International Journal of Applied Power Engineering (IJAPE)
Vol. 13, No. 1, March 2024, pp. 138~151
ISSN: 2252-8792, DOI: 10.11591/ijape.v13.i1.pp138-151

Optimal feeder routing and phase balancing for an unbalanced distribution system: a case study in Cambodia

Sopheak Kay[1], Vannak Vai[2], Samphors Eng[1]
[1]Research and Innovation Center, Institute of Technology of Cambodia, Phnom Penh, Cambodia
[2]Department of Electrical and Energy Engineering, Institute of Technology of Cambodia, Phnom Penh, Cambodia

Article Info

Article history:

Received Mar 13, 2023
Revised Jun 4, 2023
Accepted Jun 24, 2023

Keywords:

Distribution system
Economic analysis
Feeder routing
Genetic algorithm
Optimization
Phase balancing
Shortest path algorithm

ABSTRACT

This paper aims to minimize the distance of the feeder path from high-voltage/medium-voltage (HV/MV) substation to medium-voltage/low-voltage (MV/LV) transformers and minimize power loss in an unbalanced distribution system by the phase-swapping concept-based load balancing. The shortest path algorithm (SPA) and the genetic algorithm (GA) for optimal feeder routing and phase balancing separately in the MV unbalanced distribution network are proposed. First, the relevant data for the system is collected. These data include substation coordinates (X, Y), active and reactive power (P, Q), phase connections, and lines' impedance (Z). secondly, the performance of the existing configuration of the test system with numerous indications is presented. Finally, the proposed method is performed to minimize the length and power losses. The real 47-bus test system in Cambodia is chosen to demonstrate the proposed method. In this study, overall power losses, the maximum voltage imbalance, and voltage regulation are computed by the backward/forward sweep load flow. The results based on the simulation indicate the importance of the proposed approach, especially for distribution system designers and operators.

Corresponding Author:

Vannak Vai
Department of Electrical and Energy Engineering, Institute of Technology of Cambodia
P.O Box 86, Russian Conf. Blvd, Phnom Penh, Cambodia
Email: vannak.vai@itc.edu.kh

1. INTRODUCTION

Distribution networks play an important role in Cambodia due to their supply power for local, industrial, commercial, and agricultural needs in the capital city and all other provinces [1]. The high-voltage/medium-voltage (HV/MV) transformer, consumer, and grid substation are all connected through the distribution system. It has two voltage categories, low-voltage (LV) and medium-voltage (MV). The MV and LV voltage ratings for the distribution grids operated by Electricité Du Cambodge (EDC) are 22k V and 400 V, respectively. Additionally, despite having higher power losses, both distribution grids operate radially in order to minimize investment costs [2]. Feeder routing and phase balance have become the key distribution planning challenges in Cambodia. The main objectives of the distribution system project planning include determining the placement, capacity, and service area of the substation as well as the quantity and routes of feeders. Khun NayKieng with the code 335L, one of SNKRP Company's distributor licensees, provides power to an area via a transmission line that passes through parts of Srey Santhor District and Khsach Kandal District in Kampong Cham and Kandal Provinces, respectively. The electrical license from EDC [1], which is running and covering MV and LV distribution lines, depicts this region. The MV system in rural areas is usually constructed with a combination of 3-phase and 2-phase line arrangements, which causes concern with voltage imbalance index, voltage drop, and increases overall power loss.

For the problem of feeder routing, one of the traditional solutions applied dynamic programming techniques and geographical information systems (GIS) facilities [3]. A real work study scenario is used to highlight the algorithm's usefulness. The direct solution methods suggested by Samui *et al.* [4] and Kumar *et al.* [5] a entirely based on finding in supplying a bus among all the possible paths. Regarding numerical approaches, the mixed-integer linear programming (MILP) model is established in [6]–[8] to determine the optimal feeder routing of the primary real MV distribution for minimizing the total power loss with layout constraints and differential crow search algorithm respectively. However, many researchers have focused on the minimum spanning tree to minimum feeder routing for distribution network planning, such as in [9], which used graph theory based on the minimum spanning tree for optimal feeder routing in distribution networks with distributed generation (DG) units. The selection of the network topology, the decision on cable size, and optimal network calibers are the main objectives of network planning [10]. The grid topology must be carefully designed in order to evaluate a grid's electrical performance, including power losses, voltage, and conductor loading, among other factors. The overall grid length for conductors is minimized using the conventional minimum spanning tree technique. The genetic algorithm (GA) was utilized to determine the substation's location within the distribution network. Additionally, in order to determine optimal network routing, the feeders that link the loads to the grid substations utilize the minimum spanning tree (MST) [11]. Furthermore, by implementing radial distribution system optimizations, it is possible to search for the optimal system topologies by the shortest path algorithm that has been developed [12].

Phase balancing in the system is the main issue in the distribution network, and three methods may be used for power loss reduction and voltage profile improvement in distribution networks: i) system reconfiguration, ii) the integration of DGs, and iii) phase exchange. Several techniques for carrying out reconfigurations by changing the sectionalizing switches status are developed by many authors. The problem of integrating DGs is made more difficult by the fact that renewable sources often require the control of active power production. The last technique, phase swapping, enables low-cost connection changes through the use of deference methods. Rios *et al.* [13] applied a genetic algorithm and group theory codification to balance phases in an unbalanced system using a 3-phase group and a 3-phase subgroup based on several IEEE test feeders. There is a 3-phase subgroup for distribution system feeders for industrial applications. In master-slave, the vortex search algorithm (VSA) specifies phase swapping in different types of phase connections and performs phase balancing for the unbalanced distribution network [14]. The slave state has been implemented with the unbalanced backward-forward swap load flow.

Mixed-integer nonlinear programming is also used [15] to solve phase rebalancing for consumers with a 1-phase in order to identify the phase swapping in the existing distribution network. For reducing the annual operating costs of the systems, the authors in [16]–[19] use a master-slave optimization approach with a modified sine-cosine, hurricane-based optimization algorithm (HOA) and slap swarm algorithm (SSA) used by the master stage helped it determine the best three-phase transformer connection and they used a three-phase load flow that was based on triangles for the sleeve stage. In order to reduce the sum of the square currents passing in the line multiplied by the line's average resistance in a three-phase network, the mixed-integer quadratic convex (MIQC) approach was presented in [20]–[22]. The study in [20], [21] developed the MIQC model and tested it with several IEEE test systems, and compared the simulation result with metaheuristic solvers such as GA, black hole, and sine cosine. By re-phasing at the distribution system level, Granada Echeverri *et al.* [23] deployed a specific genetic algorithm. Ivanov *et al.* [24] used real test systems from an urban area to study active power loss reduction in LV distribution systems and MV distribution networks by using a hybrid differential evolutionary particle swarm optimization (DEEPSO) and compare the results to the conventional PSO and a genetic algorithm was used in [25] to considered power losses and energy losses in three scenarios using unbalanced test systems that conform to the IEEE-13 and IEEE-37 standards.

In the last review of the manuscripts already published, many researchers worked in phase balancing and feeder routing separately. The main objective of this paper, we combination of the two objective functions as well as feeder routing and phase balancing. In addition, the shortest path algorithm (SPA) is selected to find the optimum feeder routing of HV/MV substations that are connected to all MV/LV loads. GA is used to find the best phase balancing for 3-phase unbalanced distribution networks to minimize power loss. The materials and method used to achieve the research goal are described in section 2, along with the algorithm development. The case study's key elements are presented in section 3. It consists of a test system for 47 buses, including a substation as the slack bus that is placed at bus 1 and will operate at 22 kV. Section 4 includes the simulation findings and discussion. Section 5 concludes with the conclusion and perspective.

2. METHODOLOGY AND DEVELOPED ALGORITHMS

Three-phase and mixed bi-phase MV/LV transformers, as well as MV distribution systems in rural areas, are currently in operation. Both three-phase and two-phase MV/LV transformers were installed on the real MV distribution line of Khun NayKieng Electricity, one of Cambodia's utilities [1]. The system also has a two-phase line built into almost all of its branches. Therefore, selecting which phase to separate the 2-phase MV/LV transformer and 2-phase branch line may be challenging. Based on their previous experiences, they approach this by identifying the phase with the least current flow and providing the new load to it. As a result, there were significant losses and unbalanced loads. The objective of this research aims at minimizing the length of the feeder route from the HV/MV substation to MV/LV transformers in the distribution system and minimizing power loss by phase swapping as much as possible. The two objectives are proposed in this paper: i) the shortest length of radial topology by using SPA and ii) reducing phase unbalancing and power loss by using GA. All required system information, including load consumption (PQ) system configuration (Z), route line, and system topology, as well as the locations of the load point (X, Y), and slack bus voltage nominal, are needed to determine power loss and the length of system. Then, using these input coordinates (X, Y), the SPA is started to find the system's shortest conductor length. Next, GA is applied for improving phase balancing and minimizing power losses in the system.

2.1. Feeder routing

The distribution network may be characterized by graph theory [6], in which power is directed from the substation to all transformers via distribution lines, which is a directed path. A directed graph G≡(V,A) is an ordered pair with being a collection of nodes and A being a set of ordered pairs of vertices known as directed edges. Integer programming is used to identify the minimum overall length of the distribution networks in order to meet the objective function, as shown by the written as (1) [10].

$$min(Z = \sum_{i}^{n} l_i x_i) \quad (1)$$

Where Z is the total distance of the system; l_i is the distance of route I; and x_i (1, 0) is a binary variable that indicates whether route i is taken (x_i=1) or not (x_i=0).

2.2. Shortest path algorithm

The MV/LV transformer in Cambodia is usually composed of a two-phase or three-phase transformer which receives power from a three-phase HV/LV substation. The objective of the optimal distribution network topology is to minimize the total distance of the conductor from the HV/MV. The shortest path (SP) is used to achieve this goal. According to graph theory [6], the SP looks for a path among two vertices in the graph so that the weights added to its edges are kept to a minimum. This SP approach aims to connect all of the transformers to the HV/MV substation that is nearest to them.

Selecting a way to link the specified load' sets with the minimum distance of systems could be interesting because the capital cost of the system is dependent on its overall length. This issue is known as the SP in graph theory. The SP creates a network with the lowest possible length from HV/MV substation by generating a set of links that connect all specified MV/LV loads while ensuring that the total cost of each bus is as minimal as possible. The substations coordinate (X, Y) is required for feeder routing in this study. The SP algorithm has been used in this paper to determine the minimum feeder routing for MV systems, as stated in the previous section. However, the only shortest path algorithm seems unable to implement our required optimal routing. We used Google earth map to determine the possible routes in this distribution system. Later, we utilize the shortest path’s algorithm (as shown in Algorithm 1) to find optimal feeder routing for those points of MV/LV substations from HV/MV substations, minimizing the total distance of the system.

```
Algorithm 1: Shortest path algorithm for feeder routing
Initialization:
S: Total sending-end bus
R: Total receiving-end bus
W: Distance between sending-end bus to receiving bus
for i=1:S
        for j=1:R
                W^i=W_i,j
                W=min (W^i)
        end
end
```

2.3. Phase balancing

The objective of a phase balancing is satisfied by the following mathematical expression to determine the minimum power loss in the systems [26].

$$min\left(P_{\text{loss}} = \sum_{i=1}^{n} R_i \times \frac{P^2{}_i + Q^2{}_i}{V^2{}_i}\right) \tag{2}$$

Where P_{loss} is the total active power loss; n is the total number of feeders; R_i is the resistance of ith line; V_i is the sending-end voltage of ith line; P_i and Q_i are the sending-end active and reactive power of ith line. Subject to the constraints as (3) and (4).

- Voltage constraint [27]

$$0.95 \text{ pu} \leq V_{phase} \leq 1.05 \text{ pu} \tag{3}$$

- Voltage unbalanced factor [26]

$$V_{max\_unbalance} \leq 3\% \tag{4}$$

where:

$$V_{unbalance} = \frac{max(|V_{A,i} - V_{\text{ave},i}|, |V_{B,i} - V_{\text{ave},i}|, |V_{C,i} - V_{\text{ave},i}|)}{V_{\text{ave},i}} \tag{5}$$

2.4. Genetic algorithm

The genetic algorithm (GA) is applied to determine the objective function for optimal phase balancing in a distribution network. For distribution network operation, it used natural selection to determine the greatest phase connections in systems. Based on Darwin's evolution theory, GA provides solutions to optimization issues by employing approaches that are modeled after natural processes such as reproduction, genetic transmission, and processes of individual selection, species evaluation, and species evaluation. Natural processes led to the emergence of new species, which displaced those that weren't suitable for their environment as well as themselves. The pseudocode of Algorithm 2 is provided below.

```
Algorithm 2: Genetic algorithms for phase balancing
Input data: BusData; LineData; ibus=0; Nbus=47bus
Call function: Func = @ SwapPhase
Define the number of variables of GA:  Nvar of x
Define lower-bound (LB) and upper-bound (UB) of GA: (Bi-phase connection has 6 for upper-bound, and
Three-phase connection has 6 possible connections. For LB is start with 1 for all Nvar.
Implement ga solver in MATLAB:
        [x_1..Nvar, F_value] = ga(Func , Nvar, LB, UB);
Function: f_obj = SwapPhase(x_1..Nvar)
        while ibus ≤ Nbus? do
                ibus = ibus+1;
               if Bi-phase connection of ibus
              then
                      Swap phase by x_i;
                      Linedata is connected [AB or BA; AC or CA; BC or CB];
                      Busdata is changed based on Linedata
               else if three-phase connection of ibus
               then
                      Swap phase by X_i;
                      Linedata is connected [ABC or ACB or BAC or BCA or CAB or CBA];
              End

        end
        Compute the load flow:
                        f_obj = w_1 × P_loss + w_2 × V_limit
end
```

Moreover, Figure 1 also shows the procedure for enhancing the system. All system data requires, including configuration, geographic, topology, and loads, must be presented in the first stage after feeder routing as an objective I has been achieved. In the next step, the original system's backward-forward 3-phase load flow will be used to compute the voltage magnitudes and angles at each node of the bus, as well as the total active power P (kW), reactive power Q (kVar), and active power loss P (kW) depending on the load model that has been defined at each node. In the next stage, we look for possible nodes which the phase allocations can be switched. The 1-phase MV/LV bi-pole ties to 3-phase lines at these nodes, where the 2-phase line separates from the 3-phase mainline. We have utilized GA to find alternative phase allocations for the nodes that fulfill the minimum voltage imbalance index and voltage standard in order to decrease overall power loss.

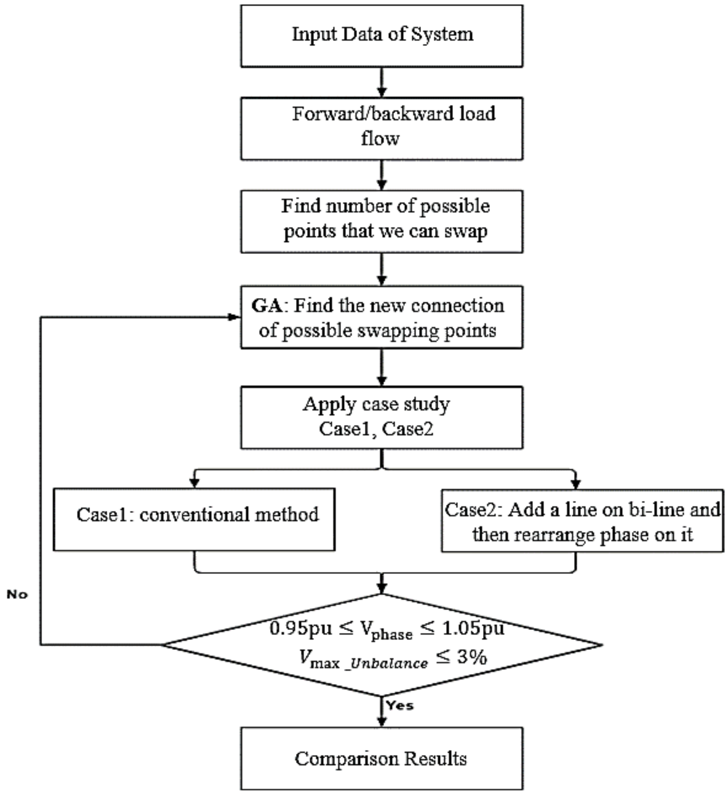


Figure 1. The flowchart of the phase balancing method with GA

2.5. Energy loss cost

This section investigates energy loss when applying load profile characteristics (24h) into the distribution system. The cost of energy loss depends on the energy consumption over the planning study. The cost of energy loss on an annual basis is given by [28].

$$E_{cos\,t} = E_{\text{loss}} \times E_c \times T \tag{6}$$

Where E_{cost} is the cost of energy loss in [USD/Year]

$$E_{loss} = \left(\sum_t^{24h} P_{loss}^i \times t\right) \text{ in [kWh/day]} \tag{7}$$

E_c= 0.129 USD/kWh is the Cambodia electricity tariff and T= 365 days/year.

2.6. Three-phase unbalanced load flow

As it is used both during operations and in the planning and design stages, 3-phase load flow is an important tool for analyzing power systems. Several numerical methods have been presented in the literature on 3-phase networks such as the Newton–Raphson (NR) [29], backward/forward sweep [30], method based on graph [31], and the triangular-based load flow [32]. To resolve the problem of load flow in unbalanced 3-phase systems in this paper, we have chosen to use the backward/forward sweep method, in which the system operates radially with the unbalanced system.

3. A CASE STUDY AND LOAD CURVE

The rural area located in Srey Santhor District and Khsach Kandal District in Kampong Cham and Kandal Provinces, respectively, in Cambodia has been selected. All MV/LV transformers as legend in red points (left) and blue triangles (right) are energized by a 115/22-kV transformer in the HV/MV substation. A daily load profile with the 1h-interval is based on [27]. Figures 2 and 3 show the locations of the test system for the medium voltage distribution system and show the daily load profile in Cambodia. The more details of the case study are listed in Tables 1 to 3.

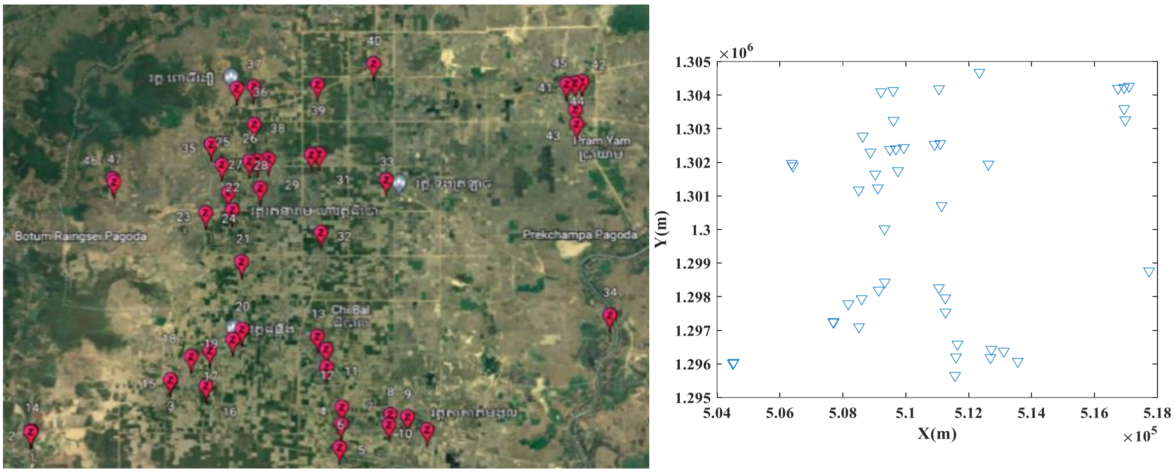


Figure 2. Real 47 test system in Cambodia

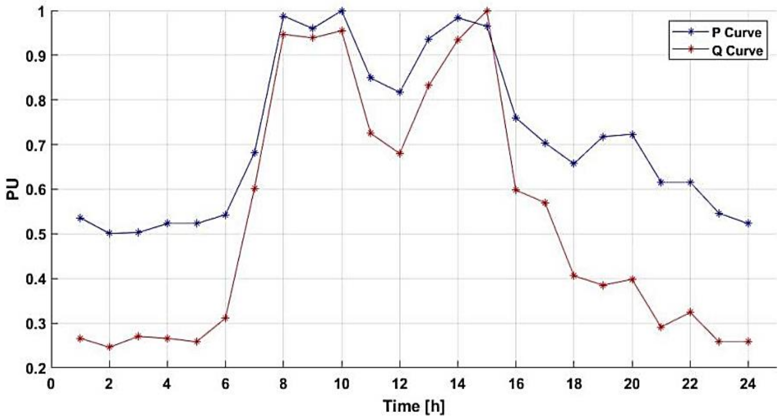


Figure 3. Daily load profile in Cambodia

Table 1. Impedance matrix for the 47-real test system's conductor types

Configuration	Impedance matrix (Ω/km)		
	$0.7140 + j0.78482$	$0.0493 + j0.43047$	$0.0493 + j0.39625$
1	$0.0493 + j0.43047$	$1.0065 + j0.79627$	$0.0493 + j0.43047$
	$0.0493 + j0.39625$	$0.0493 + j0.43047$	$0.7140 + j0.78482$
	$1.0065 + j0.79627$	$0.0493 + j0.39625$	0
2	$0.0493 + j0.39625$	$1.0065 + j0.79627$	0
	0	0	0
	0	0	0
3	0	$1.0065 + j0.79627$	$0.0493 + j0.43047$
	0	$0.0493 + j0.39625$	$1.0065 + j0.79627$
	$1.0065 + j0.79627$	0	$0.0493 + j0.39265$
4	0	0	0
	$0.0493 + j0.39265$	0	$0.7140 + j0.78482$
	$1.0065 + j0.79627$	$0.0493 + j0.39625$	$0.0493 + j0.39625$
5	$0.0493 + j0.39625$	$1.0065 + j0.79627$	$0.0493 + j0.43047$
	$0.0493 + j0.39625$	$0.0493 + j0.43047$	$1.0065 + j0.79627$

Table 2. Lengths from node A to node B

Node A	Node B	Length(m)	Node A	Node B	Length(m)	Node A	Node B	Length(m)
1	2	4	16	17	846.46	31	32	1845.338
2	3	3587.6544	17	18	454.33	31	33	1714.5873
3	4	3995.3519	17	19	606.48	33	34	6272.7653
4	5	292.824	19	20	1440.1966	25	35	582.3
5	6	554.4217	20	21	1234.2446	35	36	1440.42
5	7	1101.6419	21	22	611.6854	36	37	391.35
7	8	245.76	22	23	420.6471	37	38	890.92
8	9	476.87	22	24	671.7579	37	39	1461.4893
7	10	887.9928	24	25	819.0961	39	40	1376.181
4	11	936.8674	25	26	644.07	40	41	5416.8205
11	12	441.13	26	27	189.73	41	42	195.9292
12	13	381.5883	27	28	189.73	41	43	638.6056
2	14	35	27	29	252.317	43	44	399.2239
14	15	3587.6544	29	30	981.8605	42	45	159.9802
15	16	819.8836	30	31	183.3054	25	46	2519.87
						46	47	94.07

Table 3. Load specification of the case study

Node	Coordinate		Pa (kW)	Qa (kVAr)	Pb (kW)	Qb (kVAr)	Pc (kW)	Qc (kVAr)
	X(m)	Y(m)						
1	504502	1296018	0	0	0	0	0	0
2	504506	1296019	0	0	0	0	0	0
3	507703.6911	1296019	30	14.53	30	14.53	30	14.53
4	511643.4963	1296585.5216	15	7.264	15	7.264	15	7.264
5	511596.7531	1296206.704	7.264	10.897	7.264	10.897	7.264	10.897
6	511565	1295654	16.875	8.172	16.875	8.172	0	0
7	512692.8026	1296186.9585	22.5	10.897	22.5	10.897	0	0
8	512718.68	1296431.22	0	0	0	0	0	0
9	513115.22	1296377.31	22.5	10.897	22.5	10.897	0	0
10	513560.3277	1296074.2658	22.5	10.897	22.5	10.897	0	0
11	511264	1297540	16.875	8.172	16.875	8.172	0	0
12	511255.85	1297963.24	13.5	6.538	13.5	6.538	0	0
13	511053.4785	1298264.8887	11.25	5.448	11.25	5.448	0	0
14	504525	1296045	15	7.264	15	7.264	15	7.264
15	507694	1297259	0	0	0	0	0	0
16	508511.6317	1297101.3205	0	0	0	0	0	0
17	508597.21	1297939	0	0	0	0	0	0
18	508172.76	1297789.19	0	0	22.5	10.897	22.5	10.897
19	509139.1479	1298192.7653	30	14.529	30	14.529	30	14.529
20	509332.9995	1298432.9231	0	0	11.25	5.448	11.25	5.448
21	509323.8518	1300021.0359	0	0	13.5	6.538	13.5	6.538
22	509110.4225	1301235.9093	0	0	0	0	0	0
23	508503.0899	1301173.0998	0	0	11.25	5.448	11.25	5.448
24	509026.808	1301647.5205	0	0	22.5	10.897	22.5	10.897
25	508873.7632	1302301.4587	30	14.529	30	14.529	30	14.529
26	509496.03	1302380.76	15	7.264	15	7.264	15	7.264
27	509686.2	1302398.263	0	0	0	0	0	0
28	509750.9587	1301747.9602	11.25	5.448	0	0	11.25	5.448
29	509935.7929	1302435.1279	15.75	7.628	0	0	15.75	7.628
30	510913.1037	1302533.9759	22.5	10.897	0	0	22.5	10.897
31	511095	1302533.9759	0	0	0	0	0	0
32	511136.0012	1300710.8555	13.5	6.538	0	0	13.5	6.538
33	512625.946	1301943.8332	13.5	6.538	0	0	13.5	6.538
34	517734.3079	1298766.1026	11.25	5.448	0	0	11.25	5.448
35	508626.57	1302777.36	0	0	13.5	6.538	13.5	6.538
36	509212.8975	1304095.5982	15	7.264	15	7.264	15	7.264
37	509597.12	1304132.78	0	0	0	0	0	0
38	509609.96	1303246.6	0	0	6.75	3.269	6.75	3.269
39	511054.621	1304185.8588	15	7.264	15	7.264	15	7.264
40	512339.5003	1304677.3854	22.5	10.897	0	0	22.5	10.897
41	516745.8185	1304200.054	22.5	10.897	0	0	22.5	10.897
42	516939.882	1304226.9989	22.5	10.897	0	0	22.5	10.897
43	516939.882	1303594.1104	16.875	8.172	0	0	16.875	8.172
44	516978.4514	1303260.1617	16.875	8.172	0	0	16.875	8.172
45	517095.7484	1304263.0282	16.875	8.172	0	0	16.875	8.172
46	506375.06	1301965.08	0	0	0	0	0	0
47	506409.29	1301892.65	120	58.11	120	58.11	120	58.11

4. SIMULATION RESULTS AND DISCUSSION

All simulation results in this section, are generated by using MATLAB software, Dell Latitude 3540 on a personal computer with i5-4200U, 8-GB RAM, 1.6 GHz, and 64-bit Windows 10 Pro. Two results of applied algorithms, including the genetic algorithm and the shortest path in the real 47-bus system, are given in this section sequentially. The findings of the original system were provided in section 4.1, while the results of the shortest path algorithm were presented in section 4.2. After that, we divided the findings of the phase balance into two sections: case study-01 is in section 4.3 and case study-02 is in section 4.4. Lastly, sections 4.5 to 4.7 present comparative results on power loss, energy loss, and economic evaluation.

4.1. Simulation results of the original system

This test system is the MV grid of distributor license that has a total length of about 52.758 km and it consists of two types: i) three-phase main line using a cable size of 50 mm^2 is 27.758 km and ii) three-phase lines using a cable size of 50 mm^2 is 25 km. With the system data requirement in Tables 1 to 3, respectively, then we get results from computing load flow analysis such that the total power loss is 37.65 kW and the maximum voltage drop is 4.22 %. Additionally, we have one more table presenting some main parameters as we can see in Table 4.

Table 4. Several indications of the original system

S.L.	Items	Phase-A	Phase-B	Phase-C
1	Load (kVA)	702.27	415.92	811.88
2	Current flow at the slack bus (A)	65.36	43.34	48.57
3	Unbalanced load (%)		34.83	
4	Unbalanced current at the slack bus (%)		24.57	
5	Maximum voltage unbalance (%)		1.321	
6	Maximum voltage drop (%)		4.22	
7	Total load (kVA)		1914.591	
8	Total Power Loss(kW)		37.65	
9	Total Length (km)		52.758	

Moreover, Figure 4 shows a drawing or painting of the architecture of the original network. A purple square represents the HV/MV substation, and triangles are represented as loads which are labeled with the different colors as in the legend. Also, the blue and red colors represent the 3-phase line with a cable size of 50 mm^2 and a cable size of 35 mm^2, respectively.

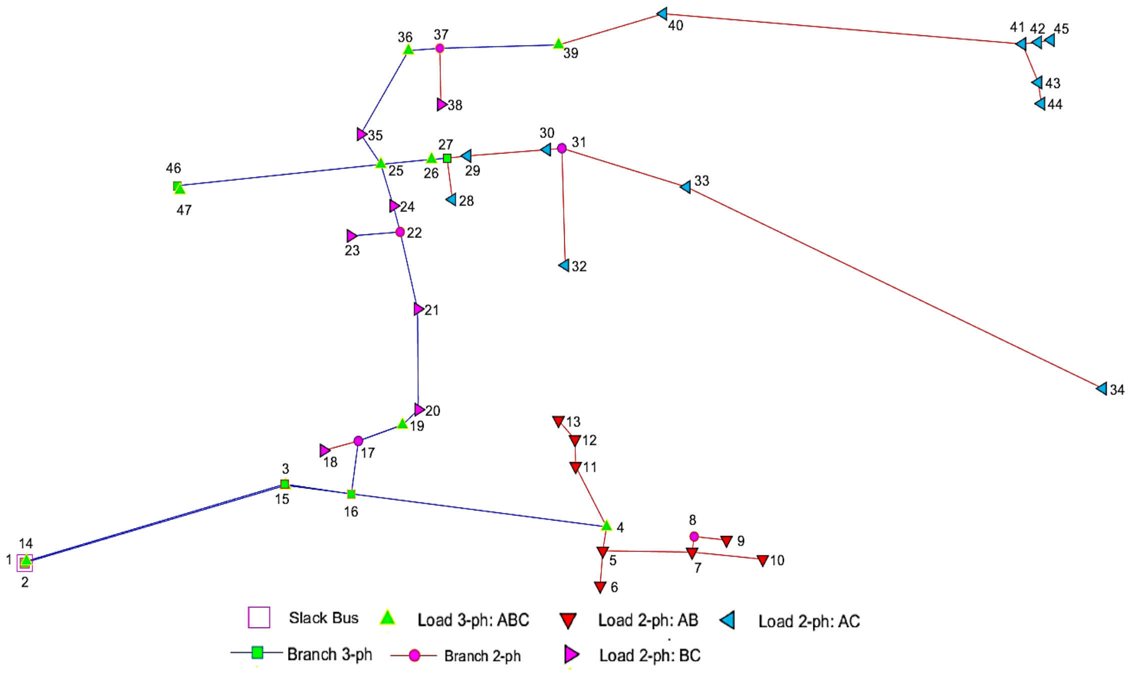
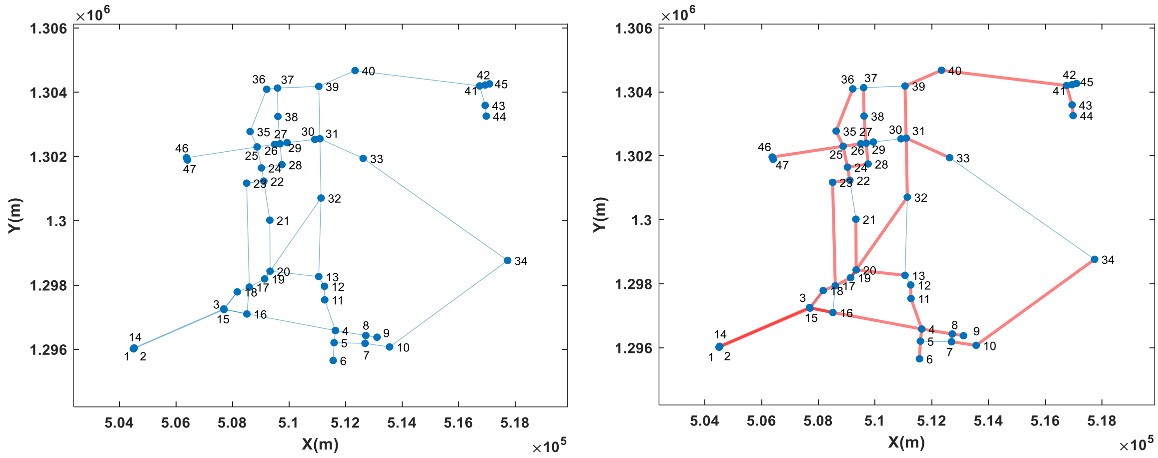


Figure 4. Original real 47 buses test system

4.2. Simulation results of the feeder routing

The distribution feeder planning problem is discussed in this part with the same system from [33]. Also, the available routes of 57 with 47 buses which will be supplied from the 115-kV/22-kV substation at bus 1 are provided in Table 2 and Figure 5(a). The optimal graph topologies were found using the shortest path algorithm shown in Figure 5(b). Moreover, a supplementary configuration of the 47-bus real test network in which the minimum distance of the system is 63.31573 km by using the SP. According to the optimal radial topology shown in Figure 5(b), The 11 lines have been not connected from substations such as the line from bus 5-7, 12-13, 13-32, 15-18, 16-17, 21-22, 26-27, 29-30, 33-34, 36-37, and 37-39 were removed.



(a) (b)

Figure 5. 47-bus real test system for (a) available routes and (b) selection of optimal routes

4.3. Simulation results of the phase balancing (case study-01)

The improved actual distribution network of 47-bus in Cambodia has been chosen to evaluate the proposed methods to reduce power losses in the distribution network. A configuration and topology of the improved actual distribution network are shown in Figure 6.

The slack bus is represented by a double purple square, and all triangles are loads which are given with different color labels. Additionally, the blue hues are a 3-phase main line with a cable size of 50 mm^2 and a 3-phase line of 35 mm^2. In addition, Table 5 provides the key performance of the original actual distribution network. It illustrates that the highest voltage drop is 3.594% and the overall power loss is 35.704 kW.

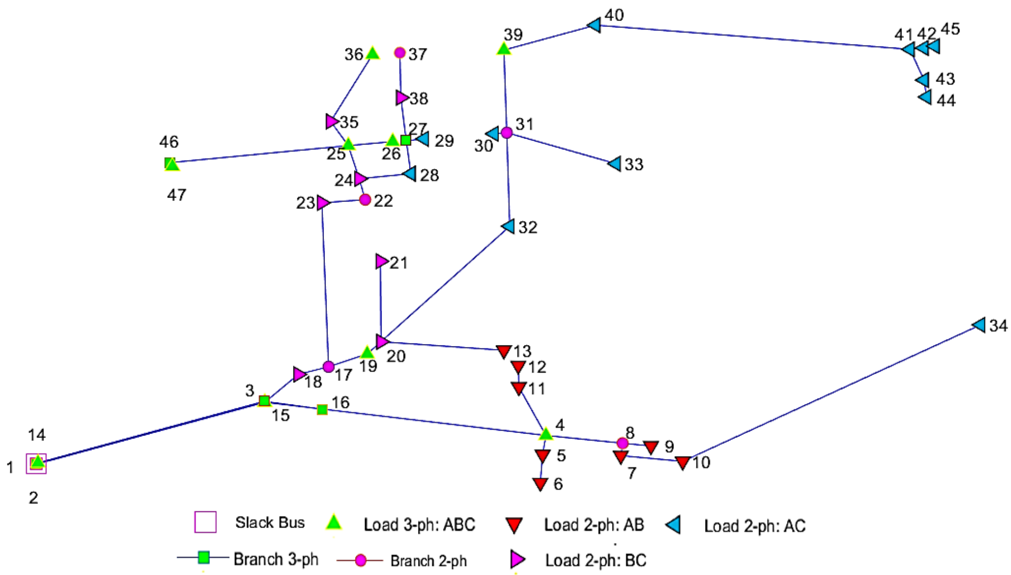


Figure 6. Improved actual 47 buses test system

Table 5. Several indications of the case study 01

S.L.	Items	Phase-A	Phase-B	Phase-C
1	Load (kVA)	702.27	415.92	811.88
2	Current flow at the slack bus (A)	65.25	43.36	48.57
3	Unbalanced load (%)		34.83	
4	Unbalanced current at the slack bus (%)		24.54	
5	Maximum voltage unbalance (%)		1.13	
6	Maximum voltage drop (%)		3.594	
7	Total load (kVA)		1914.591	
8	Total power losses (kW)		35.704	
9	Total length (km)		63.315	

4.4. Simulation results of the phase balancing (case study-02)

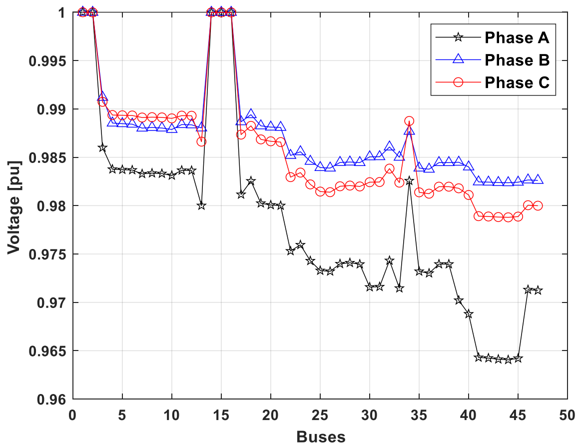
We obtained a new configuration with mixed 3-ph and 2-ph line systems after utilizing GA to compute the process of phase swapping. The results of GA's modified original network are shown in Table 6. Maximum voltage drop is reduced by 1.0243%, and the overall power loss is 31.840 kW.

Table 6. Several indications of case study-02

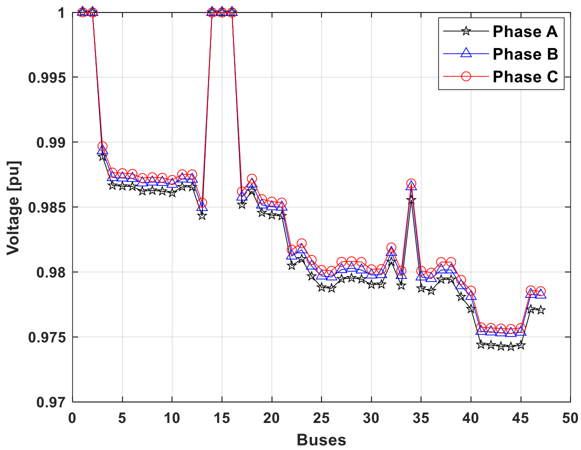
S.L.	Items	Phase-A	Phase-B	Phase-C
1	Load (kVA)	612.67	644.68	658.01
2	Current flow at the slack bus (A)	51.17	51.15	51.23
3	Unbalanced load (%)		4.000	
4	Unbalanced current at the slack bus (%)		0.091	
5	Maximum voltage unbalance (%)		0.101	
6	Maximum voltage drop (%)		2.570	
7	Total load (kVA)		1914.591	
8	Total power losses (kW)		31.840	
9	Total length (km)		63.315	

4.5. Comparative results with case studies 01 and 02

The simulation results for the two approaches have been compared in this section. Tables 2 and 3 list a number of indicators. Additionally, Figures 7(a) and 7(b) show the voltage profile before as well as after GA, respectively. As in the figures, the voltage value of each phase in the original system was remarkable. Between phase-A and phase-C, given that buses 41 to 45 commonly exceed the minimum voltage of 0.964pu, this is very possible to implement. When some loads are moved from phase-A to phase-B, as shown in Figure 7(b), the voltage profile on phase-A is raised while remaining within the acceptable range (0.95pu≤V_{phase}≤1.05pu) with GA.



(a)



(b)

Figure 7. Voltage profile of (a) a case study-01 and (b) a case study-02

4.6. Comparative results of energy loss evaluation

Table 7 provides the result with different case studies focused on energy loss, energy losses cost, and profit, based on the result in Table 6 and the electricity cost of 0.129 USD/kWh. The energy loss and the expense of the energy losses for case study 1 for the real 47 buses are 156.106 MWh per year and 20.137 kUSD per year, respectively.

Table 7. Several indications with different case studies

S.L.	Parameters	Base case	Case 01	Case 02
1	Energy losses (MWh/year)	164.647	156.106	140.282
2	Energy losses cost (USD/year)	21.237	20.13	18.096
3	Profit from loss reduction (USD/year)	-	1.1	2.041
4	Total profit (USD/year)		3.141	

Figures 8(a)-8(c) provides the curve of daily loss for the original system, case 1 by SP's algorithm and case 2 by GA's algorithm respectively. The power loss on the original system has the highest value at 10 am with 36.9773 kW and case 1 has a high-power loss at 10 am with 35.0497 kW but it is lower than that of the original system. However, it can be seen that case 2 simultaneously improves power loss by 31.2948 kW at 10 am as shown in Figure 8(c).

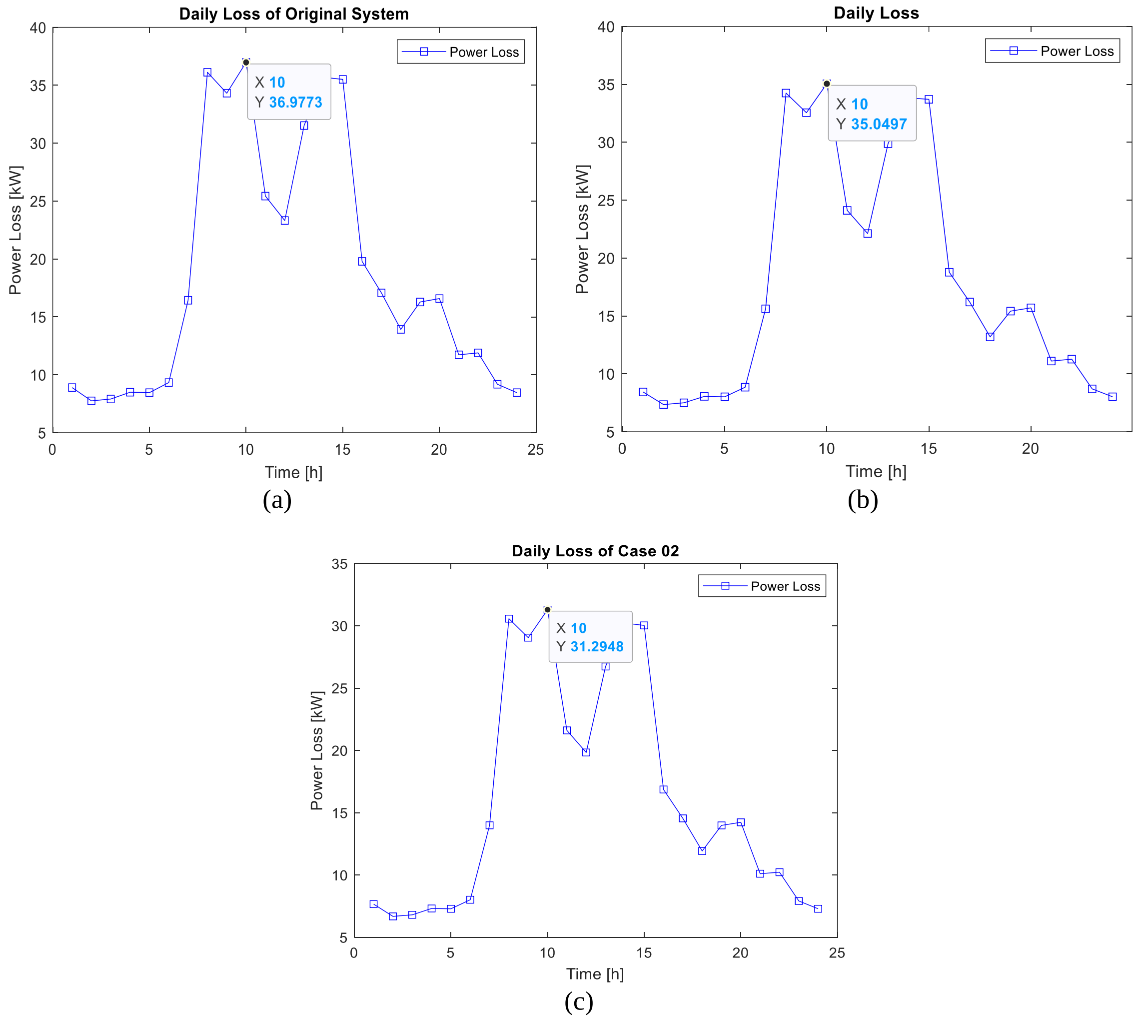


Figure 8. Results of the power loss curve in (a) base case, (b) a case study-01, and (c) a case study-02

4.7. Comparative results for economic evaluation

In this section, we study how much we can save after improving the existing system through objective I and objective II. The energy reduction will be assumed to be estimated by MATLAB programming. To calculate the annual saving of the system, we have to know the price of energy which we draw from the national utility. The price of electricity in Cambodia is 0.129 USD/kWh. Table 8 summarizes the profit; we see that in a year savings from the original system is 1100$/year for objective I and 2041 $/year for objective II.

Table 8. Several indications of economic with different case studies

S.L.	Parameters	Base case	Case 01	Case 02
1	Total load (kVA)	1914.591	1914.591	1914.591
2	Total power loss (kW)	37.65	35.704	31.84
3	Total energy loss (MWh/year)	-	156.106	140.232
4	Energy loss reduction (MWh/year)	-	6.4829	15.824
5	Profit from loss reduction (USD/year)	-	1100	2041

However, to make an easy understanding column chart is made. In the column chart below is the cash flow of the payback period of the system. The column chart in Figure 9 shows the cash flow of the payback period which is limited to 30 years. The blue column is the net income that gets from annual savings with pay for capital cost and the orange column is the cumulated cash which is the amount of money that we invested in the improved system. The payoff starts when the cumulated cash flow becomes positive as shown in Figure 9 and the point indicates also the payback period of the project is 10 years. Thus, our study will pay back within 10 years.

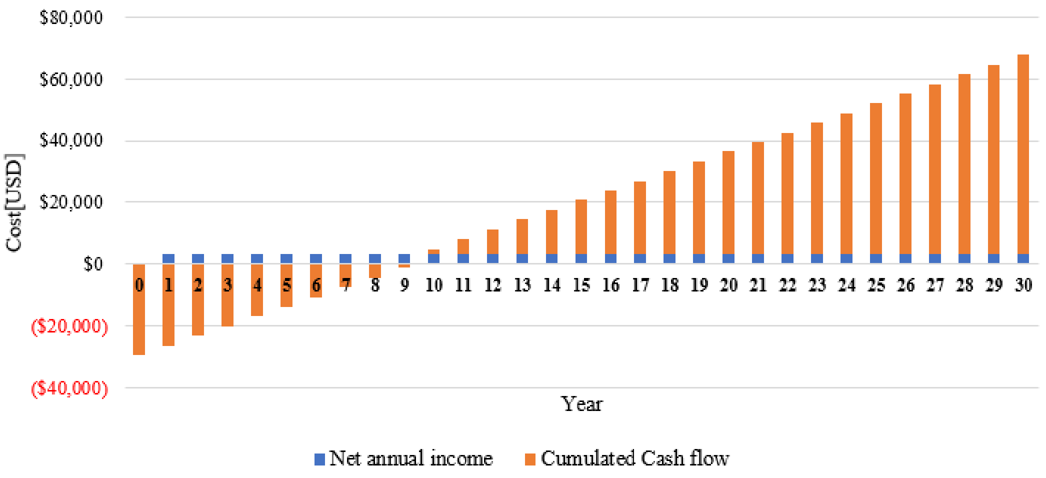


Figure 9. Cash flow of the payback period

5. CONCLUSION

This work used a genetic algorithm and the shortest path to solve an optimal architecture design problem for the 47-bus of distribution system, in a rural area, in Cambodia. The shortest path used to search for the shortest length from the substation to all transformers, the total distance was 63.3157 km. A genetic algorithm was used to identify the load connections throughout the distribution network stages, and the voltage profiles were improved despite complying with the limitations of voltage regulation. This resulted in a reduction of the total power losses of 3.864 kW in comparison to the existing 47-bus systems. Moreover, the shortest path feeder routing (SPA) and GA load balancing (GALB) of the proposed method to add the line on the existing system get greater benefit from power loss reduction significantly and the payback period is 10 years which is a good period one in the improved the existing system.

Finally, the result has come successfully both of shortest path and genetic algorithm is the best planning tool for optimum configuration in Cambodia to improve the existing system and for the next planning. In future work, we will combine the algorithm to search the minimum length and power loss and testing with non-existing system planning including algorithm development to find out the lowest energy losses including the investment cost. Combining an algorithm to search for minimum length and power loss and test with non-existing system planning will be addressed in future work.

ACKNOWLEDGEMENTS

This work was funded by Cambodia Higher Education Improvement Project (Credit No. 6221-KH) at the Institute of Technology of Cambodia. The authors would like to acknowledge the National University of Battambang (NUBB) for supporting Mr. Sopheak Kay's tuition fee and monthly allowance.

REFERENCES

[1] EAC, "Report on power sector of the Kingdom of Cambodia-English-2020," Cambodia, 2021.

[2] EAC, "Electric Power Technical Standards of the Kingdom of Cambodia," Cambodia, 2004.

[3] N. G. Boulaxis and M. P. Papadopoulos, "Optimal Feeder Routing in Distribution System Planning Using Dynamic Programming Technique and GIS Facilities," *IEEE Power Engineering Review*, vol. 21, no. 11, pp. 63–63, Jul. 2008, doi: 10.1109/mper.2001.4311190.

[4] A. Samui, S. Singh, T. Ghose, and S. R. Samantaray, "A direct approach to optimal feeder routing for radial distribution system," *IEEE Transactions on Power Delivery*, vol. 27, no. 1, pp. 253–260, 2012, doi: 10.1109/TPWRD.2011.2167522.

[5] D. Kumar, S. R. Samantaray, and I. Kamwa, "A radial path building algorithm for optimal feeder planning of primary distribution networks considering reliability assessment," *Electric Power Components and Systems*, vol. 42, no. 8, pp. 861–877, 2014, doi: 10.1080/15325008.2014.896434.

[6] A. Bosisio, A. Berizzi, E. Amaldi, C. Bovo, and X. A. Sun, "Optimal feeder routing in urban distribution networks planning with layout constraints and losses," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 5, pp. 1005–1014, 2020, doi: 10.35833/MPCE.2019.000601.

[7] S. Ayazi and A. Askarzadeh, "Finding optimal path of feeder routing problem in power distribution network by an efficient and new methodology," *International Transactions on Electrical Energy Systems*, vol. 31, no. 12, Dec. 2021, doi: 10.1002/2050-7038.13196.

[8] M. Trageser *et al.*, "Automated routing of feeders in electrical distribution grids," *Electric Power Systems Research*, vol. 211, pp. 108–217, Oct. 2022, doi: 10.1016/J.EPSR.2022.108217.

[9] D. Kumar and S. R. Samantaray, "Feeder routing in DG interfaced power distribution networks using MSTB-GT approach," in *2012 Annual IEEE India Conference, INDICON 2012*, 2012, pp. 659–664. doi: 10.1109/INDCON.2012.6420700.

[10] O. D. Montoya, F. M. Serra, C. H. De Angelo, H. R. Chamorro, and L. Alvarado-Barrios, "Heuristic methodology for planning ac rural medium-voltage distribution grids," *Energies*, vol. 14, no. 16, 2021, doi: 10.3390/en14165141.

[11] I. J. Hasan, M. R. Ab Ghani, and C. K. Gan, "Optimum Substation Placement and Feeder Routing Using GA-MST," *Applied Mechanics and Materials*, vol. 785, pp. 9–13, 2015, doi: 10.4028/www.scientific.net/amm.785.9.

[12] S. E. Vai, Vannak, "Study of Grid-Connected PV System for a Low Voltage," *Energies*, vol. 15, no. 5003, pp. 1–12, 2022, doi: 10.3390/ en15145003.

[13] M. A. Rios, J. C. Castano, A. Garces, and A. Molina-Cabrera, "Phase balancing in power distribution systems: A heuristic approach based on group-theory," *2019 IEEE Milan PowerTech, PowerTech 2019*, 2019, doi: 10.1109/PTC.2019.8810723.

[14] B. Cortés-Caicedo, L. S. Avellaneda-Gómez, O. D. Montoya, L. Alvarado-Barrios, and H. R. Chamorro, "Application of the vortex search algorithm to the phase-balancing problem in distribution systems," *Energies*, vol. 14, no. 5, pp. 1–35, 2021, doi: 10.3390/en14051282.

[15] O. Pereira, J. Quiros-Tortos, and G. Valverde, "Phase Rebalancing of Distribution Circuits Dominated by Single-Phase Loads," *IEEE Transactions on Power Systems*, vol. 36, no. 6, pp. 5333–5344, 2021, doi: 10.1109/TPWRS.2021.3076629.

[16] O. D. Montoya, A. Molina-Cabrera, L. F. Grisales-Noreña, R. A. Hincapié, and A. Granada, "Improved genetic algorithm for phase-balancing in three-phase distribution networks: A master-slave optimization approach," *Computation*, vol. 9, no. 6, 2021, doi: 10.3390/computation9060067.

[17] J. L. Cruz-Reyes, S. S. Salcedo-Marcelo, and O. D. Montoya, "Application of the Hurricane-Based Optimization Algorithm to the Phase-Balancing Problem in Three-Phase Asymmetric Networks," *Computers*, vol. 11, no. 3, pp. 1–25, 2022, doi: 10.3390/computers11030043.

[18] B. Cortés-Caicedo, L. F. Grisales-Noreña, and O. D. Montoya, "Optimal Selection of Conductor Sizes in Three-Phase Asymmetric Distribution Networks Considering Optimal Phase-Balancing: An Application of the Salp Swarm Algorithm," *Mathematics*, vol. 10, no. 18, pp. 1–34, 2022, doi: 10.3390/math10183327.

[19] J. A. Mora-Burbano, C. D. Fonseca-Díaz, and O. D. Montoya, "Application of the SSA for Optimal Reactive Power Compensation in Radial and Meshed Distribution Using D-STATCOMs," *Algorithms*, vol. 15, no. 10, pp. 1–16, 2022, doi: 10.3390/a15100345.

[20] O. D. Montoya, L. F. Grisales-Noreña, and E. Rivas-Trujillo, "Approximated Mixed-Integer Convex Model for Phase Balancing in Three-Phase Electric Networks," *Computers*, vol. 10, no. 9, pp. 1–12, Aug. 2021, doi: 10.3390/computers10090109.

[21] D. P. Bohórquez-Álvarez, K. D. Niño-Perdomo, and O. D. Montoya, "Optimal Load Redistribution in Distribution Systems Using a Mixed-Integer Convex Model Based on Electrical Momentum," *Information*, vol. 14, no. 4, pp. 1–22, 2023, doi: 10.3390/info14040229.

[22] V. M. Garrido, O. D. Montoya, Á. Medina-Quesada, and J. C. Hernández, "Optimal Reactive Power Compensation in Distribution Networks with Radial and Meshed Structures Using D-STATCOMs: A Mixed-Integer Convex Approach," *Sensors*, vol. 22, no. 22, pp. 1–15, 2022, doi: 10.3390/s22228676.

[23] M. Granada Echeverri, R. A. Gallego Rendón, and J. M. López Lezama, "Optimal Phase Balancing Planning for Loss Reduction in Distribution Systems using a Specialized Genetic Algorithm," *Ingeniería y Ciencia*, vol. 8, no. 15, pp. 121–140, 2012, doi: 10.17230/ingciencia.8.15.6.

[24] O. Ivanov, B.-C. Neagu, A.-I. Nitu, and M. Gavrilas, "An Improved Metaheuristic Algorithm for Load Balancing in LV Distribution Networks," in *2021 9th International Conference on Modern Power Systems (MPS)*, Jun. 2021, pp. 1–5. doi: 10.1109/MPS52805.2021.9492680.

[25] D. Eam, V. Vai, L. You, P. Hem, S. Heang, and S. Eng, "Phase Balancing Improvement in Unbalanced MV Distribution Systems," *19th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, 2022, doi: 10.1109/ECTI-CON54298.2022.9795560.

[26] S. Kay, V. Vai, S. Eng, and T. Him, "Planning of Optimal Phase Balancing for an Unbalanced Distribution System: A Case Study of Cambodia," in *2022 11th International Conference on Power Science and Engineering, ICPSE 2022*, 2022, pp. 108–111. doi: 10.1109/ICPSE56329.2022.9935454.

[27] V. Vai, S. Suk, R. Lorm, C. Chhlonh, S. Eng, and L. Bun, "Optimal reconfiguration in distribution systems with distributed generations based on modified sequential switch opening and exchange," *Applied Sciences*, vol. 11, no. 5, pp. 1–14, 2021, doi: 10.3390/app11052146.

[28] H. Arghavani and M. Peyravi, "Unbalanced current-based tariff," *CIRED - Open Access Proceedings Journal*, vol. 2017, no. 1, pp. 883–887, 2017, doi: 10.1049/oap-cired.2017.0129.

[29] K. Khon, C. Chhlonh, V. Vai, M. C. Alvarez-Herault, B. Raison, and L. Bun, "Comprehensive Low Voltage Microgrid Planning Methodology for Rural Electrification," *Sustainability*, vol. 15, no. 3, pp. 1–23, 2023, doi: 10.3390/su15032841.

[30] B. Sereeter, K. Vuik, and C. Witteveen, "Newton power flow methods for unbalanced three-phase distribution networks," *Energies*, vol. 10, no. 10, 2017, doi: 10.3390/en10101658.
[31] T. Shen, Y. Li, and J. Xiang, "A graph-based power flow method for balanced distribution systems," *Energies*, vol. 11, no. 3, 2018, doi: 10.3390/en11030511.
[32] A. Marini, S. S. Mortazavi, L. Piegari, and M. S. Ghazizadeh, "An efficient graph-based power flow algorithm for electrical distribution systems with a comprehensive modeling of distributed generations," *Electric Power Systems Research*, vol. 170, 2019, doi: 10.1016/j.epsr.2018.12.026.
[33] O. D. Montoya, J. S. Giraldo, L. F. Grisales-Noreña, H. R. Chamorro, and L. Alvarado-Barrios, "Accurate and efficient derivative-free three-phase power flow method for unbalanced distribution networks," *Computation*, vol. 9, no. 6, p. 61, 2021, doi: 10.3390/computation9060061.

BIOGRAPHIES OF AUTHORS

Sopheak Kay was born in 1997 in Pursat, Cambodia. He graduated with an engineer's degree in electrical and energy engineering from the Institute of Technology of Cambodia (ITC), Cambodia, in 2021. Currently, he is a master student at the Energy Technology and Management Unit, Research and Innovation Center, Institute of Technology of Cambodia (ITC). His research interests focus on distribution system planning and optimization. He can be contacted at email: sopheak_kay@gsc.itc.edu.kh.

Vannak Vai received his Engineer's degree in Electrical and Electronic Engineering from the Institut de Technologie du Cambodge (ITC), Phnom Penh, Cambodia, in 2012, his M.Res. degree in Electrical Energy from the Institut Polytechnique de Grenoble (Grenoble INP-Ense3), Grenoble, France, in 2013, and his Ph.D. degree in Electrical Engineering from the Université Grenoble Alpes (UGA), Grenoble, France, in 2017. He was a visiting researcher with the Grenoble INP/UGA-G2Elab for one year in 2023. He has been a lecturer-researcher in the Department of Electrical and Energy Engineering at ITC since 2013. His research interests include power system planning and operation, microgrid and hybrid energy systems, and applied optimization. He can be contacted at email: vannak.vai@itc.edu.kh.

Samphors Eng was born in Kompong Cham, Cambodia, in 1992. Samphors is a graduate of the Institute of Technology of Cambodia (ITC), where she received an engineering diploma in electrical and energy engineering in 2017. She received her M.Eng. degree in electrical engineering from Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia, in 2019. After graduation, she is working as a lecturer in the department of electrical and energy engineering at ITC. Her research interests concern smart power systems, distribution automation, and distribution system reliability. She can be contacted at email: samphors@itc.edu.kh.