STUDY ON THE IMPACT OF INTEGRATED PV UNCERTAINTIES INTO AN OPTIMAL LVAC TOPOLOGY IN A RURAL VILLAGE

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Abstract

This paper addresses a comparative study of radial topologies and the impact of the topology with the integration of PV for a rural village considering the shortest line and load balancing improvement. This research paper aims to develop and compare the AC low voltage (LVAC) topology with different developed algorithms. The shortest path (SP) algorithm is developed to search for minimizing the conductor usage in the first step. Two different algorithms, are repeated phase sequence (RPS-ABC) and first fit bin packing (FFBP), which are established in the second step to find out the load balancing in three-phase LVAC topology. Then, the comparative analysis of different methods is investigated considering the energy losses. Next, an impact of integrated photovoltaic (PV) uncertainties in both sitting and sizing into the optimal LVAC topology are performed using the Monte-Carlo (MC) simulation method. In this paper, simulation results obtained confirm the proposed method.

Keywords: First-fit bin-packing, Monte-Carlo, Photovoltaic, Repeated phase sequence, Shortest path

Introduction

The energy consumption has continuously increased year by year due to population growth and economic condition. To meet the need of society and people, the researchers are currently finding innovative methods in order to improve network performance [1]. Furthermore, a low voltage (LV) distribution networks are almost radial unbalanced network due to the presence of 1-phase loads [2]–[11], it is therefore required to design an appreciate topology with an effective method for load balancing improvement.

Many grid developments for rural electrification were addressed in the literature. To cope with the problem of topology, the authors in [12] developed a radial distribution system to find the lowest investment cost with the path search algorithm. Authors in [13] obtained the optimal radial topology by using a dynamic programming method. Also, the optimal planning of the urban system taking into account a topology with adapted simulated annealing algorithm was studied in [14]; this work proposed to minimize the upgrades of the existing system necessary for expansion. However, these authors almost considered MV distribution as a balanced system.

Furthermore, various authors have studied the planning of low voltage (LV) distribution systems. The optimal radial topology by considering the load demand uncertainties (i.e. growth rate and new connected load) with bin packing and mixed-integer quadratically constrained programming (MIQCP) was developed in [15], [16]. In [17], the MIQCP was also applied to find out the radial topology in an urban area. Also, the single-phase as the mainline of LV radial topology was studied in [18] by using the shortest path conception. However, these authors considered the urban areas and single-phase as mainline.

Numerous authors investigated an isolated grid based on renewable energy resources. The hybrid of diesel generators with renewable energy was considered to provide electricity for electrification in the village [19]–[24]. The techno-economic analysis of PV and diesel with a battery as a charging station in Cambodia was also studied in [25]. In [18], [26], the authors discussed the planning of a PV system with battery energy storage for a rural village considering technical and economic aspects for developing countries. However, these authors focused on an isolated system without taking into account the optimal grid topology.

An overview of the load balancing of electrical power distribution has been provided in [27]; this work described the methodologies and techniques to solve the load balancing. In [28], the authors focused on loss reduction in distribution systems with an optimal load balancing by using mixed-integer nonlinear optimization; this method reduced the line current and improved the factor of unbalanced voltage. Other methods to swap the single-phase loads such as the mixed-integer programming in [29], mixed-integer linear optimization in [30], and simulated annealing in [31] were developed. The authors in [32] studied phase load balancing by using particle swarm optimization; this method considered electricity-saving through loss reduction. The phase balancing in distribution systems was also conducted in [33]; the authors used a greedy randomized adaptive search procedure to find a configuration that minimizes the unbalanced voltage. However, these authors almost examined for the phase load balancing of existing radial topology. Thus, this paper will propose algorithms not only for phase load balancing but also for the shortest radial topology.

The main purpose of this research work is to study a comparison of two different algorithms for radial optimal LVAC topology and the impact of integrated PV uncertainties in the LV distribution system for a rural village in Cambodia. The rest of this paper is structured as follows: the methodology of LVAC topology design, as well as the description of the algorithms, are detailed in the second section. The case study of a rural village in Cambodia including the input parameter as a hypothesis is provided in the third section. Section four provides the simulation results and discussion of two different methods with integrated PV of LVAC design. Section five finally gives the conclusions and future works.

Methodology

In this paper, the proposed method aims at searching for the optimal radial topology of low voltage distribution networks in a rural village by means of different proposed algorithms while satisfying the bus voltage and current constraints. Three following objectives will be achieved in this paper; 1) optimal LVAC topology with conductor used minimizing by using shortest path (SP), 2) load balancing improvement by using two different algorithms which are repeated phase sequence-ABC (RPS-ABC) and first-fit bin-packing (FFBP), 3) comparative study of the two proposed algorithms and 4) impact of integrated PV uncertainties into the radial optimal topology. A flowchart presenting the numerous steps of the proposed algorithm is provided in Figure 1. The load data (i.e. PQ), as well as line impedance (Z) and coordinates (X, Y), are required to be as inputs. Then, the shortest-path algorithm is launched with those inputs in order to get the shortest conductor used in the system. Next, the RPS-ABC and FFBP are applied in order to obtain the load balancing. Then, the comparison between the two algorithms is discussed. The impact of PV integration in both sitting and sizing into the grid such as voltage, current and reverse power flow are provided in this paper.

Graph Theory

A graph [34] is used as an electrical network which is defined as a pair of sets $G \equiv G(V,E)$, where $V=\{1.2 \ldots N\}$ is a set of N nodes of the graph representing the number of households and $E \subseteq V \times V = \{e_{ij}\}(i, j) \in V\}$, $\{e_{ij}\}$ is a set of segments between nodes i and j representing the lines of the grid. The topology of a graph characterizes the networks is provided in figure 2 [35].

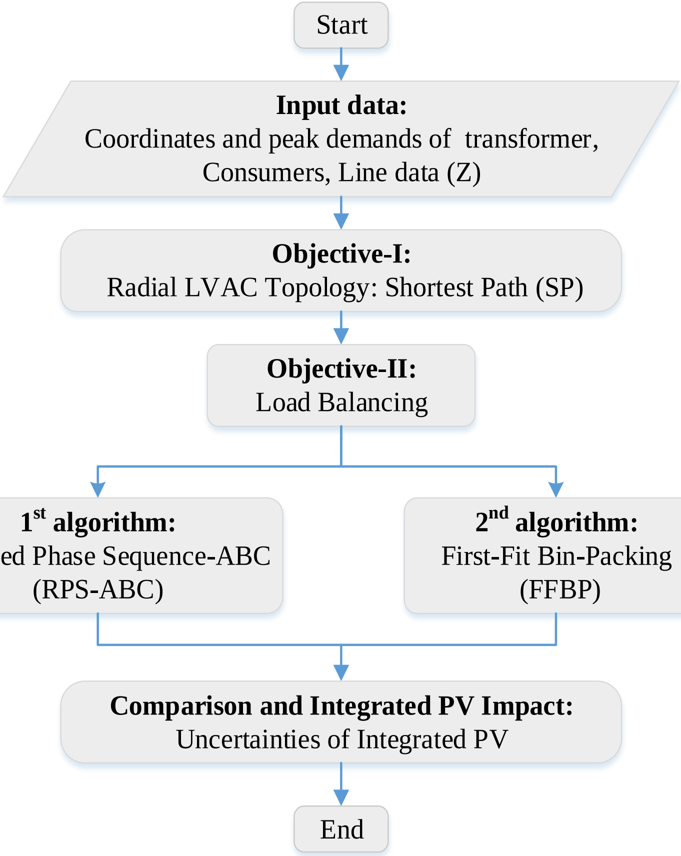

Figure 1. Flowchart of proposed method

Shortest Path (SP)

The LV system in Cambodia consists of single-phase or three-phase LV feeders going from a three-phase MV/LV distribution transformer to several single-phase poles. Each household is connected to an electrical pole. The optimal radial topology is designed by ensuring the minimization of the conductor length. With this aim, the shortest path (SP) concept is applied. In the graph theory, the SP problem contains in searching for a path between two nodes in a graph so that the summation of the weights of its segments is minimized. This SP algorithm is run to search for the closest pole's node to connect the households. The pseudocode of the shortest path is shown in Figure 3.

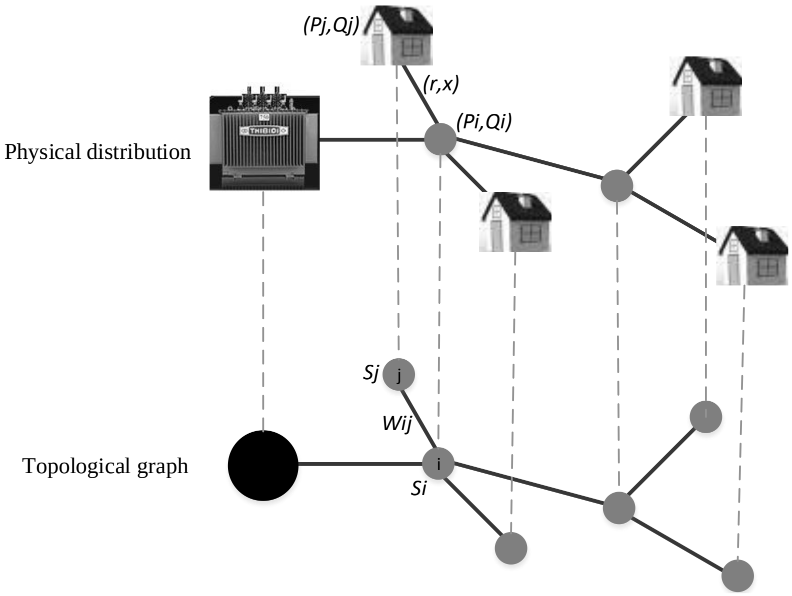

Figure 2. A graph representation of systems

```
$T$: bus of electrical poles
$L$: bus of  loads
$C$: closest loads from the electrical poles
$d$: distance between two buses
for $i = 1:L$
    for $j = 1:T$
        $d^i = d_i^j$
        $d = \min(d^i)$
        $p = find(d^i = d)$
        $Line_i = [p \quad i]$
    end
end
```

Figure 3. Pseudocode for shortest path

Repeated Phase Sequence (RPS-ABC)

To cope with load balancing, the repeated phase sequence ABC (RPS-ABC) as 1st algorithm is proposed to balance the loads for each electrical pole. This proposed algorithm is applied for the total demand at each electrical pole, it means there is only one phase that can be connected to the electrical pole. The ABC phase sequence connection is repeated for every three connected poles in order to get the load balancing, once the shortest radial topology found by the SP. Figure 4 illustrates the concept of RPS-ABC for this paper. The pseudocode of this algorithm is also provided in Figure 5.

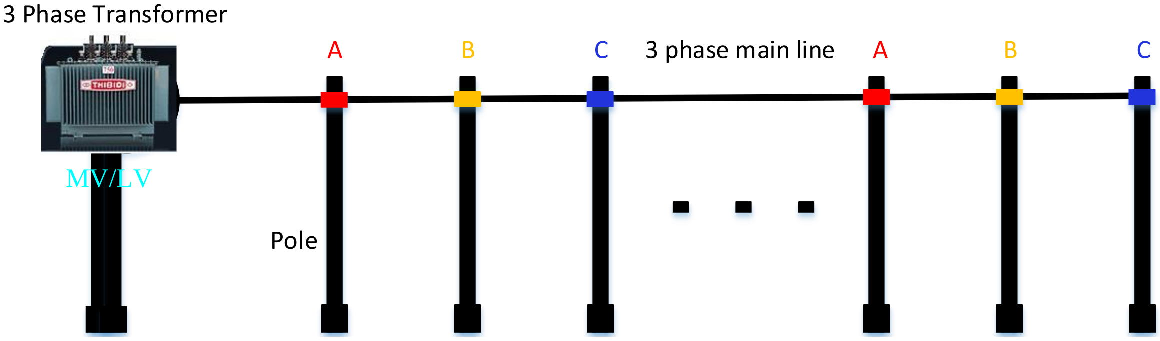

Figure 4. Repeated phase sequence (RPS-ABC) concept

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$T$: bus of electrical poles
$y_T^\alpha$: phase connection at electrical pole T, $\alpha$ = A, B or C
$k = 1$
for $i = 1:3:T$
    $[y_k^A, 0, 0] = [1, 0, 0]$
    $[0, y_{k+1}^B, 0] = [0, 1, 0]$
    $[0, 0, y_{k+2}^C] = [0, 0, 1]$
    $k = k + 3$
end
```

Figure 5. Pseudocode for repeated phase sequence-ABC

First-Fit Bin-Packing (FFBP)

With the problem of phase load balancing, the first fit bin packing (FFBP) is applied as the 2nd algorithm. The problem of FFBP contains in packing all items into a defined bins' number,

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$T$: bus of electrical poles
$P_T^\alpha$: load demand at electrical pole T, $\alpha$ = A, B or C
$y_T^\alpha$: phase connection at electrical pole T, $\alpha$ = A, B or C
for $i = 1:T$
  if $(sum(P_{i-1}^A) < sum(P_{i-1}^B) \,\&\, sum(P_{i-1}^A) < sum(P_{i-1}^C))$
      $[y_i^A, y_i^B, y_i^C] = [1, 0, 0]$
  elseif $(sum(P_{i-1}^B) < sum(P_{i-1}^A) \,\&\, sum(P_{i-1}^B) < sum(P_{i-1}^C))$
      $[y_i^A, y_i^B, y_i^C] = [0, 1, 0]$
  elseif $(sum(P_{i-1}^C) < sum(P_{i-1}^A) \,\&\, sum(P_{i-1}^C) < sum(P_{i-1}^B))$
      $[y_i^A, y_i^B, y_i^C] = [0, 0, 1]$
  elseif $(sum(P_{i-1}^A) == sum(P_{i-1}^B) \,\&\, sum(P_{i-1}^A) < sum(P_{i-1}^C))$
      ph = [1,0]
      idx = randperm (numel(ph))
      $[y_i^A, y_i^B, y_i^C] = [\mathrm{ph(idx)}, 0]$
  elseif $(sum(P_{i-1}^A) == sum(P_{i-1}^C) \,\&\, sum(P_{i-1}^A) < sum(P_{i-1}^B))$
      ph = [1,0]
      idx = randperm (numel(ph))
      $[y_i^A, y_i^B, y_i^C] = [\mathrm{ph(idx(1))}, 0, \mathrm{ph(idx(2))}]$
  elseif $(sum(P_{i-1}^B) == sum(P_{i-1}^C) \,\&\, sum(P_{i-1}^B) < sum(P_{i-1}^A))$
      ph = [1,0]
      idx = randperm (numel(ph))
      $[y_i^A, y_i^B, y_i^C] = [0, \mathrm{ph(idx)}]$
  else
      ph = [1,0,0]
      idx = randperm (numel(ph))
      $[y_i^A, y_i^B, y_i^C] = \mathrm{ph(idx)}$
  end
end
```

Figure 6. Pseudocode for first fit bin packing (FFBP)

whilst minimizing the difference of the total weight of each bin. In this paper, the items are the loads (P, Q) and the bins are the phases (A-B-C) of the network, respectively. Firstly, the SP is run to find the closet electrical pole's node to connect the household, and then the FFBP is applied to equilibrium the phases of those connected households. Figure 6 provides the pseudocode of the first fit bin packing.

Monte-Carlo (MC) Method

Monte-Carlo (MC) method is a class of computational algorithms that rely on repeated random sampling to compute their results [16]. The MC method works as the following pattern: 1) the determination of data boundary, 2) generate data from a probability distribution of the input, and 3) Deterministic calculation from the data. To study the impact of uncertainties of integrated PVs, the MC simulation method is employed to find out the occurrence indicators which will impact the system considering uncertainties of location and sizing with proposed scenarios.

Case Study: A Rural Village in Cambodia

Case Study Description

The rural village located in Sandek commune, Cambodia is chosen as a case study in this paper. The households are supplied by 22/0.4-kV transformer from the 1st bus to the 129th bus. The total active power of the system is about 43kW with a power factor of 0.95, which takes from a normal distribution of a 400 W mean and a 50 W standard deviation. The detailed information for a specified location and load data is provided in [26]. Figure 7 demonstrates the studied site in a rural village of the paper.

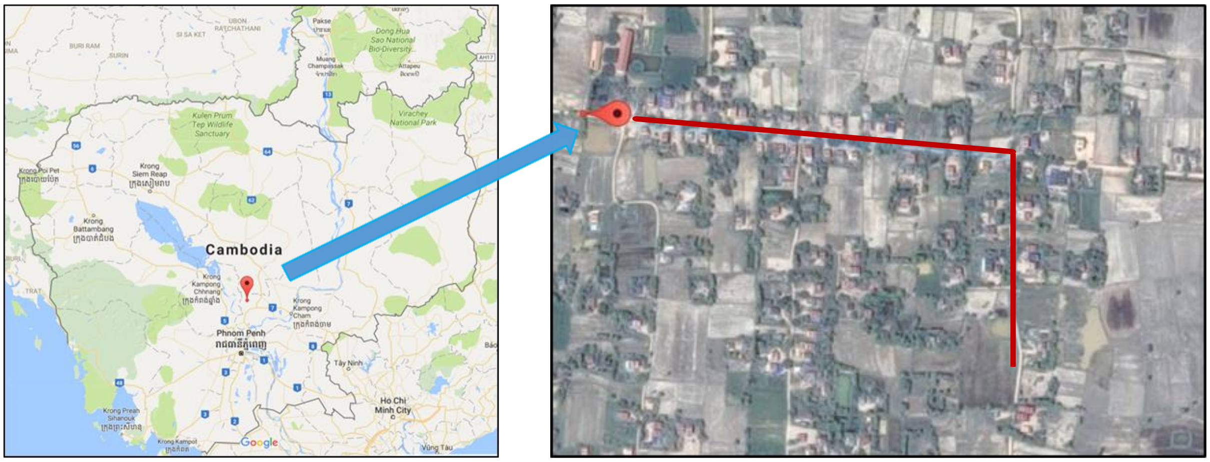
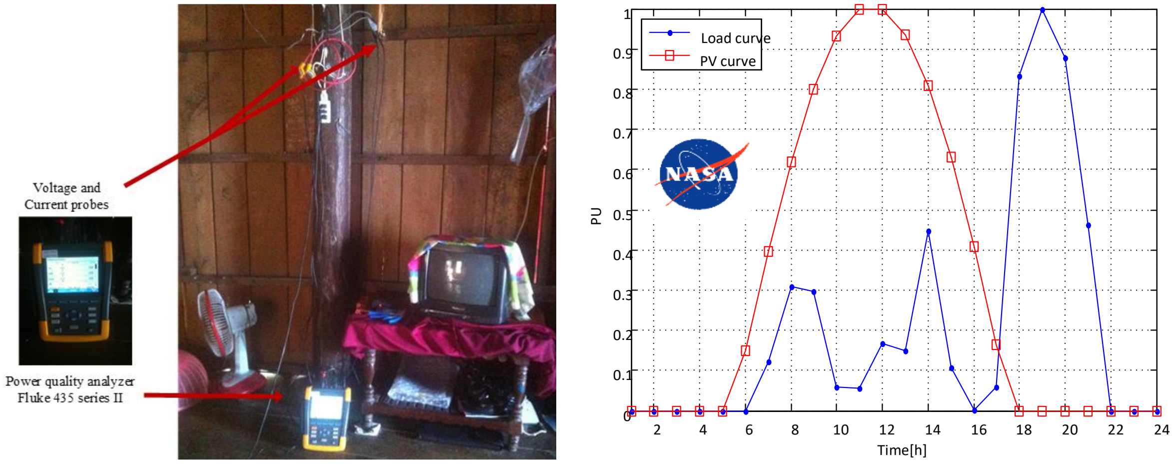


Figure 7. Studied site in Sandek commune [12°08’35” N, 104°57’30” E]

Normalized Daily Load and PV Curve

A normalized daily load curve in a one-hour interval is taken from local measurements from three different households in a rural village, which is given in Figure 6 (a). Figure 8 (b) provides the normalized daily PV (NASA) and load curves [26]. This normalized curve of loads is used to simulate in order to validate the proposed method in this paper. Also, this curve will be repeated for annual simulation.



(a) (b)

Figure 8. Load measurement set-up (a) and normalized daily PV including load curve (b)

Scenarios on PV Integration

In this research work, the uncertainty impacts of PV integration into the LVAC grid are focused considering the technical aspect (i.e. voltage, current and power). To do that, two scenarios on the sitting and sizing of PVs as scenarios are proposed and shown in Table 1. The first scenario focused on time-series of sitting and sizing of PVs; this scenario assumes that all households are equipped with PV and their capacities are varied from 50 Wp to 400 Wp with an incremental of 50 Wp. Moreover, the worst-case (i.e. highest difference of PV and load) is proposed as the second scenario; this scenario considers the uncertainty on the location of three households over 105 households with 3 households incremental and their capacities from 50 Wp to 400 Wp with 50 Wp incremental.

Table 1. Scenarios of integrated PV

Scenarios	Description	
S1: Time-series	All households are equiped with	50 Wp to 400 Wp with 50 Wp incremental
S2: Worst case (Highest diference of PV and Load)	Randomly 3 households to 105 households with 3 houses incremental	Randomly 50 Wp to 400 Wp with 50 Wp incremental

Simulation Results and Discussions

Optimal LVAC Topology

In this part, the optimal radial topologies of two different algorithms are performed by using SP-FFBP and SP-RPS-ABC algorithms as provided in Figure 9 and Figure 10. Furthermore, a classical cable size of 50 mm^2 is used for the mainline and 4 mm^2 from the main feeder to each energy meter which is currently the standard in Cambodia. The total active power at each phase for two different algorithms is depicted in Table 2. As seen in the table, the 2nd algorithm is quite balanced by comparing it to the 1st algorithm. The reason is the fact that the 2nd algorithm has tried to balance the load at each energy meter from the MV/LV distribution transformer to the end of the pole. In contrast, the 1st algorithm has only respected the phase sequence (ABCABC…) from the distribution transformer in order to balance the phase load of the households.

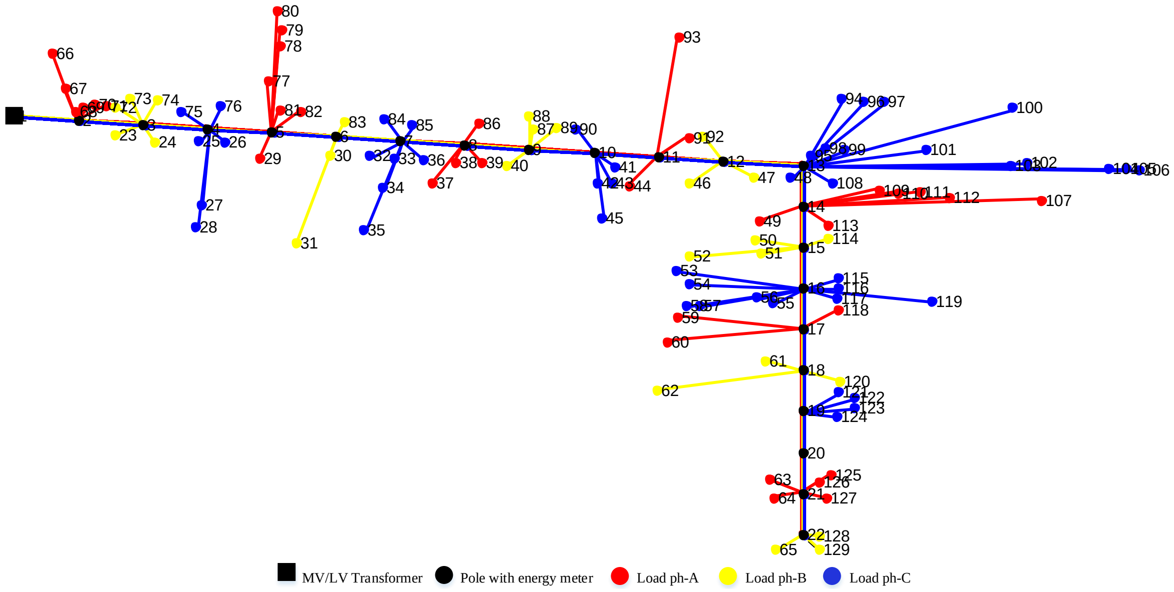


Figure 9. Radial LVAC topology by using SP-RPS-ABC

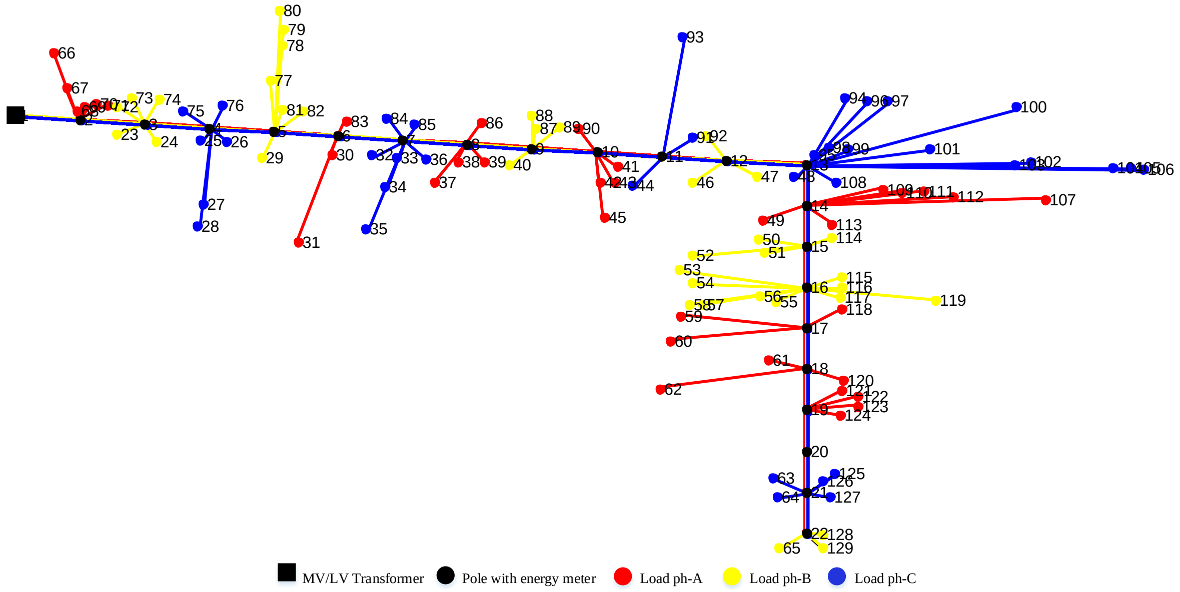


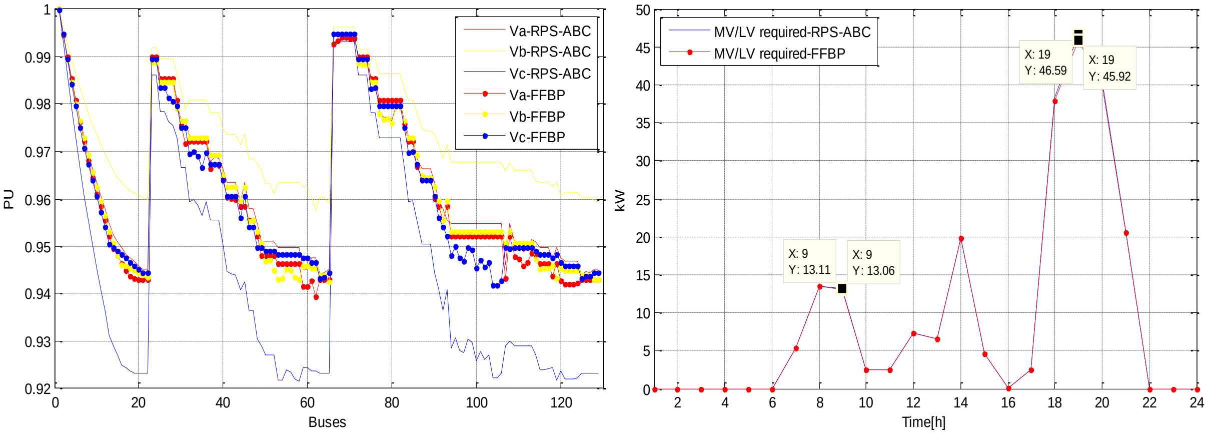
Figure 10. Radial LVAC topology by using SP-FFBP

Table 2. Active Power of Each Phase

Algorithms	Total Active Power (kW)		
	A Phase	B Phase	C Phase
1st algorithm	14.05	10.04	18.91
2nd algorithm	13.98	14.29	14.93

Voltage Profile and MV/LV Distribution Transformer

These two algorithms aim at balancing the load demand while respecting the voltage and current constraints. However, the voltage profile and active power at MV/LV distribution transformer in both algorithms are different. Figure 11 provides the voltage profile (at peak load) and the distribution transformer required of different algorithms over a day. By applying backward/forward power flow [36], as a result regarding voltage limit (i.e. 0.9pu in Cambodia), there is no problem with the classical cable, which is presently used in Cambodia. Also, the 2nd algorithm is quite good in both voltage and active power at MV/LV distribution transformer, comparing to the 1st algorithm.



(a) (b)

Figure 11. Voltage profile at peak load (a) and active power at distribution transformer (b)

Comparison of SP-RPS-ABC and SP-FFBP

In order to compare the two proposed algorithms, the performance indicators have been illustrated in Table 3. Also, minimal power loss and annual energy use are the main indicator for these algorithms. As seen in the table, the indicator for the 2nd algorithm is lower than the 1st algorithm (SP-RPS-ABC) that is because of the fact that the 2nd algorithm (SP-FFBP) is

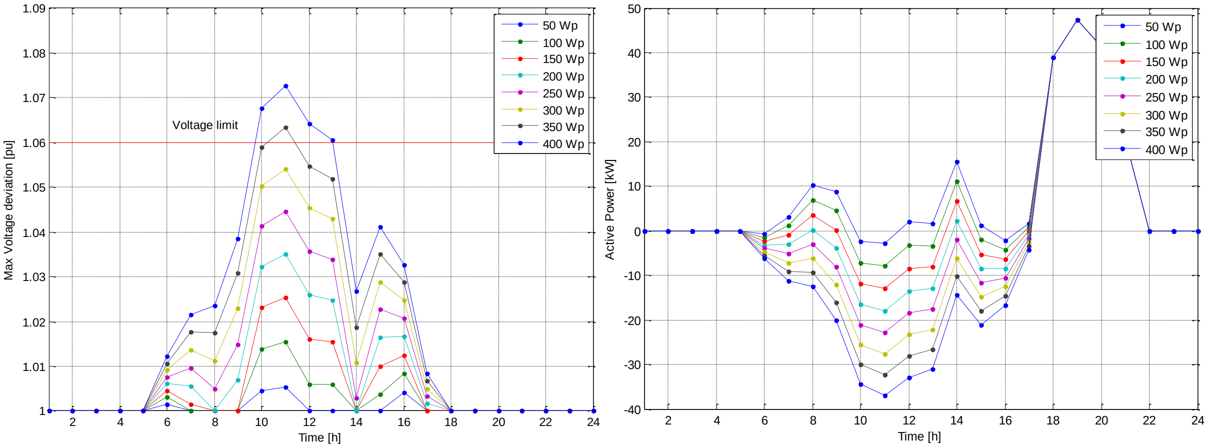
Table 3. Performance Indicators of the LVAC Topologies

Items	1st Algorithm	2nd Algorithm
MV/LV required [kW]	46.60	45.90
Maximum Power loss [kW]	3.60	2.90
Minimum Voltage [PU]	0.92	0.94
Maximum Current in Line [A]	91.87	70.16
Annual Energy Used [kWh]	81670.25	80934.69

more reparation of load balancing including voltage profile improvement as well. According to this table, it can be thus concluded that the 2nd algorithm is selected as the best choice for the optimal radial topology.

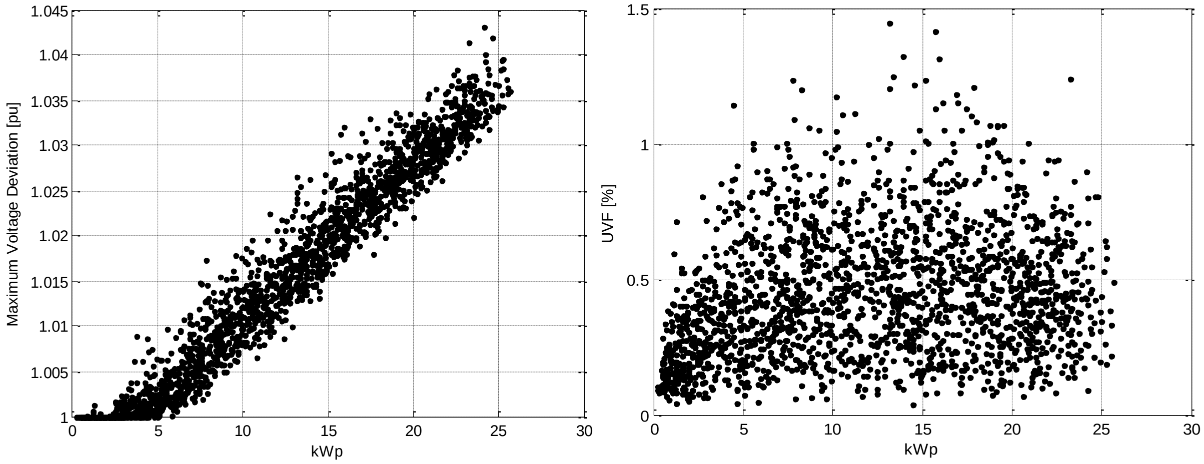
Impact of PV Integration

Two scenarios are proposed on the impact of integrated PVs uncertainties in both sitting and sizing into the optimal radial topology. Scenario 1 focuses on the time series analysis of PV penetration from 50 Wp to 400 Wp for each household. Figure 12 shows a maximum voltage deviation and active power at distribution transformer with the integrated PV for each household. According to these figures, the voltage limit [35] is reached from 350 Wp and reverse power flow occurred at some time over a day for each PV penetration.



(a) (b)

Figure 12. Daily maximum voltage deviation (a) and active power of distribution transformer (b) for each PV penetration levels



(a) (b)

Figure 13. Daily maximum voltage deviation (a) and unbalanced voltage factor (b) with total integrated PV over 2000 samplings

The uncertainties in both sitting (3 to 105 households with 3 incremented households) and sizing (50 Wp to 400 Wp with 50 Wp incremented power) are considered in the 2nd scenario. This scenario has considered on a worst-case (i.e. highest difference of the PV production and load consumption) at 12 PM using the Monte-Carlo method over 2000 samplings. With results in Figure 13, it can be sized the maximum peak power which integrates into the grid by considering on a criterion such as voltage limit (i.e. 1.06 PU), voltage unbalanced factor (i.e. 2%) [37] and reverse power flow with maximum current as shown in Figure 14. It can be noticed that there are no problems with voltage but there is the reverse power flow occurring with these proposed uncertainties in a rural village.

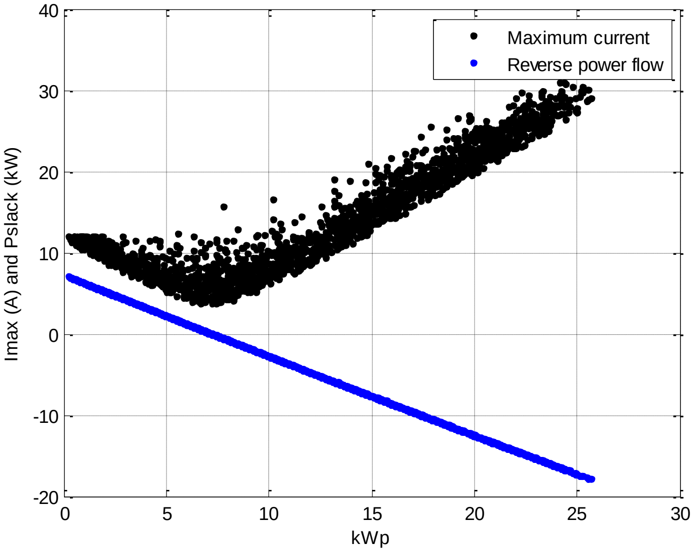


Figure 14. Maximum current (blue) and reverse power flow (black) with total integrated PV over 2000 samplings

Conclusions

In this paper, the optimal LVAC topology for electrification in a rural village is realized by using different proposed algorithms. The shortest path is applied in order to search for radial topology considering the minimal conductor used by inserting the coordination of each item (i.e. transformer, poles, and households). Then, two different algorithms are called the repeated phase sequence (RPS-ABC) and the first-fit bin-packing (FFBP), which are developed to find out the load balancing in order to improve the voltage and current profiles. The comparative study of algorithms considering the power losses and energy use is also conducted so as to make the decision on which should be selected. The impact of integrated PV uncertainties into the optimal LVAC topology is studied using the Monte-Carlo method simulation by taking into account the sitting and sizing. Also, the radial topologies of the systems are automatically envisioned with different colors for the purpose of visualization of the system. However, other novel algorithms will be developed in order to compare to these proposed algorithms with the same problem. A study of low voltage distribution systems, Cambodia is particularly targeted, by taking into account the distributed generation integration such as PV, wind and energy storage with techno-economic aspects will be also investigated.

Acknowledgment

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