



# Article Study of Grid-Connected PV System for a Low Voltage Distribution System: A Case Study of Cambodia

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Abstract: The low voltage (LV) distribution systems are extended year by year due to the increase in energy demand. To overcome this issue, distribution system utilities have been focusing on designing and operating an appropriate distribution system with minimum capital and operational expenditure for supplying electricity to users. This article compares different algorithms to design an LVAC distribution system in a rural area, which focuses on minimizing the total length of lines and the power losses and balancing the loads among the three phases including the economic evaluation of the grid-connected PV system. Firstly, the shortest path (SP) algorithm is established to search for the minimization of the conductor used. Secondly, three different algorithms which are repeated phase sequence (RPABC), first fit bin packing (FFBP), and mixed-integer quadratic programming (MIQP) algorithms are developed to balance the load and minimize power losses. Next, a comparative result of three different algorithms is provided. Finally, the techno-economic analysis of the grid-connected PV system with different electricity tariffs with hybrid optimization of multiple energy resources (HOMER) software is studied in the planning period. To validate a proposed method, the 129-buses low voltage distribution in a rural village, in Cambodia, is tested. The simulation result confirms the optimal solution of the MIQP algorithm and PV system integration in designing a distribution system in a particular case study.

**Keywords:** grid-connected PV; cost of energy; net present cost; economic analysis; distribution system planning; load balancing; first fit bin packing; MIQP; shortest path; optimization

#### 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, 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] in networks. Various authors have studied the planning of LV distribution systems for electrification. The optimal algorithms for radial topologies by considering the load demand uncertainties (i.e., growth rate and new connected load) in an urban village have been developed in [4,5]. The optimal radial topologies for an urban area have been studied in [6,7]; the authors have proposed mixed-integer quadratic programming to search for the topology with the shortest length and load balancing improvement. In rural areas, the authors [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 without minimum power loss as the operation investment for both urban and rural villages with a single-phase distribution network. Therefore, the planning method for the radial topology of a low voltage distribution network with the lowest power loss is considered.



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**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Moreover, radial distribution network optimizations have been developed to search for optimal network topologies by implementing simulated annealing [10] and a path search algorithm [11]. Additionally, distribution network planning methods [12–17] have been addressed with a reliable solution for an optimal radial feeder. To minimize the unbalance factor of current in resulting load balancing improvement, the particle swarm optimization, and genetic algorithm were implemented in [18,19]. However, these authors have focused on medium voltage distribution networks and existing radial low voltage distribution networks. Thus, the method for greenfield planning and low voltage distribution network is attractive for development.

Furthermore, renewable energy sources give an effective way relevant to fuel depletion and the environment. A solar PV source particularly is attractive for electricity utilities as an alternative and potential resource. The analysis and optimization of islanded and grid-connected solar PV systems with the tariff of utility are provided in [20]. The technoeconomic analysis of hybrid PV, diesel, and the battery is studied in [21]; the lowest cost of energy (COE) and net present cost (NPC) are shown using HOMER. The optimal placement and sensitivity analysis of hybrid microgrid [22] is also studied with HOMER; the microgrid consists of the highest resources of solar and wind for off-grid and on-grid systems. The authors [23] have implemented HOMER to study the AC/DC microgrid for an islanded village. The optimal design and sizing of a hybrid microgrid system for the industrial sector are studied in [24]; the authors have considered several indicators including NPC, COE, and environmental emissions using HOMER. The authors in [25] have focused on the optimal design of the hybrid PV/battery/diesel with dispatch strategy for rural electrification using HOMER and the developed algorithm with MATLAB considering techno-economic and environmental performances. It is notable that the integration of PV systems as a green energy source in the grid is more interested in investigating by distribution network designers and operators.

For the above reasons, a novel algorithm for optimal radial topologies with the PV system as a grid-connected PV system is considered in this study. The main purpose of this article is to study a comparison of three different algorithms for optimal radial topology and techno-economic analysis of the grid-connected PV system in the LVAC distribution system considering the balanced load, minimum power loss, and lowest capital and operational expenditure for a rural village in Cambodia. The rest of the article is structured as follows. The proposed methodology, algorithm development, and a case study are described in Section 2. Section 3 gives simulation results and discussion. The conclusion and future perspective are provided in Section 4.

## 2. Materials and Methods

In this article, 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 four following objectives are considered in this article: (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 ABC (RPABC), first-fit bin-packing (FFBP), and mixed-integer quadratic programming (MIQP), (3) to compare the three proposed algorithms in terms of power losses and operational expenditure, and (4) to analyze the economics of the grid-connected PV system into the optimal distribution system.

A flowchart presenting the numerous steps of the proposed algorithm is provided in Figure 1. The load data (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 RPABC, FFBP, and MIQP are applied to achieve load balancing and power loss minimization. Then, the economic analysis with system designs is illustrated.



Figure 1. Flowchart of the proposed method.

# 2.1. Developed Algorithms

2.1.1. Shortest Path

In Cambodia, the LVAC systems comprise a single-phase or three-phase main feeder supplying from a three-phase MV/LV distribution transformer to several single-phase electrical poles to which all households are 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. Figure 2 shows the shortest path pseudocode.

- 1 P: Total electrical poles
- 2-H: Total households
- 3-C: Closest households to electrical poles
- 4-D: distance between household to electrical poles
- 5-for i = 1: H6- for j = 1: P7-  $D^{i} = D_{i}^{j}$ 8-  $d = \min(D^{i})$ 9-  $p = find(D^{i} = d)$ 10-  $Line_{i} = [p \ i]$ 11- end 12-end

Figure 2. Pseudocode of the shortest path algorithm.

#### 2.1.2. Repeated Phase ABC

To deal with a balanced load, the repeated phase sequence ABC (RPABC) as the 1st algorithm is implemented [26]. 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 RPABC algorithm is illustrated in Figure 3.



Figure 3. Repeated phase ABC (RPABC) algorithm.

# 2.1.3. First Fit Bin Packing

With the same problem of load balancing, the 2nd algorithm named first-fit binpacking (FFBP) is applied [27]. 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 article, 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.

## 2.1.4. Mixed-Integer Quadratic Programming

A graph theory [28] can be represented for the distribution network, which is defined as a pair of the 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 power loss minimization is formulated as a mixed-integer quadratic programming (MIQP) given by:

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

where:

$$x_{ij}, x_{ij}^A, x_{ij}^B, x_{ij}^C \in \{0, 1\}$$
: State of connection between *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

$$\sum_{\substack{(i,j)\in\delta^{in}(j)\\\delta^{in}(j): \text{ set of incomming edge for } j^{th} \text{ vertex}} x_{ij} + x_{ji} \leq 1, \forall (i,j) \in E$$

$$x_{ij}^{A} \leq x_{ji}, \forall (i,j) \in E$$

$$x_{ij}^{B} \leq x_{ji}, \forall (i,j) \in E$$

$$x_{ij}^{C} \leq x_{ji}, \forall (i,j) \in E$$

$$x_{ij}^{C} \leq x_{ji}, \forall (i,j) \in E$$
(2)

#### • Phase connection of load

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

# 2.2. Economic Analysis by HOMER Pro

In the HOMER Pro, there are several main indicators to evaluate the economic performance of the system configuration which are described as follows:

Capital recovery factor (CRF): this indicator is used to find out the annuity present value over the project period. The value of the indicator is provided as follows:

$$CRF(r,N) = \frac{r \times (1+r)^{N}}{(1+r)^{N-1}}$$
(4)

3.7

where

*N* : the project period (years)*r* : the annual real discount rate (%)

Net present cost (NPC): this indicator describes the installation and operating cost of the system. It comprises the cost of capital, operation, maintenance, replacement, etc. It is the core economic result in which all feasible system rankings in the optimal results are listed. The indicator value is given as follows:

$$NPC = CF_0 + \sum_{y=1}^{N} \frac{CF_y}{(1+r)^y}$$
(5)

where

N: the project period (years)  $CF_0$ : the initial capital cost (USD)  $CF_y$ : the cash flow (USD)

Levelized cost of energy (LCOE): this indicator is used for the average cost (USD/kWh) of electric energy provided by the system design. The value of indicator is calculated by the ratio of  $C_{ann,total}$  and  $E_{pri}$ . The COE and  $C_{ann,total}$  are provided by the following equations.

$$LCOE = \frac{C_{ann,total}}{E_{pri}}$$
(6)

$$C_{ann,total} = CRF(i, N) \times NPC \tag{7}$$

where

 $E_{pri}$ : the served annualized primary of load (kWh/year)  $C_{ann,total}$ : the total annualized cost (USD)

## 2.3. A Case Study

2.3.1. Studied Site and Normalized Curve

The rural village located in Sandek commune, Kampong Cham Province, in 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 h time step is taken from local measurements in a village. Figure 4 shows the geography of the test system of low voltage distribution.



Figure 4. Test of low voltage distribution system in a rural village.

Since currently there is no available information, the normalized curve is generalized to simulate a year. The detailed information of the case study is provided in [9]. The setup of load profile measurement and normalized load curve for simulation are provided in Figure 5a,b.



**Figure 5.** (a) Setup of load profile measurement for the simulation and (b) normalized daily load curve for the simulation [26].

# 2.3.2. Solar Radiation

NASA resource through HOMER Pro software [29] is used for the solar radiation data in the case study based on latitude and longitude. The average solar global horizontal irradiance (GHI) and clearness index per month are shown in Figure 6. The estimated average solar radiation per month is 4.96 kWh/m<sup>2</sup>/day.



Figure 6. Daily solar radiation and clearness index on average.

#### 2.3.3. Electricity Tariff in Cambodia

The integration of PV systems into the grid has affected the regulation of electricity utilization. The regulation for utility with only grid and grid-connected PV systems in Cambodia is listed in Table 1. It provides information relevant to electricity tariffs for different consumer types [30].

**Table 1.** Regulation for utilities and electricity tariff for consumers with meter at a low voltage of the licensee's transformer.

	Tariff Option		
Items	Option 1	Option 2	Option 3
Description	General tariff	Time of use	PV consumer
Capacity charge	-	5.80 USD/kW/Month	5.80 USD/kW/Month
Energy charge (7 a.m. to 9 p.m.)	-	0.1640 USD/kWh	-
Energy charge (9 p.m. to 7 a.m.)	-	0.13696	-
Tariff	0.17232 USD/kWh	-	0.1640 USD/kWh

# 2.4. Grid-Connected PV System

## 2.4.1. Simulation Model

The simulation model with the only grid and the grid-connected PV system at the MV/LV transformer of the low voltage distribution network including components and its specifications are built with HOMER Pro. The system design consists of the transformer loading, PV panels, converter, and grid as provided in Figure 7.



Figure 7. Schematic of the grid-connected PV system.

#### 2.4.2. System Components and Parameter

The performance of system design is evaluated within the planning period of 30 years. The cost of components, replacement, operation, and maintenance, as well as their lifetime, are listed in Table 2. The inflation rate of 3.1% [31] and a discount rate of 12% [7] are used in this article.

Table 2. Components and its specification in the case study.

_	Description		
Items	PV System	Inverter	Grid
Capacity (kW)	1	1	-
Capital cost (USD)	600	300	-
Replacement cost (USD)	600	300	-
O&M cost (USD/year)	10	10	-
Lifetime (year)	30	15	-
Degrading factor (%)	80	-	-
Efficiency (%)	-	95	-
Contract capacity (kVA)	-	-	50

# 3. Simulation Results and Discussion

3.1. Optimal Distribution System

3.1.1. Radial Distribution System Topology

In this part, the LVAC radial topologies of three different algorithms are performed by using SP-RPABC, SP-FFBP, and SP-MIQP algorithms. Furthermore, a cable size of 70 mm<sup>2</sup> is used for the mainline and 4 mm<sup>2</sup> from the main feeder to each energy meter which is currently implemented in Cambodia. Figure 8 provides the optimal radial topology which is performed with SP-MIQP.



Figure 8. Optimal radial topology by SP-MIQP algorithm.

The active power at each phase for the three different algorithms is given in Table 3. As seen in the table, the 2nd algorithm is better balanced than the 1st and 3rd algorithms, but the 3rd is the lowest power loss (see Table 4). The reason is the fact that the 1st changes the phase from the substation to the end of the pole with repeated phase ABC. The 2nd algorithm tried to balance the load using the bin packing concept from the substation. The 3rd algorithm tried to balance the load and power loss minimization at each pole from the MV/LV substation to the end of the energy meter.

**Table 3.** Active power at each phase for the low voltage distribution system.

	Total Active Power P(kW)			
Algorithms —	A-Phase	<b>B-Phase</b>	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	

Table 4. Performance indicators of different algorithms for the low voltage distribution system.

Items	Algorithms		
	1st Algorithm	2nd Algorithm	3rd Algorithm
Annual energy used (MWh)	198.57	197.02	196.94
MV/LV Required (kW)	46.60	45.92	45.89
Maximal power loss (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 (KUSD)	36.239	35.956	35.940

## 3.1.2. Voltage Profiles and MV/LV Distribution Transformer

These proposed algorithms aim to improve the balanced load and power loss while respecting the voltage and current constraints. The voltage profiles of the system for all algorithms performed by backward/forward sweep load flow [32] are shown in Figure 9. Regarding the voltage limit (i.e., 0.9 pu in Cambodia), there is no problem with the selected conductor size (i.e., 70 mm<sup>2</sup>) which is currently used in Cambodia. Moreover, the 3rd algorithm is quite good in voltage and required active power at the MV/LV distribution transformer (see Table 4) compared to others.



Figure 9. Voltage profile of the low voltage distribution system at peak load.

#### 3.1.3. Performance of Three Proposed Algorithms

To compare the three proposed algorithms, some performance indicators have been computed in Table 4. Additionally, minimal power loss and operational expenditure (OPEX) with an electricity cost of 0.1825 USD/kWh [30] are the main indicators of these algorithms. As seen in Table 4, the indicators for the 3rd algorithm (SP-MIQP) are lower than the 1st algorithm (SP-RPABC) and 2nd algorithm (SP-FFBP); this is because the 3rd algorithm minimizes power losses as well as load balancing improvement.

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 4, we can thus conclude that the 3rd algorithm is selected as the best solution for the system.

#### 3.1.4. Economic Evaluation with Different Electricity Tariffs

The simulation result for the only grid and the grid-connected PV system feasibility with several indicators are summarized in Table 5. The LCOE of option 3 (grid-connected PV system) is 0.1654 \$/kWh. The fraction of renewable energy integration contributed to the system design is 15.8%. The annual energy consumption from the LV meter of the licensee's transformer is 196.950 MWh/year which energy of 33.456 MWh/year and others from the PV system and the grid, respectively. Figure 10 illustrates the average energy production per month of the PV system and grid for the 3rd option.

T 1' (	Description		
Indicators	Option 1	Option 2	Option 3
PV (kW)	-	-	22.5
Inverter (kW)	-	-	15.8
NPC (kUSD)	360.359	353.137	345.813
LCOE (USD/kWh)	0.1723	0.1689	0.1654
Operating cost (kUSD/year)	33.938	33.258	30.850
Initial capital cost (kUSD)	-	-	18.24
Renewable energy fraction (%)	-	-	15.8
CO <sub>2</sub> Emissions (Mg/year)	124.47	124.47	104.86





Figure 10. Average energy production per month for option 3.

We also observe that the system design for the grid-connected PV system (i.e., 0.1654 \$/kWh) is cheaper than that of the only grid with different electricity tariff payments. The NPC of the grid-connected PV system and two only grids with different options is 345.813 kUSD, 360.359 kUSD (1st option), and 353.137 kUSD (2nd option), respectively. Additionally, the discount cash flow for the grid-connected PV system is given in Figure 11.



Figure 11. Discount cash flow over the planning study for option 3.

## 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-RPABC) and the first-fit bin-packing (SP-FFBP), and SP-MIQP are developed to find out the best load balancing and power losses minimization. A comparative study of these algorithms considering the yearly energy used is also conducted to make the decision

on which should be selected. Additionally, the topology of the three-phase diagram is automatically pictured with different colors for visualization. Moreover, the 3rd algorithm can be considered for the distribution system designer. The simulation result for different electricity tariff payments with and without grid-connected PV systems was also studied. The optimization software is called HOMER Pro and is used to provide the result with several indicators such as COE and NPC. The optimal system design with economic evaluation for the grid-connected PV system is more economic than that of the only grid. Additionally, the lesser capital and charge capacity cost is, the more economical is. This proposed method can be also applied to the off-grid system. Moreover, the integration of PV and storage into the low voltage distribution system at household connection points will be investigated in future work.

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