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Design of AC Microgrid Topology with Photovoltaic Uncertainties in a Rural Village

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Abstract

Energy needs are increasing day by day, especially for developing countries, due to population growth and changing lifestyles. A suitable microgrid topology with renewable energy integration is considered to fulfill the people and society's needs. This paper focuses on the design of AC microgrid topology for a nonelectrified village with the integration of PV uncertainties in both sitting and sizing. The development of an optimal algorithm based on the conductor use minimization and unbalanced load improvement is proposed. The shortest path is proposed to search for the minimum conductor use. Then, the algorithm for improving the unbalanced load with two different algorithms–phase sequence and first-fit bin packing with phase swapping–is compared based on the energy use indicator. Once the optimal AC microgrid topology is defined, the impact of the integration of PV uncertainties into the system is studied. Simulation results prove the effectiveness of the proposed method.

Abstrak

Rancangan Topologi Kisi Mikro AC dengan Ketidak-pastian Fotovoltaik di suatu Kampung Pedesaan. Kebutuhan energi terus meningkat dari hari ke hari, khususnya untuk pengembangan desa, akibat pertumbuhan populasi dan perubahan gaya hidup. Suatu topologi kisi mikro yang cocok dengan integrasi energi yang dapat diperbaharui dipertimbangkan untuk memenuhi kebutuhan rakyat dan masyarakat. Kajian ini memfokuskan pada topologi kisi mikro AC untuk suatu kampung yang belum berlistrik dengan penyatuan ketidak-pastian PV baik di dalam kedudukan maupun ukuran. Diusulkan pengembangan suatu algoritma optimal berdasarkan pada minimalisasi penggunaan konduktor dan peningkatan beban tak seimbang. Diusulkan lintasan terpendek untuk mencari penggunaan konduktor minimum. Selanjutnya, algoritma tersebut untuk meningkatkan beban tak seimbang dengan dua algoritma yang berbeda–rangkaian fase dan pengemasan wadah penyimpan hasil panen yang cocok mula-mula (*firs-fit bin*) dengan pertukaran fase–dibandingkan berdasarkan pada indikator penggunaan energi. Setelah topologi kisi mikro AC optimum terbentuk, dampak dari penyatuan ketidak-pastian PV ke dalam sistem dikaji. Hasil-hasil simulasi membuktikan keberhasilan metode yang diusulkan.

Keywords: AC microgrid, first-fit bin packing, phase sequence, phase swapping, photovoltaic, unbalanced load

1. Introduction

Energy demand is constantly increasing because of population growth and the growing needs of people. To address this electricity need, one of the solutions is to design an appropriate microgrid with an alternative source. Rural topologies provide electricity service to end-users at a lower density compared with urban areas along the road far from MV/LV distribution transformers; thus, networks face undervoltage and power loss problems [1]. AC microgrids operate radially in an unbalanced manner in nature because they consist of single-phase loads [2], [3]. Thus, an urgent task is to provide the optimal microgrid topology with an effective algorithm in terms of minimal conductor use and improving the unbalanced load in the system.

Many studies have examined rural microgrid topologies. The path search algorithm [4] is implemented to search for the lowest annual cost and operational cost of radial distribution network; this method provides the optimal route for each load in the large scale of the distribution system. The optimal radial network architecture using dynamic programming is deployed in [5]; the authors searched for the optimum design of the network based on the total cost. The optimal urban topology is provided using an adapted simulated annealing algorithm [6]; the authors proposed to minimize the improvement of the existing grid for expansion over the planning. In [7], the authors focused on loss reduction in distribution systems with optimal load balancing by using mixed-integer nonlinear programming; this method reduced the line current and improved the factor of unbalanced voltage. Other methods of swapping single-phase loads, such as mixed-integer programming in [8], mixed-integer linear programming in [9], and simulated annealing in [10], have been developed. However, these authors almost examined for medium distribution networks and load balancing of existing radial architectures.

Various authors studied the planning of microgrids in developing countries. The mixed-integer quadratically constrained programming with bin packing is implemented in [11]–[13] to find the optimal radial topology by taking into account the uncertainties of new loads and their growth rate over the planning study. The AC single-phase microgrid in a rural village is studied in [14] to search for the lowest investment and operational costs over the planning by using shortest path and actualized cost concept. The authors found the radial network with shortest conductor usage from households to energy box meters placed at electrical poles. The authors in [15], [16] used particle swarm optimization and genetic algorithm to improve the current unbalanced factor for load balancing.

Furthermore, many authors studied isolated microgrids with the integration of renewable energy resources. The authors in [17]–[22] investigated hybrid diesel generation–renewable energy to provide electricity for rural villages. The planning of PV systems with energy storage for rural villages based on technical and economic aspects in developing countries is discussed in [1], [23]. The authors in [24] focused on an optimal LV radial topology based on load balancing improvement in an urban village by using phase sequence. However, this existing algorithm and the proposed novel concepts for microgrids in rural villages need further investigation.

This paper aims at designing the optimal AC microgrid topology with the integration of PV uncertainties based on the shortest length and minimum unbalanced load using phase sequence [24] and combined first-fit bin packing with phase swapping for a rural village. The rest of this paper is organized as follows: The method of AC microgrid topology design and the description of the algorithm are detailed in Section 2. The test system of a rural village in Cambodia, including input parameters as a hypothesis in this study, is provided in Section 3. Simulation results and a discussion of the proposed method are given in Section 4. The conclusion and future directions are described in Section 5.

2. Methods

The proposed method focuses on optimal AC microgrid topology in a rural village with different algorithms and the impact of the integration of PV. This paper has four objectives: 1) to find the optimal AC microgrid topology with minimum conductor use by using shortest path (SP), 2) to minimize unbalanced load using phase sequence and combined first-fit bin packing with phase swapping, 3) to compare the two proposed concepts and 4) to study the impact of the integration of PV uncertainties in the optimal AC microgrid. Figure 1 shows a flowchart of the proposed method. The load data (i.e., active power, reactive power), line data, and placement are used as inputs. Then, the SP concept is implemented with those inputs to obtain the radial microgrid with the shortest conductor use. Next, the phase sequence and first-fit bin packing–phase swapping are applied to improve the load balancing at the energy meters placed at electrical poles. The two algorithms are compared. The impact of PV integration in both sitting and sizing on the optimal AC microgrid, such as voltage, current, and power at the slack bus, is provided.

SP. The AC microgrid system in Cambodia consists of single-phase or three-phase feeders going from a three-phase distribution transformer to several single-phase electrical poles. Each household is connected to energy meter boxes placed on the pole. The optimal AC microgrid topology is designed by ensuring the radial

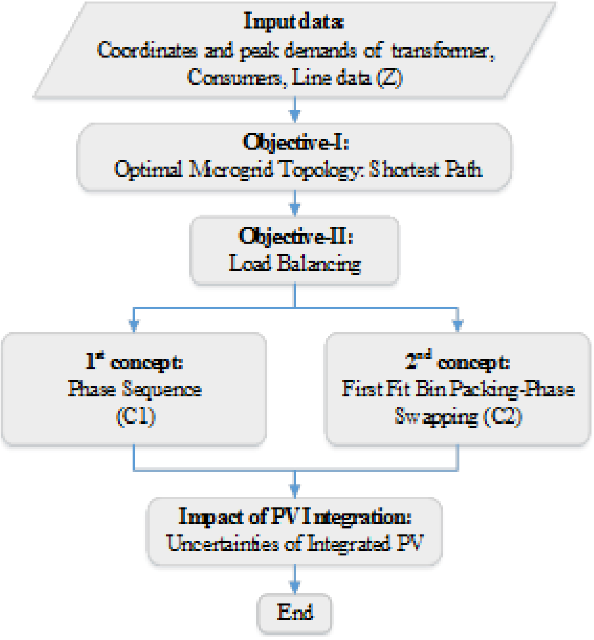

Figure 1. Flowchart of Methodology

network with minimum conductor use. The SP is implemented to deal with this issue. This SP concept searches for a path between energy meter and household with the shortest distance. This concept is run to search for the closest electrical pole's node to connect the households in the network. Figure 2 shows the pseudocode of the SP.

Phase Sequence. This concept is implemented to cope with load balancing at the first stage of the first proposed concept, adding all load demand at each electrical pole. The phase sequence is applied every three connected poles to minimize the unbalanced load. Figure 3 illustrates the phase sequence concept implemented in this paper.

First-fit Bin Packing. This concept is applied for improving load balancing as the first stage of the second concept. The concept aims to address the problem of packing total power at each energy meter box into a defined number of three-phase ABC while minimizing the difference of the total power of each phase in the AC microgrid.

Phase Swapping. Once the AC microgrid topology is obtained using first-fit bin packing, phase swapping is implemented for each energy meter to search for the optimal phase connection on the basis of minimal power loss. Figure 4 shows the pseudocode of the concept.

```
$T$: 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 2. Pseudocode of Shortest Path

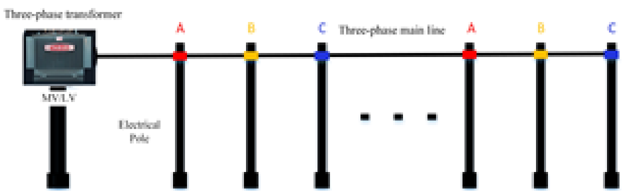

Figure 3. Process of Phase Sequence

```
Require: Line Data, Bus Data, Phase connection from the first stage of first fit-bin packing, Number of energy meter box $N_{EM}$, Number of households $N_{HH}$
for each phase connection at energy meter, $e$ belongs to $N_{EM}$
    if phase of the energy meter box connected to $i^{th}$ phase → $ph^i$
        Swap phase connection to $ph^j$ and $ph^k$, respectively
        for households of each energy meter box $h$ belongs to $N_{HH}$
            Swap phase connection of HH to EM
            Run backward/forward load flow to check sum of Ploss
            if $Ploss^A < Ploss^B$ and $Ploss^C$
                Choose an optimal phase connection → $ph^A$
            else if $Ploss^B < Ploss^A$ and $Ploss^C$
                Choose an optimal phase connection → $ph^B$
            else if $Ploss^C < Ploss^A$ and $Ploss^B$
                Choose an optimal phase connection → $ph^C$
            else
                Choose an optimal phase connection from first-fit bin packing
            end
        end
    end
end
```

Figure 4. Pseudocode of Phase Swapping with Phase Sequence and First-Fit Bin Packing

Monte Carlo Simulation. In studying the impact of PV uncertainties integration, Monte Carlo simulation [12] is implemented to determine a probability distribution considering the sitting and sizing of PV into the microgrid.

3. Test System in a Rural Village

Test System Description. A rural village located in Sandek Commune, Cambodia is selected as a case study in this paper. The total active power of the microgrid is about 43 kW with a 0.95 power factor, which is taken from a normal distribution with a 0.4 kW mean and 0.05 kW STD. Detailed information on the microgrid is provided in [1]. Figure 5 shows the microgrid site studied in this paper.

Normalized Daily Load Profile. A normalized daily load profile at a one-hour interval is taken from local measurements in a rural village, which is provided in Figure 6. Figure 7 provides the normalized daily PV (NASA) and load profiles. This normalized load profile is used for the simulation of the proposed method. This normalized profile will be used for annual simulation because of the lack of information in Cambodia. The detailed information is described in [1].

Figure 5. **Test System in Sandek Commune [12°08'35" N, 104°57'30" E]**

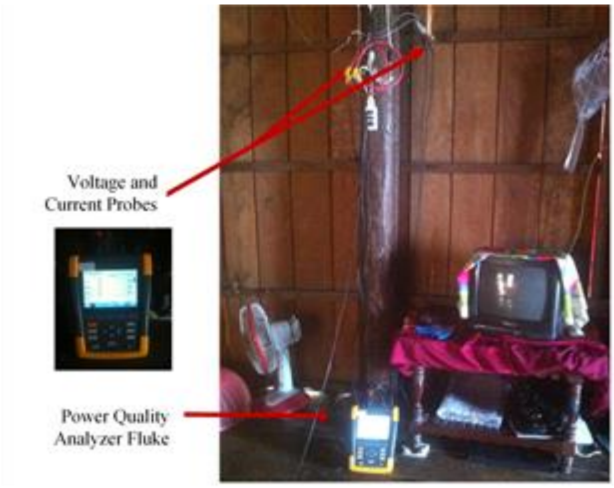

Figure 6. **Load Profile Measurement with Power Quality Aanalyzer Fluke**

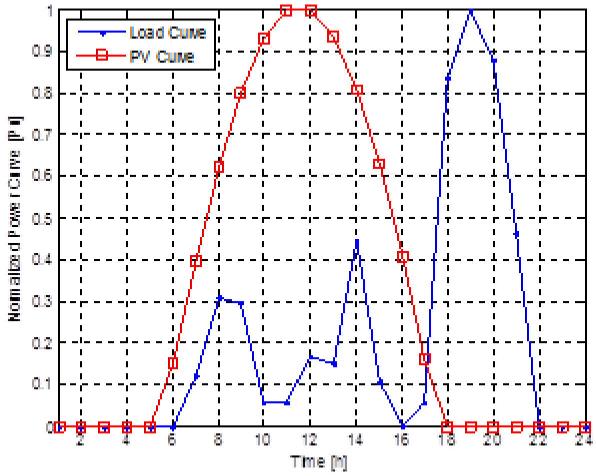

Figure 7. **Normalized Daily PV and Load Profiles in a Rural Village**

Hypothesis on PV Integration. The impact of PV integration into an AC microgrid is provided in this paper. Some scenarios on sitting and sizing of PVs are proposed in Table 1.

Table 1. **Hypothesis of Integrated PV Impact**

Scenario	**Description of scenarios**	
	Sitting	**Sizing**
S1: Time series	All households are equipped with	100 to 500 Wp with 100 Wp increment
S2: Lowest difference of PV and load	Random 5 to 105 households with 5-household increment	Random 100 to 500 Wp with 100 Wp increment

4. Simulation Results and Discussion

Optimal AC Microgrid Topology. The optimal AC microgrid topology is found based on a comparison of two different concepts, namely, phase sequence and the combination of first-fit bin packing and phase swapping, as shown in Figure 8. In Cambodia, classical cable sizes of 50 and 4 mm^2 are used for the mainline and the main feeder, respectively, to each energy meter placed at electrical poles. Table 2 shows the total active power at each phase of different concepts, in which the second concept is more balanced than the first concept. This condition is due to the fact that the second concept tried to balance the load at each pole from MV/LV substation and then changed the phase connection by using phase swapping based on the lowest power loss indicator.

Voltage Profile and MV/LV Substation. The proposed concepts aim to minimize unbalanced load while all the voltage and current constraints are taken into consideration. Figure 9 shows the voltage profile at peak load different concepts over a day, and Figure 10 presents the active, reactive power, and power losses. The computation is provided by backward/forward load flow [25]. With regard to the undervoltage limit (i.e., 0.9 pu) and maximum current, no problem with the classical cable exists, as seen in the figure. Moreover, the second concept is better in terms of voltage and active power at the MV/LV distribution transformer compared with the first concept.

Table 2. **Active Power at Each Phase**

Concept	**Total active power P (kW)**		
	A	**B**	**C**
1st concept [24]	14.05	10.04	18.91
2nd concept	16.26	14.29	12.45

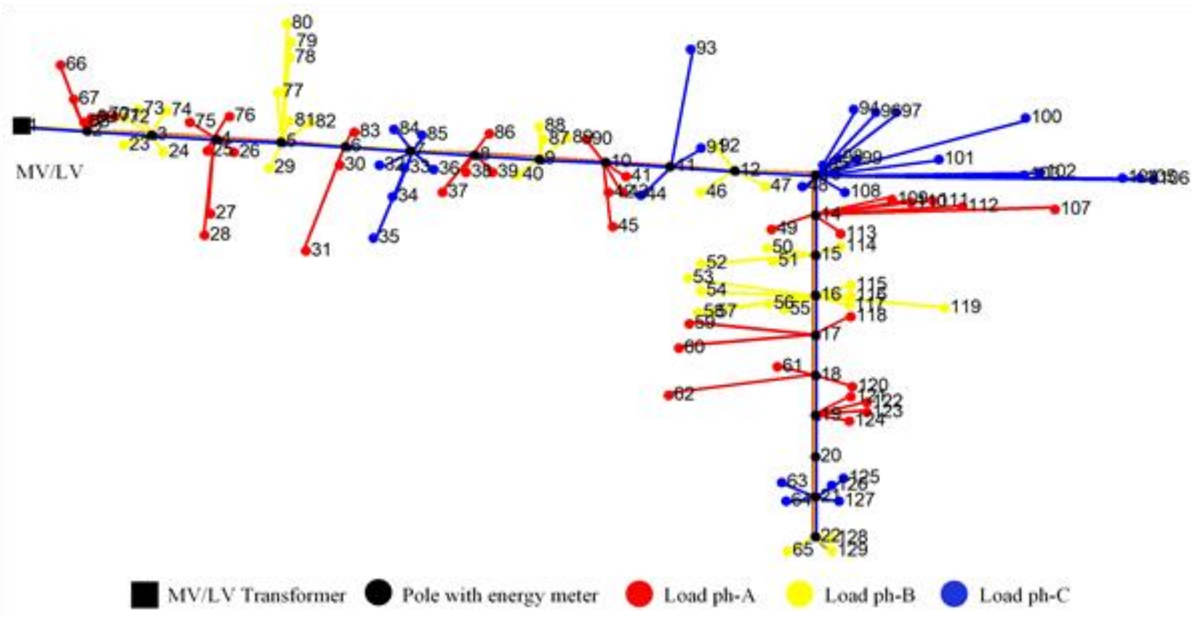

Figure 8. **Optimal AC Microgrid Topology by a Combined First-Fin Bin Packing and Phase Swapping**

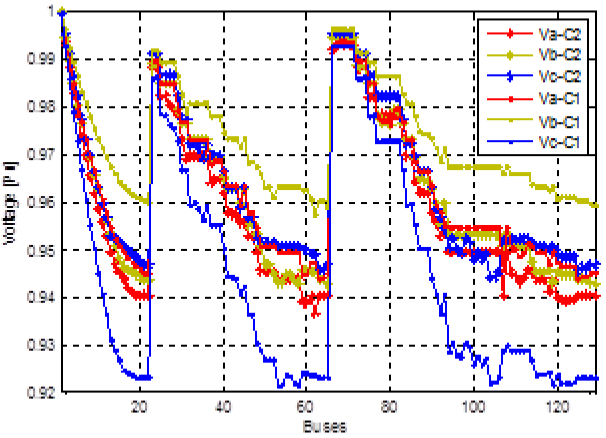

Figure 9. **Voltage Profiles by Two Different Concepts**

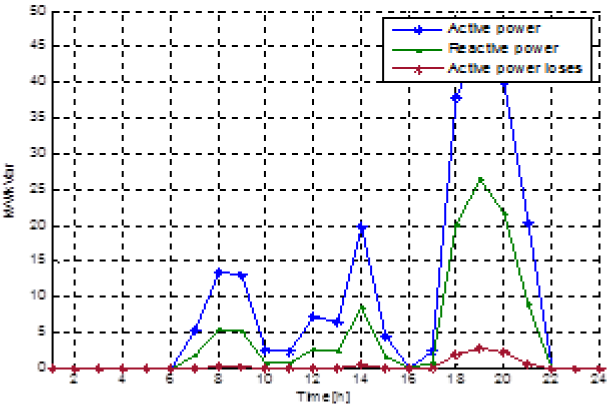

Figure 10. **Daily Active, Reactive, and Power Loss at MV/LV Distribution Transformer by the Second Concept**

Table 3. **Performance Indicators of the Microgrid**

Items	**First Concept [24]**	**Second Concept**	**Choice**
Max. power loss [kW]	3.60	2.91	C2
Sizing of transformer Required [kVA]	55.08	52.95	C2
Annual energy Used [kWh]	81670.25	80933.97	C2
Minimum Voltage [PU]	0.9216	0.937	C2
Max. Current in Line [A]	91.87	77.18	C2

Comparison Between Two Different Concepts. Table 3 illustrates the performance indicators of different proposed concepts. The indicators for the second concept (C2) are lower than those of the first concept (C1) because the second concept focuses more on the reparation of loads, including voltage profile improvement, in the microgrid system.

Table 3 shows the annual energy of two different proposed concepts. This annual energy takes into account energy losses and energy computation over a year. With regard to the annual energy used in Table 3, we thus conclude that the second concept is the best solution due to the lowest value in our system.

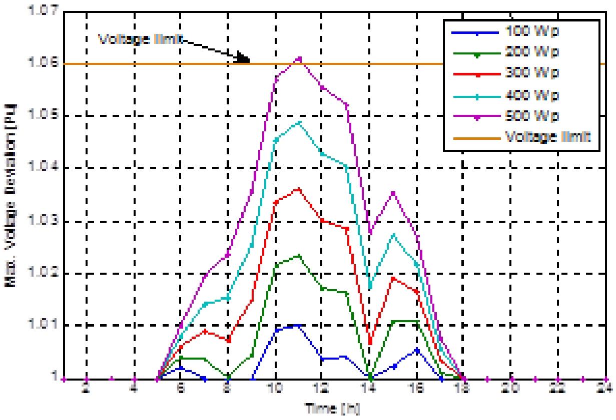

Figure 11. **Daily Maximum Voltage Deviation for Each PV Penetration Level**

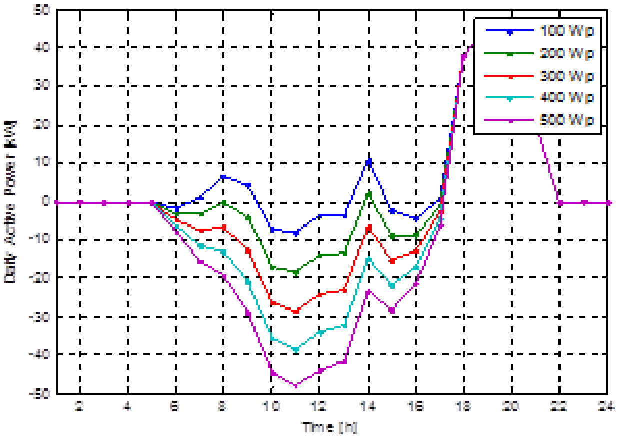

Figure 12. **Daily Active Power at the Transformer for Each PV Penetration Level**

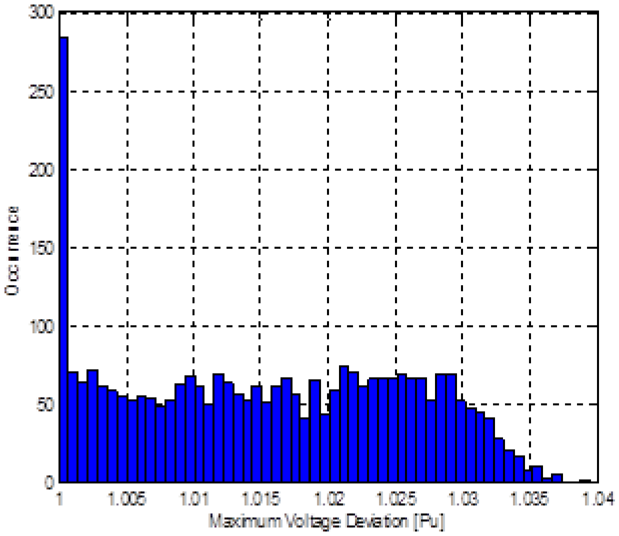

Figure 13. **Histogram of Maximum Voltage Deviation with PV Penetration Over 3,000 Samplings**

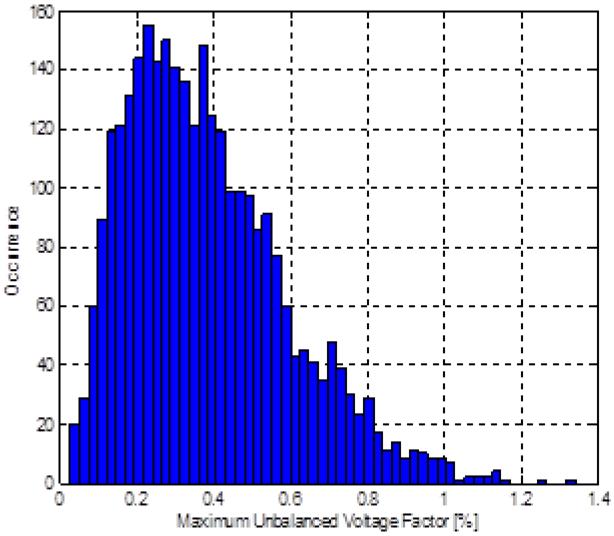

Figure 14. **Histogram of Maximum Unbalanced Voltage Factor with PV Penetration Over 3,000 Samplings**

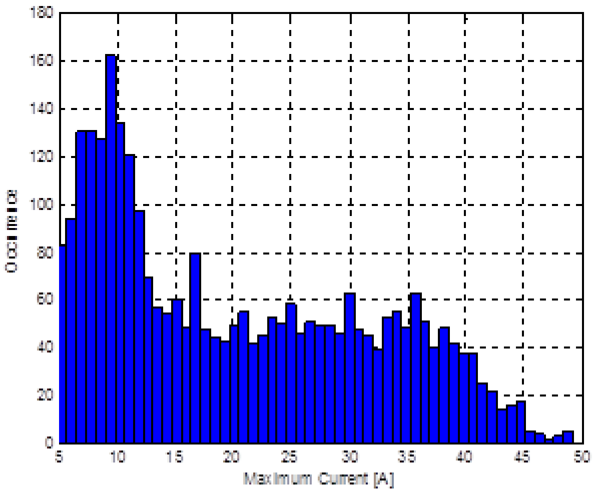

Figure 15. **Histogram of Maximum Current with PV Penetration Over 3,000 Samplings**

Impact of PV Integration. In this part, we propose two scenarios relevant to PV uncertainties' impact in both sitting and sizing. The first scenario focuses on the time series analysis of PV capacity on households from 100 Wp to 500 Wp. Figures 11 and 12 illustrate the maximum voltage deviation and swing power with PV integration, respectively. As shown, the overvoltage limit issue occurs from 500 Wp at 11 a.m., and reverse power flow happened at a certain time over a day with each PV penetration level.

The uncertainties in both placement (5 to 105 households with 5 incremented households) and sizing (100 Wp to 500 Wp with 100 Wp increments) are considered to be integrated into the optimal AC microgrid. In the second scenario, we consider the worst case (i.e., lowest difference of the PV production and load consumption) by using Monte Carlo simulation over 3,000 samplings. The histogram of the PV peak power integration into the microgrid in terms of voltage deviation, unbalanced voltage factor (i.e., 2%) [26], and maximum current is shown in Figures 13 to 15, respectively. No problems with voltage (i.e., voltage deviation and unbalanced factor) and current occur under the proposed uncertainties.

5. Conclusion and Future Work

The optimal AC microgrid topology with the integration of PV for electrification of a rural village is provided based on a comparison of different proposed concepts. The shortest radial topology of the microgrid is determined using the SP algorithm. Two different concepts–phase sequence and combined first-fit bin packing with phase swapping–are used to search for load balancing improvement. The two concepts are compared considering the energy use to determine the best solution. The impact of uncertainties of PV on both placement and sizing integrated into the optimal microgrid is studied by using the Monte Carlo method. The AC microgrid topology with three-phase diagrams is automatically visualized with different colors. A novel method needs to be developed for comparison with the existing methods to cope with the optimal microgrid topology designs. The integration of different types of renewable energy sources and energy storage will be considered in future work.

References

[1] V. Vai, PhD Thesis, Grenoble Alpes University, 2017.

[2] K.V. Khatsevskiy, A.I. Antonov, V.F. Khatsevskiy, Dynamics of Systems, Mechanisms and Machines (Dynamics), 2017, p.1-6.

[3] S. Leschenko, International Conference on Electrical Power Quality and Utilisation, 2011, p.1.

[4] V. Kumar, R. Krishan, Y. Sood, Int. J. Electron. Electr. Eng. 1/3 (2013) 182.

[5] N.G. Boulaxis, S. Member, M. Papadopoulos, IEEE Trans. Power Deliv. 17/1 (2002) 242.

[6] V. Gouin, M.-C. Alvarez-Herault, B. Raison, International Conference on Electricity Distribution, 2015, p.1.

[7] M. Granada Echeverri, R. Gallego Rendón, J.M. López Lezama, Ing. Cienc. 8/15 (2012) 121.

[8] J. Zhu, M.Y. Chow, F. Zhang, IEEE Trans. Power Syst. 13/4 (1998) 1487.

[9] H.M. Khodr, I.J. Zerpa, P.M. Deoliveirade Jesus, and Manuel A. Matos, IEEE/PES Transmission & Distribution Conference and Exposition: Latin America, 2006, p.1.

[10] J. Zhu, G. Bilbro, M. Y. Chow, IEEE Trans. Power Syst. 14/4 (1999) 1508.

[11] V. Vai, E. Gladkikh, M.-C. Alvarez-Herault, B. Raison, L. Bun, International Electrical Engineering Congress, 2017, p.1.

[12] V. Vai, E. Gladkikh, M.-C. Alvarez-Herault, B. Raison, L. Bun, IEEE International Conference on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe, 2017, p.1.

[13] V. Vai, L. Bun, K. Khon, M.-C. Alvarez-Herault, B. Raison, The 46th Annual Conference of the IEEE Industrial Electronics Society, 2020, p.1602.

[14] N. Toma, O. Ivanov, B. Neagu, M. Gavrila, IEEE International Conference and Exposition on Electrical and Power Engineering, 2018, p.857.

[15] O. Ivanov, B.-C. Neagu, M. Gavrilas, G. Grigoras, C.-V. Sfintes, IEEE International Conference on Electromechanical and Energy Systems, 2019, p.1.

[16] M.J. Khan, A.K. Yadav, L. Mathew, Renew. Sustain. Energy Rev. 76 (2017) 577.

[17] A. Bianchini, N. Magnelli, G. Ferrara, E.A. Carnevale, L. Ferrari, 81 (2015) 133.

[18] N. Ghorbani, A. Kasaeian, A. Toopshekan, L. Bahrami, A. Maghami, Energy 154 (2017) 581.

[19] A. Maleki, Int. J. Low-Carbon Technol. 13 (2018) 140.

[20] M.A.M. Ramli, H.R.E.H. Bouchekara, A.S. Alghamdi, 121 (2018) 400.

[21] S. Yilmaz, F. Dincer, Renew. Sustain. Energy Rev. 77 (2017) 344.

[22] M. Loebl, Discrete Mathematics in Statistical Pysics, Vieweg+Teubner, 2010, p.13.

[23] V. Vai, L. Bun, H. Ohgaki, Int. J. Adv. Sci. Eng. Inf. Tech. 10/6 (2020) 2458.

[24] R.M. Ciric, A.P. Feltrin, L.F. Ochoa, IEEE Trans. Power Syst. 18/4 (2003) 1283.

[25] P. Pillay, M. Manyage, IEEE Power Eng. Rev. 21/5 (2001) 49.