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# Designing AC Low-Voltage Topologies for a Non-Electrified Area – A Case Study in Cambodia

Chhith Chhlonh  
Univ. Grenoble Alpes, CNRS, Grenoble INP\*, G2Elab, F-38000  
Grenoble, France  
chhith.chhlonh@g2elab.grenoble-inp.fr

Marie-Cécile Alvarez-Herault  
Univ. Grenoble Alpes, CNRS, Grenoble INP\*, G2Elab, F-38000  
Grenoble, France  
marie-cecile.alvarez@g2elab.grenoble-inp.fr

Vannak Vai  
Faculty of Elect. Eng., Institute of Technology of Cambodia  
Phnom Penh, Cambodia  
vannak.vai@itc.edu.kh

Bertrand Raison  
Univ. Grenoble Alpes, CNRS, Grenoble INP\*, G2Elab, F-38000  
Grenoble, France  
bertrand.raison@g2elab.grenoble-inp.fr

**Abstract**— In the planning process of an AC low-voltage microgrid, it is necessary to design a proper structure that meets economic and technical aspects. This paper aims to optimize an AC low-voltage topology in a non-electrified area considering the total cost for 30 years planning period. First, two algorithms, the Minimum Spanning Tree (MST) and Shortest Path (SP), are proposed to build radial networks. Next, Mixed-Integer Linear Programming (MILP) is used to allocate the powers of all loads (households) to the three phases of the main feeders. This allocation can be done directly at the level of the load or at the level of the poles where loads are connected. The four possible combinations, i.e. Load Balancing – Minimum Spanning Tree (LB – MST), Load Balancing – Shortest Path (LB – SP), Minimum Spanning Tree – Pole Balancing (MST – PB), and Shortest Path – Pole Balancing (SP – PB), are finally compared considering a real non-electrified village in Cambodia. Based on the results obtained, the LB – SP has a better performance compared to others.

**Keywords**—AC low-voltage, graph theory, minimum spanning tree, shortest path, load balancing, pole balancing, MILP

*PB* : Pole balancing  
*pu* : Per-Unit  
*P<sub>3φ</sub>* : Three-phase active power [kW]  
*P<sub>slack bus</sub>* : Power at slack bus [kW]  
*P<sub>loss</sub>* : Total power losses [kW]  
*RABC* : Repeated ABC phase  
*r* : Discount rate [%]  
*r<sub>j</sub>* : Failure + restoration duration [h]  
*SAIDI* : System Average Interruption Duration Index  
*SAIFI* : System Average Interruption Frequency Index  
*SC* : Short circuit  
*SP* : Shortest path  
*TOTEX* : Total expenditure [k\$]  
*T* : Duration of the study [years]  
*t* : Hour index  
*V<sub>L-L</sub>* : Line to line voltage [V]  
*Z<sub>SC</sub>* : Positive-sequence impedance [Ω]  
*Z<sub>0</sub>* : Zero-sequence impedance [Ω]  
*cosθ* : Power factor

## ABBREVIATIONS AND NOMENCLATURE

*CAPEX* : Capital expenditure [k\$]  
*CB* : Circuit breaker  
*CPS* : Combinatorial phase swapping  
*C<sub>\$/kWh</sub>* : Cost of purchasing energy from the grid [\$/kWh]  
*C<sub>\$/kWh</sub>* : Cost of selling energy to households [\$/kWh]  
*FFBP* : First-Fit Bin Packing  
*i* : Yearly index  
*I<sub>L</sub>* : Line current [A]  
*I<sub>sc3</sub>* : Three-phase short circuit current [A]  
*I<sub>sc0</sub>* : Phase-to-ground short circuit current [A]  
*LB* : Load balancing  
*LV* : Low voltage  
*L<sub>j</sub>* : Line length of the interrupted loads  
*L<sub>total</sub>* : Total length of the network  
*MCB* : Miniature circuit breaker  
*MCCB* : Mold case circuit breaker  
*MILP* : Mixed-Integer Linear Programming  
*MIQCP* : Mixed-Integer Quadratically Constrained Programming  
*MST* : Minimum spanning tree  
*MV* : Medium voltage  
*n* : Number of branches between loads and poles  
*N<sub>j</sub>* : Number of interrupted loads  
*N<sub>total</sub>* : Number total loads  
*OPEX* : Operational expenditure [k\$]  
*OPEX<sub>invest</sub>* : Cost of purchased energy from the MV grid [k\$]  
*OPEX<sub>income</sub>* : Cost of selling energy to the households [k\$]

\* Institute of Engineering Univ. Grenoble Alpes

## I. INTRODUCTION

Frequently, the number of residential, commercial, and industrial buildings quickly increase, which causes the distribution system operator to reinforce and expand its network to supply the loads. The distribution system is categorized into two voltage levels which are medium-voltage (MV) and low-voltage (LV) [1]. Typically, the LV system faces the problem of unbalances due to the connections of single-phase and three-phase loads, which increase power losses and cost expenses. To handle these issues, various research strategies (i.e., optimal topology and load balancing) have been proposed and applied to real situations.

Many papers have been reviewed in this literature section. In [2], the authors have compared two different algorithms called RABC (Repeated ABC phase) sequence and CPS (Combinatorial Phase Swapping) in a radial topology by considering the minimum power losses and phase balancing. Based on the results, CPS has a better performance compared to RABC. In papers [3]-[4], the authors have presented algorithms called SP (Shortest Path), MIQCP (Mixed-Integer Quadratically Constrained Programming), and FFBP (First-Fit Bin Packing) techniques to define an optimized topology and phase balancing in an urban area by considering load growth over the planning period. In references [5]-[6]-[7], the authors have proposed MILP (Mixed-Integer Linear Programming) and Simulated Annealing technique to optimize phase balancing in the power system. Based on the results, this strategy has

improved voltage drops and has reduced energy losses. In another research [8], the authors aimed to optimize a radial topology of a network. The authors have proposed a K-means clustering technique to pack DC loads into some clusters. For each cluster, MST (Minimum Spanning Tree) algorithm has been applied to define the connection of each load. Next, the shortest path algorithm is used to find the shortest distance between the electrical pole and clusters. As a result, a radial topology and total discounted cost are defined. Next, the planning in the distribution network for rural areas based on graph theory to minimize conductors length is presented in [9]. In [10], the aim of this paper is to find the minimum cost route from each load in a large distribution system to a substation in order to minimize the cost of capital recovery and energy losses. The authors proposed a technique based on a search path algorithm to define radial paths in the distribution system. Thus, the proposed method has minimized the total annual costs compared to the traditional methods. Based on these reviewed articles, the balancing system and reconfiguration in the distribution networks are still the main challenges that need to be improved to minimize the cost operation and have an efficient topology. Therefore, this research provided several solutions to build an appropriate structure into a non-electrified area through surveyed data (case study). It is noted that the system balanced is based on MILP and the radial topologies building is provided by MST and SP (Shortest Path).

This paper proposes and compares methods to define radial topologies in AC low-voltage for a non-electrified area. It aims to minimize the total cost for 30 years and respect all the constraints. A case study located in Cambodia has been tested for data analysis. Moreover, the selection of protective devices and the study of the network's reliabilities (SAIDI and SAIFI) are also demonstrated in this work.

This paper is organized into the following sections. First, the process of proposed methods and cost calculations are described in section II. The data of the case study are described in section III. Next, the simulation results and discussions are provided in section IV. Finally, section V delivers conclusions and future works.

## II. METHODOLOGY

In this section, four different methods are proposed and called LB-MST (Load Balancing – Minimum Spanning Tree), LB-SP (Load Balancing – Shortest Path), MST-PB (Minimum Spanning Tree – Pole Balancing), and SP-PB (Shortest Path – Pole Balancing). The procedure of these methods is detailed in Fig. 1. It can be explained through the following steps:

- **Step 1:** Input data for the simulation. It contains the coordinates of the MV/LV transformer, electrical poles, and loads. These coordinates are provided in detail in the reference [11].
- **Step 2:** In this step, there are two different categories, and each category contains two different methods.

### 1. Power balancing then topologies building:

First, each input power from each load has been allocated to a phase of the system based on MILP to ensure the phase balancing of the full system. Second, to build the topologies, the MST and SP are proposed. The MST is applied to loads that are in the same phase to define all connections (load to load and load to electrical pole). However, the SP is employed for all

loads to directly connect them to the nearest electrical pole. Thus, the combinations of the techniques are LB-MST and LB-SP which provided two different radial topologies.

### 2. Topology building then power balancing:

First, based on the locations of the loads and poles, the MST constructed a radial topology that identified the connections between the loads and electrical poles. Second, the total power of each electrical pole is allocated to one phase of the system based on MILP. Similarly, the SP is used to build a radial topology which means all the loads are directly connected to the nearest electrical pole. Then, the MILP is applied to balance the total power of each electrical pole into phases A, B, and C. Therefore, the MST-PB and SP-PB provide two different radial networks.

**Note:** [12] and [13] have demonstrated how the MST and SP algorithms work, respectively. In addition, the MST has used a technique called KRUSKAL technique to build a structure.

- **Step 3:** At this point, the topologies have been implemented by backward-forward 4 wires unbalanced load flow to compute the electrical parameters such as voltages, currents, power at the slack bus, and power losses [14]. This load flow is computed for each year until the 30<sup>th</sup> year with a yearly load growth of 3% [11].
- **Step 4:** Finally, all the expense and income costs are determined for 30 years. It included the CAPEX, OPEX (OPEX<sub>invest</sub> and OPEX<sub>income</sub>), and TOTEX. It is noted that the CAPEX includes cable costs, protective devices, and MV/LV transformer. Furthermore, the OPEX<sub>invest</sub> is the cost of purchasing energy from the MV grid (included energy losses) and OPEX<sub>income</sub> is the cost of selling energy to the households (excluded energy losses).

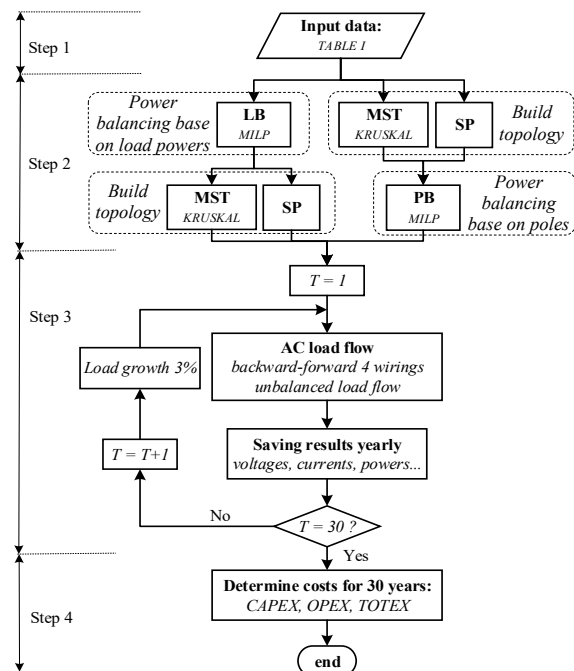


Fig. 1. Flowchart of the proposed methods

### A. Mixed Integer Linear Programming (MILP)

In this paper, the MILP is used to balance the power of loads to three-phase main feeders. The MATLAB tool called *linprog* function is used as a tool for MILP. The specified equations of the objective function and constraints have been provided in reference [8].

### B. Costs Calculation

For T years planning of the network, the global cost is calculated. It contains CAPEX,  $OPEX_{invest}$ ,  $OPEX_{income}$ , and TOTEX. The cost formulations are provided [15]:

$$TOTEX = CAPEX + OPEX_{invest} - OPEX_{income} \quad (1)$$

$$OPEX_{invest} = \sum_{i=1}^T \left( \sum_{t=1}^{8760} \frac{P_{slack\_bus}(t,i) \times C_{S/kWh}}{(1+r)^i} \right) \quad (2)$$

$$OPEX_{income} = \sum_{i=1}^T \left( \sum_{t=1}^{8760} \frac{[P_{slack\_bus}(t,i) - P_{loss}(t,i)] \times C'_{S/kWh}}{(1+r)^i} \right) \quad (3)$$

Based on equation (1), the TOTEX value is reduced caused by the costs of selling energy to the households ( $OPEX_{income}$ ).

### C. Protective Devices Selection

CBs (Circuit breakers) are used for protection in this research. They are located at the secondary of the MV/LV substation and on each pole. To select proper protective devices, rated currents and short circuit currents (SC) must be calculated. The three-phase and phase-to-ground short circuit current formulations are provided as the following equations [16]:

- Line current:  $I_L = \frac{P_{3\phi}}{\sqrt{3}V_{L-L} \cos \theta} \quad (4)$

- Three-phase SC:  $I_{sc3} = \frac{V_{L-L}}{\sqrt{3}Z_{SC}} \quad (5)$

- Phase-to-ground SC:  $I_{sc0} = \frac{V_{L-L}}{\sqrt{3}(Z_{SC} + Z_0)} \quad (6)$

References [16] and [17] illustrate how to determine  $Z_{SC}$  (positive-sequence) and  $Z_0$  (zero-sequence) impedances, accordingly.

### D. SAIDI and SAIFI

The SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index) are reliability indicators of a network. Since the value of the fault probability is not available in the studied area thus, it is approximated by the ratio of the line length of interrupted loads by the total line length of the network. Therefore, the equations are written as the following:

$$SAIDI = \frac{\sum_{j=1}^n r_j N_j L_j}{L_{total} N_{total}} \quad (7)$$

$$SAIFI = \frac{\sum_{j=1}^n N_j L_j}{L_{total} N_{total}} \quad (8)$$

## III. CASE STUDY

The input parameters for economic analysis are indicated in TABLE I. Located in Toul Tumpong village, Kampan commune, Memot district, Tboung Khmum Province, a rural village has been selected for a case study [11°56'31.4"N 106°02'08.5"E]. Fig. 2 shows a top view from Google Maps of the site location. Fig. 3 is a converted topology in XY coordinates and it contains the location of a 22/0.4 kV transformer, electrical poles, and all the loads (households). There are 24 electrical poles (including the MV/LV transformer pole) with an average distance of 40m from each other. The total number of loads is 68 and the total power is 33.6 kW in the initial year with a 0.95 power factor. Fig. 4 provides the daily load curve for the network (based on a survey, i.e., times of use of load's consumption). Moreover, the cost of MV lines along the road to supply the power to the village is estimated and included also. The distance of MV lines is approximately 14 km (estimated by Google Maps). The conductor sizes are indicated on each topology.

TABLE I. INPUT PARAMETERS

Items	Values	
Total load power in initial year	33.6 kW	
Total load power in 30 <sup>th</sup> year	81.5 kW	
Load growth yearly [11]	3 %	
Line to line voltage ( $V_{L-L}$ ) [18]	400 V	
Planning period	30 years	
Discount rate [11]	6 %	
Failure + restoration duration ( $r_i$ ) [19]	16 h	
Cost of purchased energy from MV grid [20]	0.000121 k\$/kWh	
Cost of selling energy to households [20]	0.000152 k\$/kWh	
Three-phase transformer 22/0.4 kV, 100kVA [21]	2.5 k\$	
Mold Case Circuit Breaker 4P 125A B curve [22]	0.67 k\$	
Miniature Circuit breakers [23], [24]	1P+N 10A B curve	0.025 k\$
	1P+N 20A B curve	
	1P+N 32A B curve	
	1P+N 63A B curve	
Cable costs [25], [26], [27]	4 mm <sup>2</sup> (2 cores)	3.6 k\$/km
	6 mm <sup>2</sup> (2 cores)	6.2 k\$/km
	35 mm <sup>2</sup> (1 core)	16.5 k\$/km
Cost of MV cable 22kV, 95 mm <sup>2</sup> (1 core) [28]	8.5 k\$/km	
Limited voltage [18]	$V_{max}$	1.1 pu
	$V_{min}$	0.90 pu

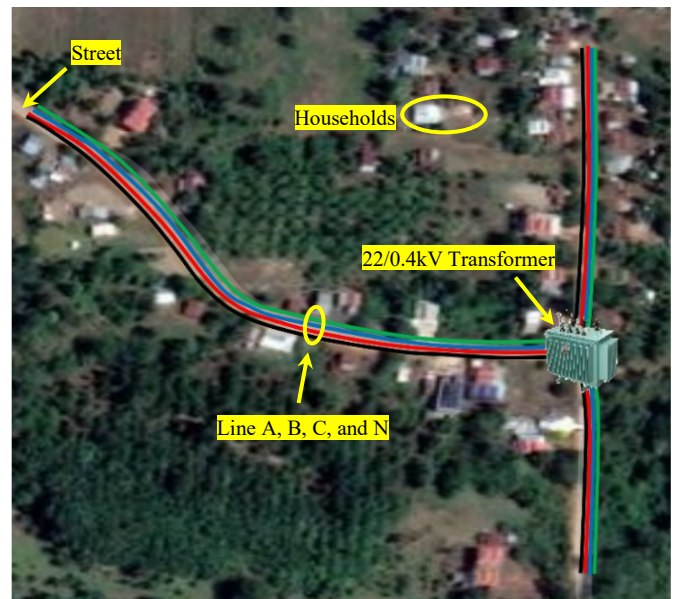


Fig. 2. A top view from the Google Maps of the site location

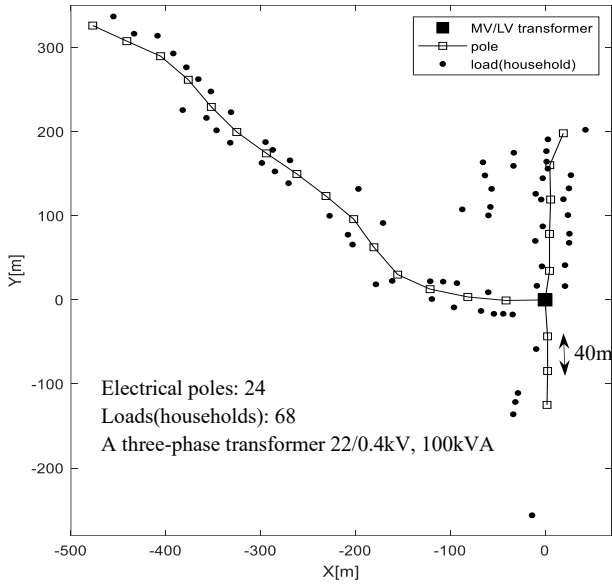


Fig. 3. Location of MV/LV transformer, electrical poles, and loads

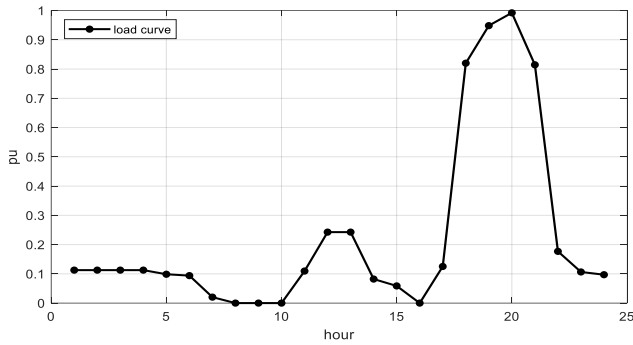


Fig. 4. Daily load curve in pu

#### IV. RESULTS OF SIMULATION AND DISCUSSION

There are some assumptions in this study. First, the load curve shape remains the same starting from the initial year until the 30<sup>th</sup> year. The yearly load growth is 3% for the entire load curve, and there are no new connected customers to the studied network. Second, all the loads are single-phase. The simulation results for each proposed method over 30 years are provided in TABLE II. The minimum voltages and all costs (CAPEX and OPEX) are provided in Fig. 5 and 6, respectively. Likewise, the radial topologies of each proposed method are illustrated in Fig. 7. It is also included SC currents values and the number of protective devices.

TABLE II. RESULTS OF SIMULATION FOR 30 YEARS

Items	LB – MST	LB – SP	MST – PB	SP – PB
Total length [km]	6.48	7.04	6.01	7.12
SAIDI [h/yr]	6.62	5.85	7.57	5.85
SAIFI [fail./yr]	0.4	0.35	0.45	0.35
Peak power loss [kW]	2.14	1.92	2.74	2.09
Peak power from grid [kW]	83.52	83.3	84.12	83.47
Energy purchase from the grid for 30 years [MWh]	3258.76	3255.06	3268.77	3258.04
CAPEX [k\$]	404.7	405.8	406.8	407.4
OPEX <sub>invest</sub> [k\$]	159.3	159.1	159.7	159.3
OPEX <sub>income</sub> [k\$]	198.8	198.8	198.8	198.8
<b>TOTEX [k\$]</b>	<b>365.2</b>	<b>366.1</b>	<b>367.7</b>	<b>367.9</b>

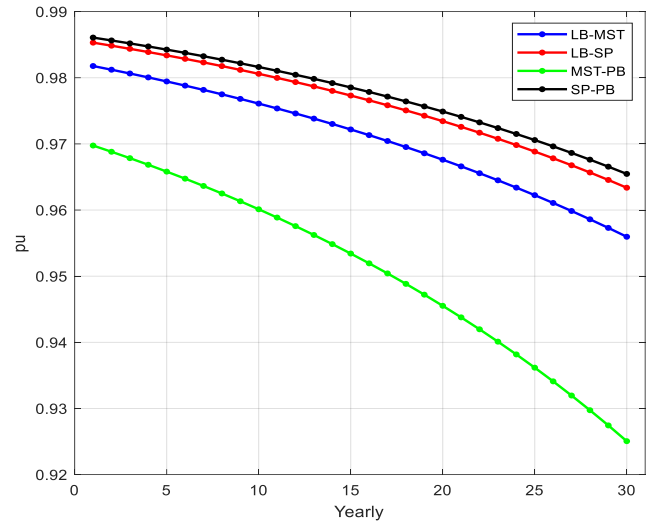


Fig. 5. The minimum voltages of each topology for each year

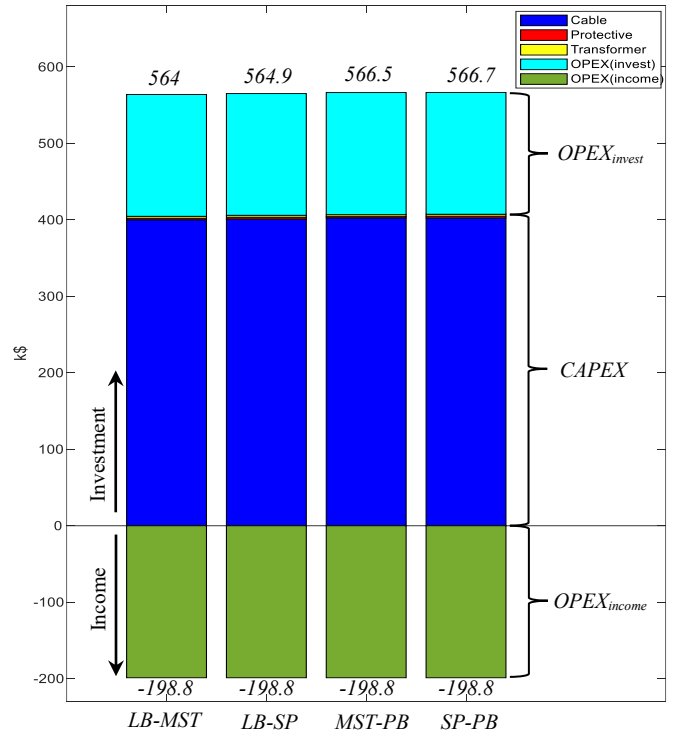


Fig. 6. TOTEX, CAPEX and OPEX of each topology for 30 years

As mentioned above, these topologies are protected by circuit breakers. Based on calculations, the three-phase ( $I_{sc3}$ ) and phase-to-ground ( $I_{sc0}$ ) short-circuit currents for the main feeders ( $35\text{mm}^2$ ) are estimated at 5752A and 492A, correspondingly. The maximum line current for the main feeders in the 30<sup>th</sup> year is  $I_L = 123.9\text{A}$ . Thus, a MCCB (4P, 125A, B curve) [22] is selected as a protective device due to its breaking capacity is 25kA (higher than  $I_{sc3}$ ).  $I_{sc0}$  is defined to ensure the MCCB is tripped when the line current reach three times (B curve) or higher than the MCCB rated current (125A). Similar to secondary feeders, the phase-to-ground short-circuit currents are  $I_{sc0\_max} = 1706\text{A}$  (for load has the lowest line impedance) and  $I_{sc0\_min} = 225\text{A}$  (for load has the highest line impedance). The maximum and minimum line currents are 46.4A and 0.13A, respectively. Therefore, the selected MCBs are indicated on each topology in Fig. 7.

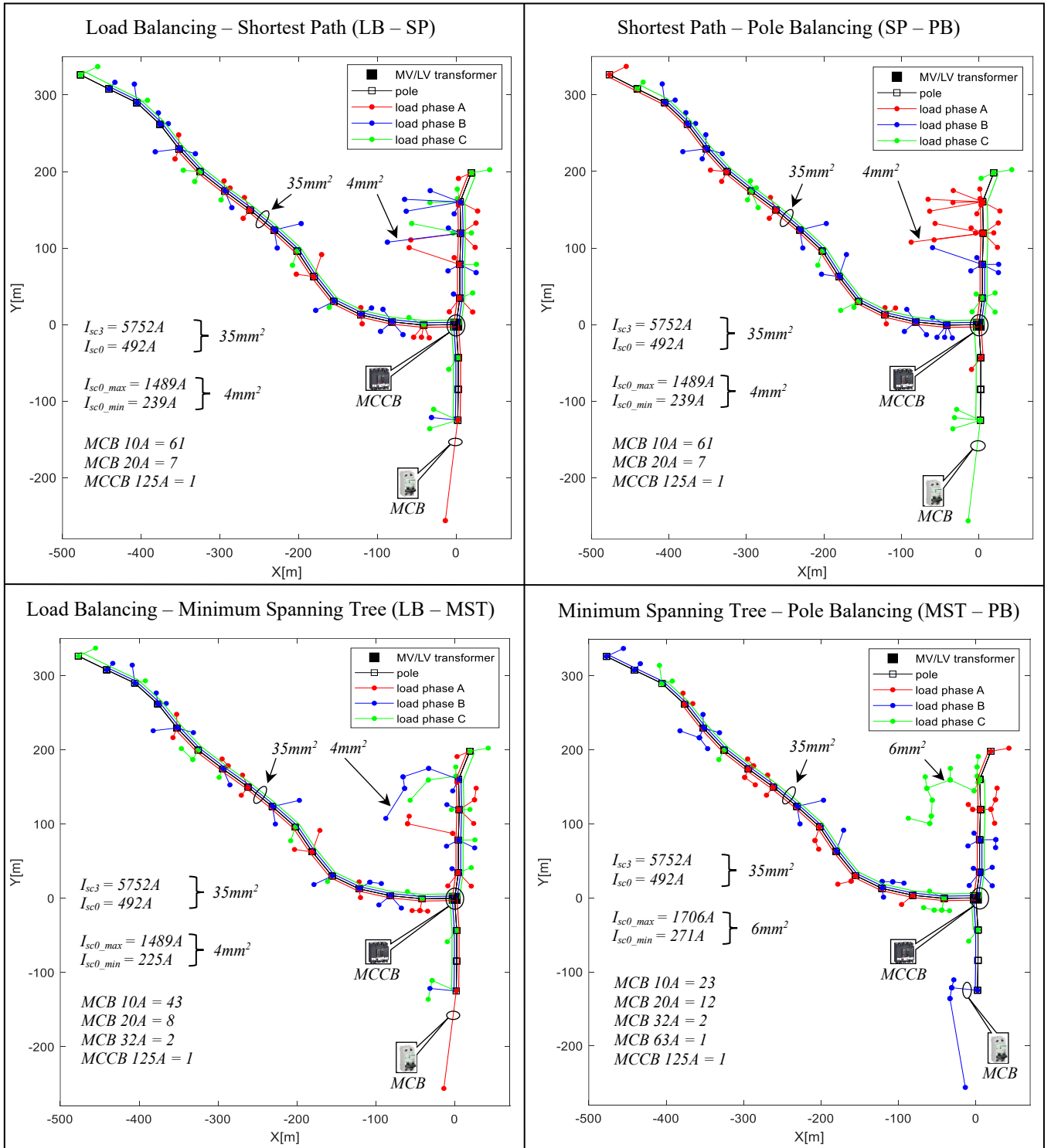


Fig. 7. Simulation results of the radial topologies of each method

Based on the simulation results in TABLE II, LB-MST is the most optimized result with a TOTEX of 365.2k\$. Even if the TOTEX difference is small (less than 0.73% between the LB-MST and the SP-PB), the SP – PB has a much better voltage profile (0.96pu). The LB – SP and SP – PB have higher investment costs (CAPEX) since the length of the conductors is higher and require more protective devices. However, the reliabilities (SAIDI and SAIFI) of LB – MST have lower performance compared to LB – SP and SP – PB due to the impact of the long length of conductors and more interrupted loads when the network has faults. On the other hand, the MST-PB has the highest power losses (peak hour at

20h00) caused by the long-connected conductors. Also, the cross-section of secondary feeders has to be increased to 6mm<sup>2</sup> to maintain the system voltage higher than 0.9pu (Fig. 5). To sum up, since the TOTEX difference is small thus, the selected method is based on the reliabilities index. Therefore, LB – SP is the most suitable method in this study.

## V. CONCLUSION AND FUTURE WORKS

This paper has proposed and compared four different methods which are LB – MST, LB – SP, MST – PB, and SP – PB to build an appropriate topology and minimize the total cost for a non-electrified area for over 30 years. The MST and SP algorithms enable to search for radial

structures. The MILP algorithm is applied to balance power for three-phase in the networks. Moreover, the selection of protective devices and the study of the reliabilities of the networks are also illustrated. A case study is tested and has provided the results for analysis. Based on simulation results in this work, although the four methods have similar TOTEX, the LB – SP is the most interesting one in terms of reliability (SAIDI and SAIFI) compared to others. Next, future research will focus on sensitivity analysis of network parameters (load density, powers, load profiles etc.).

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