methods for radial networks. The basic operation principle of BFS involves the power or current flow solutions starting from the branch of the end nodes and moving toward the branch connected to the reference node. The forward sweep calculates the voltage at each node starting from the reference node to the end nodes. During the backward sweep, the voltage is held constant, and during the forward sweep, the current of power value is held constant, and during the forward sweep, the current or power value is held constant [13].

- The node/bus injection current could be calculated:

$$I_i^k = \mathrm{conj}\left(\frac{S_i}{V_i^{k-1}}\right) \quad \text{(Eq. 1)}$$

where:
I_i^k is the injection current at node is i on iteration k
S_i is the power injection at node i
V_i^{k-1} is the voltage of node i at iteration k-1

- The second step is the backward sweep which is performed starting from the last ordered branch from the root node, it may be calculated:

$$J_{i-1,i}^k = I_i^k + \sum\left(J_{i,i+1}^{(k)}\right) \quad \text{(Eq. 2)}$$

where:
$J_{i-1,i}^k$ is the current of the branch connecting node i to its upstream node i-1
$\sum\left(J_{i,i+1}^k\right)$ is the sum of all currents of branches emanation from node i.

- The next step is forward sweep which calculates currents for each node, and it can calculate:

$$V_i^k = V_{i-1}^k - J_{i-1}^k Z_{i-1,1} \quad \text{(Eq. 3)}$$

where:
V_i^k is the voltage of node i at iteration k
V_{i-1}^k is the voltage of the immediate upstream node of node i
J_{i-1}^k is the current of branch connecting node i to its immediate upstream node
$Z_{i-1,i}$ is the impedance of branch connecting node I to its immediate upstream node.

2.4 Protective Devices Selection

Fuses are used as protective devices in this system. They are at the primary side of the MV/LV transformer on each pole. To properly select the protective equipment, it is essential to calculate the rated currents using the following equations [14]:

- Line current:

$$I_L = \frac{P_{3\phi}}{\sqrt{3}V_{L-L}\cos\theta} \quad \text{(Eq. 4)}$$

- Based on the [15] fuse can be sizing:

$$I_{fuse} = 1.4 \times I_L \quad \text{(Eq. 5)}$$

2.5 Tie Line

Tie lines are additional lines in the electrical distribution system. It serves as a vital connection to ensuring efficient power transfer and reducing the duration of customer interruptions of the grid [9]. For this research's purposes, there are some specific conditions that need to be set up in order to define the tie line interconnecting the system under study. The conditions for specifying the tie line in this research are as follows:

- All feasible interconnections between the systems could be a potential form for a tie line.

- The candidate tie lines must be within the initial range of connection of topology.
- The existing loads across the systems must remain fully connected.
- The overall system topologies must maintain their radial structure throughout the analysis.

2.6 Economic of Topology

- *Investment cost*

The upfront purchase of all system equipment in the whole project such as cable cost, protective cost, and other accessories cost (excluding a small ongoing maintenance cost).

$$\text{Investment cost} = \sum_{i=1}^{n} C_i \qquad \text{(Eq. 6)}$$

where:

C_i is all the cost involving the system ($)

- *Net present cost*

The net present cost is the life cycle cost which is a variance between the present amount of payments during the project lifetime and the present amount of income during the same period. The following formula can obtain the net present cost [16]:

$$C_{NPC}=\frac{C_{ann,tot}}{CRF_{i,n}}=\frac{C_{ann,tot}\times(1+i)^n-1}{i\times(1+i)^n} \qquad \text{(Eq. 7)}$$

where:
$C_{ann,tot}$ is the total annualized cost ($/year)
CRF(i,n) is the capital recovery factor that represents a series of equal annual income
i is the real discount rate (%)
n is the project lifetime (year)

The real discount rate is the real interest rate that is used to convert between annualized and in-time costs. The real interest rate is calculated according to the following equation:

$$i=\frac{i^{'}-f}{1+f} \qquad \text{(Eq. 8)}$$

where:
i' is the nominal interest rate (%)
f is the annual inflation rate (%)

2.7 Study Area

- *Standard test system*

To validate the result, the dataset of the 9-bus test and 25-bus test feeder are going to be used which is based on the paper [5]. The 9-bus with 14 possible routes and the 25-bus with 42 possible routes.

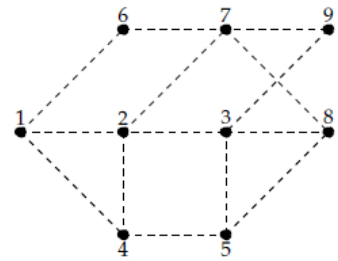

Fig. 2. Possible routes of the 9-bus test system [5]

- *Real test system in Cambodia*

The real area is going to be conducted in Prektamak, Khsach Kandal district, Kandal province supplied by a 115/22kV transformer from the HV/MV substation. The total real power is 1604.25kW and the reactive power is 776.973 kVar and the position (X, Y) of each pole [17] is shown in Fig.3.

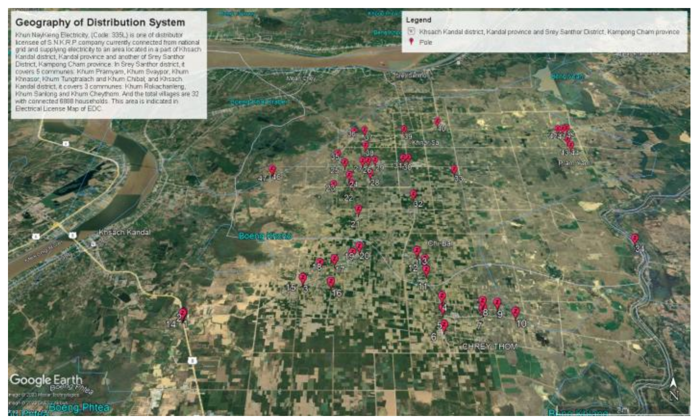

Fig. 3. The possibility of the available pole at Prektamak (Google Earth)

3. RESULTS AND DISCUSSION

All the computational of the proposed heuristic optimization method for expanding distribution networks are illustrated in this section.

3.1 Standard Test System

To route the topology, the MST and SP are applied on the 9-bus system and 25-bus system to define the shortest length. The optimal results are shown 5120m and 5770m respectively for the 9-bus system and 23.65km and 33.15km for the 25-bus system. Fig.4 shows the routing connection of MST and Fig.5 shows the routing of SP of the 9-bus test system.

3.2 Real Test System in Cambodia

By applying the MST and SP separately with 47-bus, based on the obtained results, in Fig.6 and Fig.7, the MST algorithm outperforms the SP algorithm, 43.884km and 47.30 km, respectively.

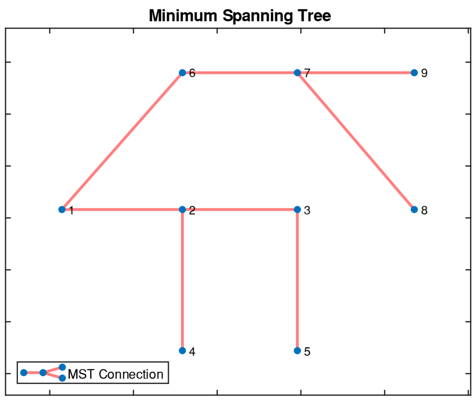

Fig. 4. The routing of 9-bus standard test system by optimizing MST

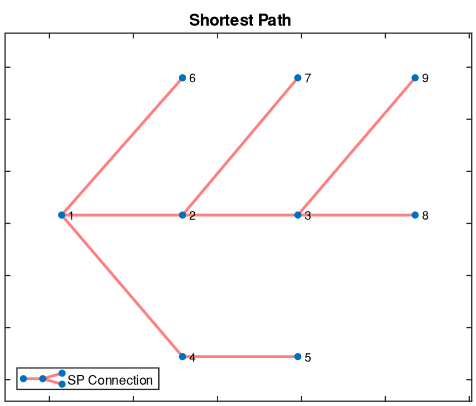

Fig. 5. The routing of 9-bus standard test system by optimizing SP

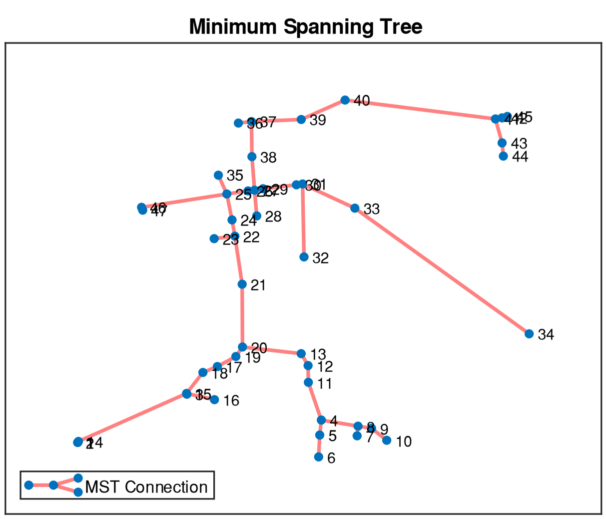

Fig. 6. The routing of the real system by optimizing MST

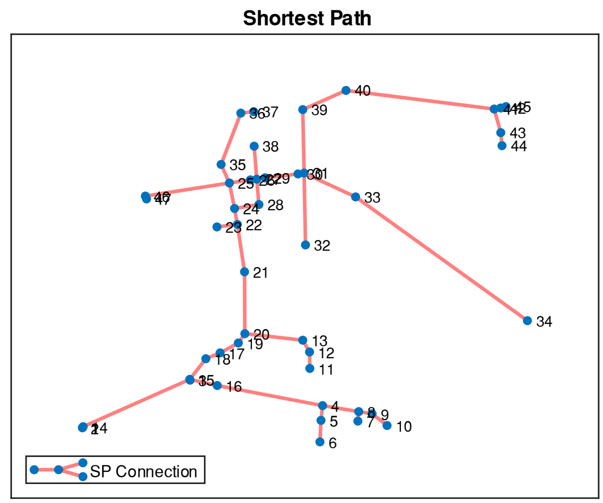

Fig. 7. The routing of the real system by optimizing SP

3.3 Conductor sizing using BWFW

To ensure alignment with voltage regulation standards, the phase voltage must be maintained within the range of 0.95 pu to 1.05 pu [18] and the algorithm is verified with [19]. Based on the results obtained from the systems, as presented in Table 1 and Table 2, it is evident that while the MST outperforms the SP in terms of routing topology, the power loss associated with SP exceeds that of MST following the power flow analysis. Additionally, it is noted that the conductors with cross-sectional areas of 35 mm2 and 70 mm^2 fall outside the acceptable range. Consequently, only the conductors with cross-sectional areas of 150 mm^2, 185 $mm^{2,}$ and 240 mm^2 are suitable for use.

Table 1. Result of BWFW of real test feeder

	MST		SP	
Length	43.88 km		47.30 km	
Cable	P_{loss} (kw)	V_{min} (pu)	P_{loss} (kw)	V_{min} (pu)
150 mm^2	68.89	0.95	62.46	0.95
1850 mm^2	55.09	0.96	49.99	0.96
240 mm^2	40.90	0.97	37.15	0.97

3.4 Economic Analysis Comparison

In this section, the analysis will be conducted on two optimal radial topologies (MST and SP). Following the evaluation of these configurations, the three different cross-section areas of conductors are also considered.

Based on the result of the simulation in Table 2 (MST is on the left side and SP is on the right side), it clearly shows that the MST is a better choice than the SP. The MST has a shorter payback period and requires less capital investment CAPEX, making it more cost-effective.

Table 2. Result of topology comparison

	MST			SP		
CSA (mm2)	**150**	**185**	**240**	**150**	**185**	**240**
Payback period (yr. mon)	0.435	0.495	1.12	0.519	0.618	1.13
Energy loss (kWh/day)	68.89	55.09	40.90	62.46	49.99	37.15
CAPEX (M$)	1.135	1.179	1.791	1.188	1.235	1.895
OPEX (M$)	0.126	0.127	0.128	0.127	0.127	0.128
NPC (M$)	15.33	15.38	14.86	15.32	15.35	14.78

While Table 1 indicates that the SP model has lower energy loss, this advantage does not outweigh the higher initial costs needed to set up the SP system. In making the decision, the 185 mm² conductor with short circuit current [20] and [14] is 1089.6A will proceed to the next step. This choice is also based on factors such as expected load growth, possible equipment errors, calculation uncertainties, and the overall cost. In contrast, the 240 mm² conductor is much more expensive, 7.2$/m, costing about double that of the 185 mm² conductor.

3.5 Tie-line Optimization

In the optimization procedure, four different cases are examined in the topology. The result was obtained for each scenario.

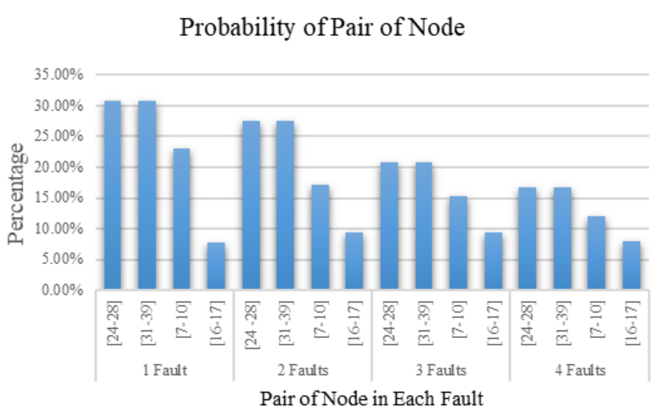

Fig. 8. The probability of pair of nodes

Based on the simulation of the fault performance (with one, two, three, and four faults) as shown in Fig.8, the optimal tie line connections are [24 28], [31 39], [7 10], and [16 17]. These specific tie line pairs were utilized in all of the fault scenarios that were simulated and analyzed. Therefore, they represent the most robust and efficient connections to maintain system stability and reliability under faulty conditions.

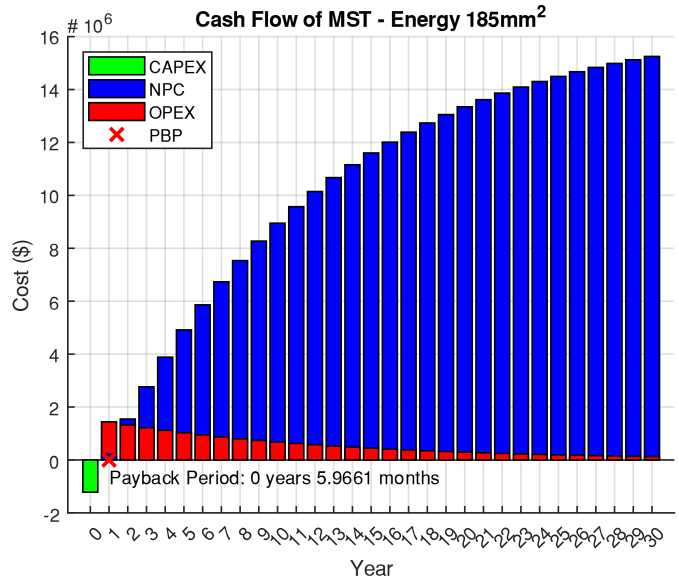

Fig. 9. Cash flow of real test feeder with tie-line

Following the optimization of the tie line, an economic analysis was performed. The cash flow for a radial topology over 30 years is depicted in Fig.9 above. An additional conductor length of 4.079 km, supported by 82 poles, has been included in the analysis. The CAPEX associated with the tie line is estimated to be $1.21 million, with an anticipated payback period of approximately six months. This favorable payback period is attributed to the special tariff for selling electrical energy, which is set at $0.2595 per kWh [21].

In short, following the previously described methodology, a simulation was conducted over 30 years to study medium voltage (MV) distribution networks using the testing system in Cambodia. This investigation achieved several objectives: optimizing the radial topology of the network, determining appropriate conductor sizing, optimizing tie lines, and analyzing the economic aspects, including estimating the payback period of the newly constructed topology. The results of this implementation are presented in Table 3 below.

Table 3. Summary of the result of the methodology

Items	**Value**
Location	Khsach Kandal District
Duration (year)	30
Feeder routing	MST
Length of conductor (km)	43.88
Cross-section area (mm2)	185
Minimum voltage (pu)	0.96
Power demand (kVA)	2300
Energy loss (kWh/day)	709.43
Tariff of purchase ($/kWh)	0.121
Tariff of sale ($/kWh)	0.2595

Items	Value
Tie-line	[24 28], [31 39], [7 10], and [16 17]
CAPEX (M$)	1.218
OPEX (M$)	0.126
NPC (M$)	15.25
Payback period (Month)	5.96

4. CONCLUSIONS

In conclusion, the optimal algorithms MST and SP were utilized to compare and determine the minimum conductor length, while the investment costs associated with the project over a 30-year timeline were also implemented behind. The results indicate that MST is the preferred choice for optimizing the new topology due to its shorter conductor length and economic performance. Although SP demonstrated superior performance in terms of power loss, the CAPEX associated with SP was higher than that of MST, which diminishes its overall advantage. Therefore, MST is favored for economic efficiency, serving as a foundational basis for bidding by electricity distributors in the initial design proposal for the project. After selecting the optimal topology, a reliability indicator is proposed by identifying the optimal line among the possible connections within the topology. This line is chosen based on its highest probability of serving as the tie line in the system.

In future work on feeder routing, we propose a combined approach utilizing both Minimum Spanning Tree (MST) and Shortest Path (SP) methods. The MST will be employed to establish the primary routing, while the SP method will be used to define the branch connections. Additionally, for the reliability evaluation of the distribution system, we will introduce several indices, including System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Interruption Frequency Index (CIFI), and Customer Interruption Duration Index (CIDI).

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