Comparative study of LVAC topology for a rural village

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ABSTRACT - This paper compares three algorithms to design LVAC topology in a rural village, which consists in minimizing the total length of lines and the power losses and balancing the loads among the three phases. Firstly, the shortest path (SP) algorithm is developed to search for the minimization of the conductor used. Secondly, three different algorithms, repeated phase sequence (RPS-ABC), first-fit bin-packing (FFBP), and mixed-integer quadratic programming (MIQP) algorithms are implemented to balance the load and minimize power losses. Then, a comparative analysis of three different methods enables to conclude that the MIQP algorithm is an optimal solution in designing a distribution system topology in particular case study.

Keywords—First fit bin packing, LVAC, MIQP, repeated phase sequence, shortest path.

1. INTRODUCTION

Energy consumption has continuously increased year by year due to population growth and people's lifestyle. To meet the need of society and people concerning electricity, the researchers are currently developing innovative methods to improve the network [1]. Moreover, the LVAC distribution networks are almost radial unbalanced networks due to the presence of 1-phase loads [2], [3], and three-phase distribution lines. Various authors have studied the planning of LV distribution systems. The optimal radial topology by considering the load demand uncertainties (i.e. growth rate and new connected load) in an urban village has been developed in [4], [5]. In [6], the authors investigated methods to find the best radial topology in an urban area. The optimal topology for an urban area has been also studied in [7]; the authors have proposed mixed-integer quadratic programming to search for the topology with the shortest length and load balancing improvement. In rural areas, [8] focused on the use of a single-phase distribution network instead of both three-phase and single-phase by using the shortest path concept. The shortest path concept is also implemented in [9] to extend a single-phase distribution system for a non-electrified village in a rural area. However, it can be noticed that these works had almost focused on length minimizing and load balancing improvement in an urban village and a rural village with a single-phase network.

The main purpose of this paper is to study a comparison of three different algorithms for optimal radial topology in the LV distribution system considering the balanced load and minimum power loss for a rural village in Cambodia.

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2. METHODOLOGY

In this paper, the proposed method aims at searching for an optimal radial topology of LVAC in a rural village with different algorithms while satisfying the bus voltage and current constraints. The three following objectives are considered in this paper: 1) to find the shortest radial topology using the shortest-path algorithm (SP), 2) to optimize the load balancing and minimize the power losses using three different algorithms: repeated phase sequence-ABC (RPS-ABC), first-fit bin-packing (FFBP), and mixed-integer quadratic programming (MIQP), and 3) to compare the three proposed algorithms in terms of power losses and operational expenditure.

A flowchart presenting the numerous steps of the proposed algorithm is provided in Fig.1. The load data (i.e. PQ), as well as line impedance (Z) and coordinates (X, Y), are required. Then, the shortest-path algorithm is launched with these inputs to obtain the shortest length of conductors used in the system. Next, the RPS-ABC, FFBP, and MIQP are applied to achieve the load balancing and power losses minimization.

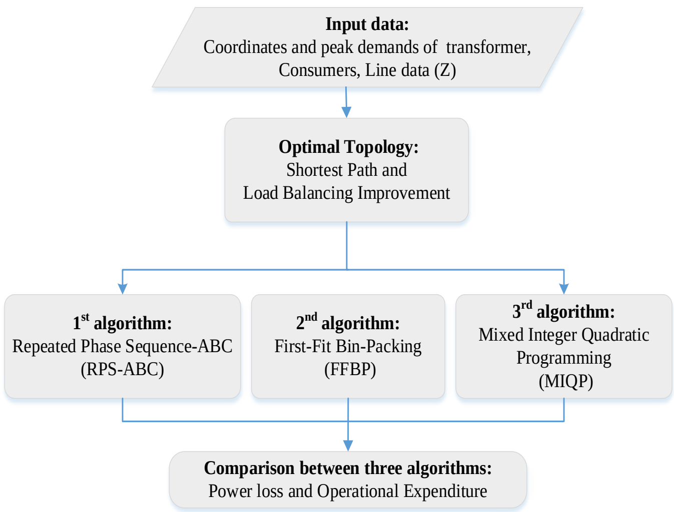

Fig. 1. Flowchart of methodology

2.1. *Shortest Path*

In Cambodia, the LVAC systems comprise of single-phase or three-phase main feeder supplying from a three-phase MV/LV distribution transformer to several single-phase electrical poles which each household is connected. The optimal distribution topology is designed to ensure that the length of the conductor is minimized. With this objective, the shortest path (SP) is implemented. In graph theory [7], the SP searches for a path between two nodes in a graph so that the sum of the weights of its edges is minimized. This SP concept is executed to find the nearest pole to connect the consumers. Fig. 2 shows the shortest path pseudocode.

```
P: Total electrical poles
H: Total households
C: Closest households to electrical poles
D: distance between household to electrical poles
for i = 1 : H
    for j = 1 : P
        D^i = D_i^j
        d = min(D^i)
        p = find(D^i = d)
        Line_i = [p   i]
    end
end
```

Fig. 2. Pseudocode of shortest path concept

2.2. *Repeated Phase Sequence ABC*

To deal with a balanced load, the repeated phase sequence ABC (RPS-ABC) as the 1st algorithm is proposed. This proposed algorithm finds the total active power at each electrical pole in the first step. Then, the phase sequence ABC is repeated for every three connected poles to balance the loads. The RPS-ABC algorithm is illustrated in Fig. 3.

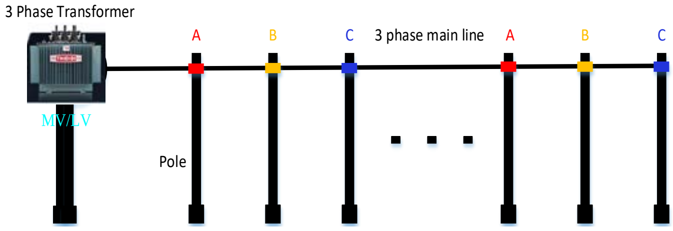

Fig. 3. Repeated phase sequence ABC (RPS-ABC) concept

2.3. *First-Fit Bin-Packing*

With the same problem of load balancing, the 2nd algorithm, named first-fit bin-packing (FFBP) is proposed. The problem with FFBP is to package all items in a defined number of bins while minimizing the difference in the total weight of each bin. In this paper, the power consumption (i.e., P and Q) of households and the phase (A-B-C) of the system are items and the bins, respectively.

2.4. *Mixed-Integer Quadratic Programming*

A graph theory [7] can be represented for the distribution network which is defined as a pair of set $G \equiv G(V,E)$, where V is a vertex-set and $E \subseteq V \times V = \{\{i,j\}(i,j) \in V\}$ is an edge set between vertices i and j. The optimization problem of minimizing a power loss is formulated as a mixed-integer quadratic programming (MIQP) given by:

$$\text{Minimize: } \sum_{(i,j)\in E} R_{ij} \cdot x_{ij} \cdot (x_{ij}^A \cdot I_{ij-A}^2 + x_{ij}^B \cdot I_{ij-B}^2 + x_{ij}^C \cdot I_{ij-A}^2) \quad (1)$$

Where:

$x_{ij}, x_{ij}^A, x_{ij}^B, x_{ij}^C \in \{0,1\}$: State of connection between two buses i and j

R_{ij} : Resistance of branch (i, j)

$I_{ij-A}, I_{ij-B}, I_{ij-C}$: Current flow in branch (i, j)

A, B, C : Phases of system

(0: bus i and bus j are not linked and 1: bus i and bus j are linked)

Subject to the following constraints:

- Arborescence

$$\begin{aligned}
&\sum_{(i,j)\in\delta^{in}(j)} x_{ij} = 1, \forall j \in V \setminus S, S \text{ is source} \\
&\delta^{in}(j) : \text{set of incomming edge for } j^{th} \text{ vertex} \\
&x_{ij} + x_{ji} \le 1, \forall (i,j) \in E \\
&x_{ij}^A \le x_{ji}, \forall (i,j) \in E \\
&x_{ij}^B \le x_{ji}, \forall (i,j) \in E \\
&x_{ij}^C \le x_{ji}, \forall (i,j) \in E
\end{aligned} \quad (2)$$

- Phase connection of load

$$\begin{aligned}
&\forall i \in V \setminus S, S \text{ is source} \\
&p_i^\alpha \in \{0,1\} : \text{phase connection of } i^{th} \text{ load}, \alpha = A, B \text{ or } C \\
&x_{ij}^A \cdot p_i^A + x_{ij}^B \cdot p_i^B + x_{ij}^C \cdot p_i^C = \begin{cases} 1, \text{if 1 phase} \\ 3, \text{if 3 phase} \end{cases}
\end{aligned} \quad (3)$$

3. Simulation Results and Discussions

3.1. *Case Study and Normalized Curves*

The rural village located in Sandek commune, Cambodia has been chosen. The consumers are supplied by a 22/0.4-kV transformer from the 1st bus. The total active power is about 43 kW with a power factor of 0.95. A normalized daily load curve with a 1-hour time step is taken from local measurements in a village. Since there is presently no available information, this normalized curve is generalized to simulate a year. The detailed information of the case study is provided in [9]. The set-up of load profile measurement and normalized load curve for simulation are provided in Fig. 4 and Fig. 5.

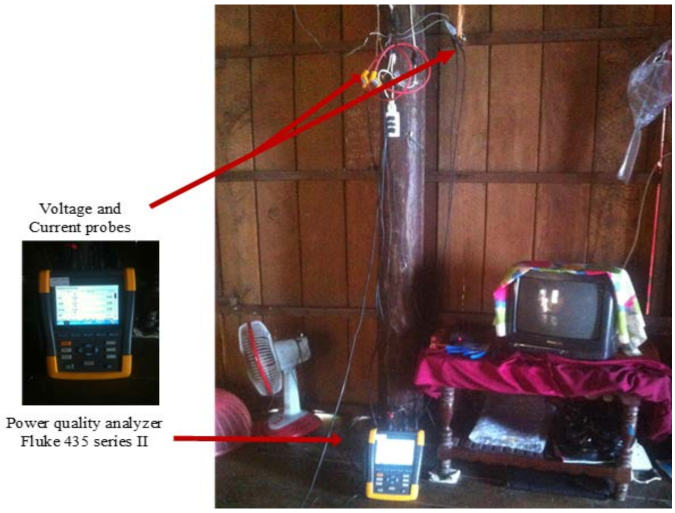

Fig. 4. Set-up of load profile measurement for the simulation

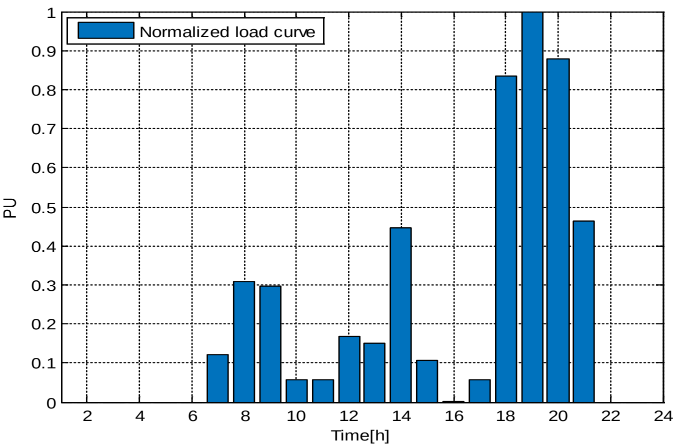

Fig. 5. Normalized daily load curve for the simulation

3.2. *Optimal Radial Topologies*

In this part, the LVAC radial topologies of three different algorithms are performed by using SP-RPS-ABC, SP-FFBP, and SP-MIQP algorithms. Furthermore, a cable size of 70 mm^2 is used for the mainline and 4 mm^2 from the main feeder to each energy meter which is currently implemented in Cambodia. Fig. 6 provides the optimal radial topology which is performed with SP-MIQP.

The active power at each phase for the three different algorithms is given in Table 1. As seen in the table, the 2nd algorithm is better balanced than the 1st and 3rd algorithm, but the 3rd is the lowest power losses (see Table 2). The reason is the fact that the 1st changes the phase from the substation to the end of the pole with repeated phase ABC. For the 2nd algorithm, it has tied to balance the load using the bin packing concept from the substation. But, the 3rd algorithm has tried to balance the load and power losses minimization at each pole from the MV/LV substation to the end of energy meter.

Table 1. Active power at each phase

Algorithm	**Total active power P (kW)**		
	A-phase	B-Phase	C-Phase
1st algorithm	14.048	10.035	18.917
2nd algorithm	13.975	14.294	14.731
3rd algorithm	13.923	15.127	13.950

3.3. *Voltage Profiles and MV/LV Distribution Transformer*

These proposed algorithms aim to improve the balanced load and power loss while respecting to the voltage and current constraints. The voltage profiles of the system for all algorithms are shown in Fig. 7. Regarding the voltage limit (i.e., 0.9 pu in Cambodia), there is no problem with the selected conductor size (i.e., 70 mm^2) which is currently used in Cambodia. Besides, the 3rd algorithm is quite good in voltage and required active power at the MV/LV distribution transformer (see Table 2) compared to others.

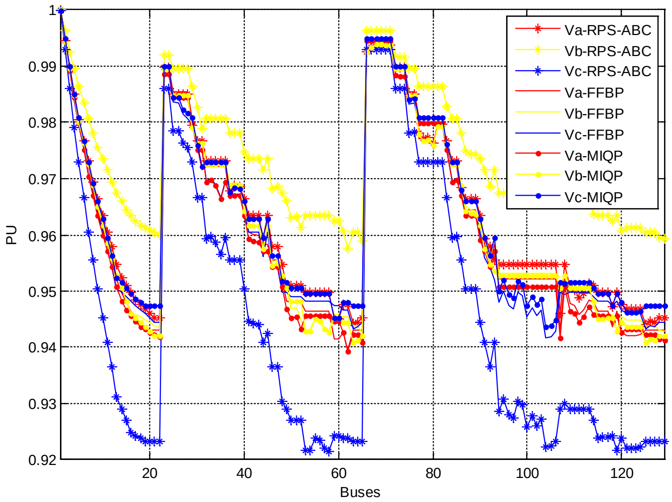

Fig. 7. Voltage profiles of the system at peak load

3.4. *Performance of Three Proposed Algorithms*

To compare the three proposed algorithms, some performance indicators have been computed in Table 2. Also, minimal power loss and operational expenditure (OPEX) with an electricity cost of 0.2 US$/kWh [10] are the main indicators of these algorithms. As seen in the table 2, the indicators for the 3rd algorithm (SP-MIQP) is lower than the 1st algorithm (SP-RPS-ABC) and 2nd algorithm (SP-FFBP), that is because the 3rd algorithm is minimizing power losses as well as load balancing improvement.

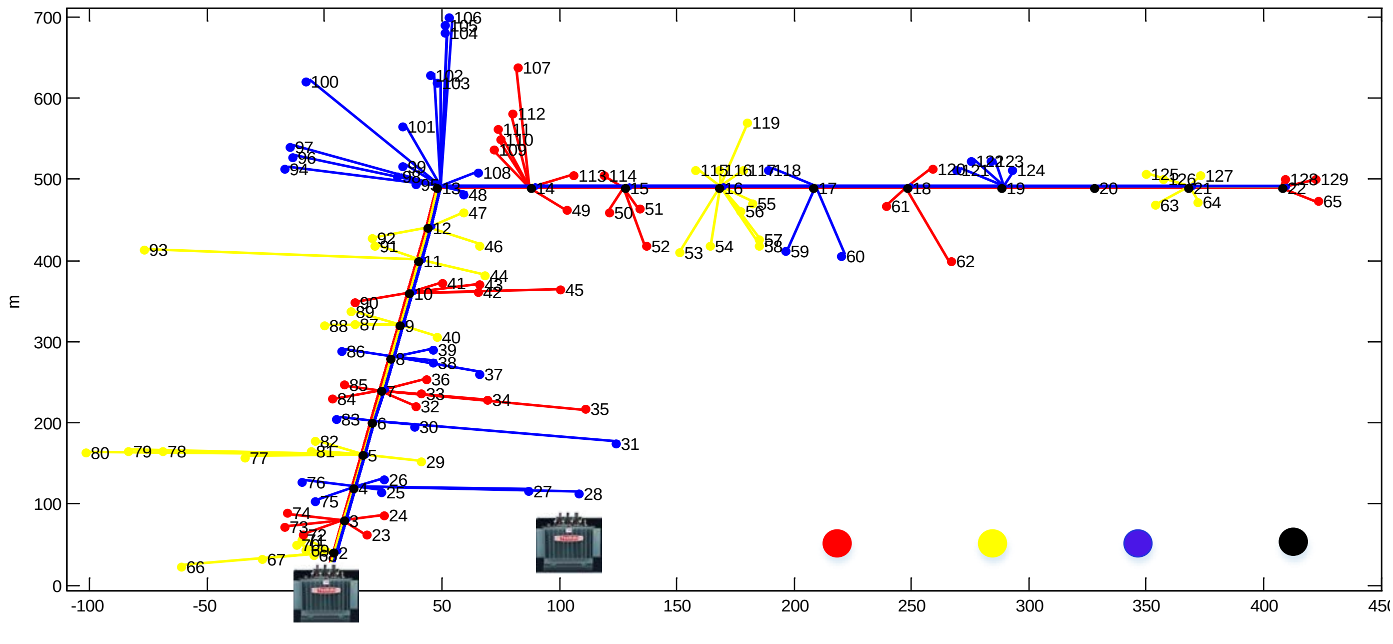

Fig. 6. Optimal radial topology by SP-MIQP algorithm

Table 2. Performance indicators of different algorithms

Items	1st algorithm	2nd algorithm	3rd algorithm
Annual Energy Used [MWh]	81.67	80.94	80.09
MV/LV required [kW]	46.60	45.92	45.89
Maximal Power losses [kW]	3.60	2.92	2.89
Maximal Current (A)	91.87	70.16	71.78
Minimal Voltage [pu]	0.9216	0.9395	0.9394
OPEX per year [kUS$]	16.334	16.188	16.018

The operational expenditure of energy used is also computed to compare the three different proposed algorithms. This energy is taken from the sum of energy losses and energy consumption over a year. According to the annual energy used in Table 2, we can thus conclude that the 3rd algorithm is selected as the best solution for the system.

4. Conclusions

In this research work, the optimal radial topology of a low voltage system for the electrification of a rural village is performed by using several algorithms. The shortest path is applied to search for the best radial topology considering the coordinates of the MV/LV transformer and energy meters. Then, three different algorithms, the repeated phase sequence (SP-RPS-ABC) and the first-fit bin-packing (SP-FFBP), and SP-MIQP are developed to find out the best load balancing and power losses minimization. The comparative study of these algorithms considering the yearly energy used is also conducted to make the decision on which should be selected. Also, the topology of the three-phase diagram is automatically pictured with different colors for visualization. Moreover, compared to the computation time and algorithms coding, the 2nd algorithm can be considered for the distribution system designer.

Acknowledgment

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