Optimal Low-voltage Distribution Topology with Integration of PV and Storage for Rural Electrification in Developing Countries: A Case Study of Cambodia

Vannak Vai, Marie-Cecile Alvarez-Herault, *Member*, *IEEE*, Bertrand Raison, *Senior Member*, *IEEE*, and Long Bun

***Abstract*—This paper addresses an optimal design of low-voltage (LV) distribution network for rural electrification considering photovoltaic (PV) and battery energy storage (BES). It aims at searching for an optimal topology of an LV distribution system as well as the siting and sizing of PV and storage over a time horizon of 30 years. Firstly, the shortest-path algorithm (SPA) and first-fit bin-packing algorithm (FFBPA) are used to search for the optimal radial topology that minimizes the total length of the distribution line and improves the load balancing. Then, the optimal siting of decentralized BES (DeBES) is determined using a genetic algorithm (GA) to eliminate the undervoltage constraints due to the load consumption. Two iterative techniques are elaborated to size the maximum peak power of PV and the minimum number of DeBES that can be connected to an LV network without violating the voltage and current constraints. Then, the sizing strategy of centralized BES (CeBES) is developed to avoid reverse power flows into the medium-voltage (MV) network. Finally, a Monte Carlo approach is used to study the impact of load profile uncertainties on the topology. A non-electrified village in Cambodia has been chosen as a case study.**

***Index Terms*—Battery energy storage (BES), low-voltage (LV) distribution network, Monte Carlo, photovoltaic (PV), electrification, planning.**

I. Introduction

MORE than 80% of people are living in rural villages in Cambodia, and about 75% of the villages are currently non-electrified [1]. The Royal Government of Cambodia has created a policy to electrify the whole country by 2020 and to ensure a minimum level of power quality for at least 70% of consumers by 2030 [2]. Moreover, Cambodia has encouraged the development of local productions based on renewable energies in order to reduce the energy import from neighboring countries [2], which represents about 25% of the total generation [3]. Also, many people living in non-electrified villages are currently investing in small-scale PV generations connected to the low-voltage (LV) grid in Cambodia. These small generation units will influence future planning decisions in the LV distribution networks due to the reverse power flows injected into the medium-voltage (MV)/LV substations. In order to address these electrification issues, an innovative method is proposed in this paper for the development of a distribution grid in which the distribution system operator (DSO) will invest in local productions and storage in order to reduce the global cost of the system infrastructure such as lines and transformers.

The LV distribution network is evolving towards a microgrid, i.e., a small-size LV network which is autonomous during some moments of the year and can be disconnected depending on the need of the main grid. The microgrid development for the electrification of territories has already been addressed in the literature. Their designs mainly include the optimization of the system components and operation strategies. To deal with the problem of the topology design, [4]-[6] studied the optimal topology in an LV distribution network by using mixed-integer quadratically-constrained optimization. This method was applied for an urban zone by considering load demand uncertainty. The optimization of the distribution system was investigated to search for the minimal investment using the path search algorithm [7]. Reference [8] used dynamic programming to get the optimal radial system. Also, the optimization of an urban distribution system integrating the topology of the streets was proposed in [9], which is in terms of adapted simulated annealing and Dijkstra algorithms. However, these works usually focused on MV balanced distribution systems, whereas this paper focuses on the LV networks which have additional constraints. Firstly, they are unbalanced due to the presence of both four-wire feeders (three phases plus neutral) and two-wire feeders

Manuscript received: March 9, 2019; accepted: July 9, 2019. Date of CrossCheck: July 9, 2019. Date of online publication: April 29, 2020.

This work was supported in part by the French Government Scholarship (BGF) and the Grenoble Electrical Engineering Laboratory (G2Elab).

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DOI: 10.35833/MPCE.2019.000141

(phase plus neutral). Secondly, at this level, there is no profusion phenomenon. It can be considered that all the maximums occur at the same time. In addition, the integration of distributed energy resources (DERs) such as renewable productions and storage are not considered.

Regarding research papers on LV networks, [10] investigated the reduction of losses in distribution systems due to an optimal phase balancing algorithm using mixed-integer non-linear programming (MINLP). This method reduced the current flow through the lines and improved the voltage unbalancing factor. Also, the mixed-integer algorithm [11], the mixed-integer linear programming (MILP) [12], and the simulated annealing algorithm [13] were proposed for phase swapping of connected loads in order to decrease the losses in the distribution system. Nonetheless, these studies only focused on the phase balancing of the existing radial topology.

The design of microgrid was studied as isolated systems in some works. The hybrid system of diesel-PV battery with an associated control strategy was examined in [14], and the optimal sizing of the hybrid system was provided in [15]. Some tools were developed to assess the technical and economic analysis for rural electrification projects integrating diesel units and batteries. These tools were applied for some case studies in countries along the Mekong river [16], [17]. However, they aimed at creating isolated microgrids unconnected to the main grid. Reference [16] studied the increase of the PV hosting capacity with two strategies, i.e., on load-tap changer (OLTC) and grid-reinforcement, including the use of information and communication technologies (ICTs). The high penetration of PV was studied in [17] where production curtailment and reactive power dispatch were proposed to elude the problem of over-voltages.

Numerous studies were conducted for the design of microgrids connected to the main grid by integrating PV and storage [18]-[23]. Reference [18] investigated the use of ICT to regulate the voltage. The OLTC and back-to-back converters were employed for the centralized voltage control in this work. Also, the impact of rooftop PV generation integrated into a balanced LV network was provided in [19] - [21]. These works illustrated the impact of high penetration of PV on the voltage profile. Likewise, [22] and [23] studied the alleviation of the voltage rise due to rooftop solar panels. The use of PV/battery energy storage (BES) at each node with its control strategies was investigated. Similarly, the decentralized storage strategy with PV as well as its management was studied in [24], which was used for preventing over-voltage. Under-voltage and over-voltage control with ICT was presented by using the storage [25]-[27] as well as OLTC in [28], [29]. The control of battery storage was studied [30] to improve the hosting capacity of PVs through a centralized control method with an analysis of the voltage sensitivity in a balanced system. The integration of PV and storage in the LV distribution network was studied for rural [31] and urban [4] areas by finding a siting and sizing of PV/BES. The authors considered that the storage with centralized control installed at the end-user is the optimal location. Nevertheless, these research works investigated solutions requiring heavy ICT investments and did not take into account the siting, sizing and investment costs of microgrid development for countries where high investments are not feasible.

It is mandatory to study an alternative planning methodology with small-scale production integrated into the LV distribution networks compared to the traditional planning based on technical and economic considerations. This paper proposes the design and control of an LV distribution network integrating PV panels and battery storage to challenge the current electrification issues in Cambodia. An optimal radial topology will be proposed by applying the shortest-path algorithm (SPA) with the first-fit bin-packing algorithm (FFBPA) in order to minimize the costs and optimize the phase balancing. Then PVs and batteries will be sized and controlled to solve over-voltage and under-voltage problems preventing the DSO from over-sizing the network. The penetration of PV production will be maximized to avoid over-voltage problems, and decentralized storage is employed to remove under-voltage problems. Centralized battery storage will be installed at the MV/LV transformer in order to eliminate the reverse power flows that may occur and lead to potential over-loading of the MV network. This design of LV distribution network could be isolated from the main grid at some moments of the year, enabling a reduction of the investments in the MV network such as MV/LV substation and power loss reductions.

The novelty and contributions of this paper are as follows:

1) Provide a planning tool of distribution system integrating PV and storage for DSO, for countries similar to Cambodia.

2) Give a general methodology in order to build a microgrid in non-electrified countries, from the building of the lines to the siting and sizing of PV and storage units.

3) Develop simple operation rules of LV distribution network without a huge deployment of ICTs which integrate the uncertainties into loads and productions.

The characteristics of the developed distribution system will be the followings:

1) Maximize the autonomy of LV network to make it less dependent on the MV network with PV and storage.

2) Decrease the sizing of MV/LV equipment to reduce the network costs, e.g., MV/LV substation and power losses.

3) Increase the local production based on renewable energies while satisfying current and voltage constraints.

The remainder of this paper is organized as follows. The general methodology of the LV distribution network planning including the explanation of the algorithms is detailed in Section II. Section III describes a case study of a real non-electrified village in Cambodia including the simulation results. Section IV describes the comparison between traditional and novel planning methods. Section V presents the main conclusions and future perspectives.

II. Planning Methodology

In industrialized countries, the MV network is quite robust with a fast backup process in case of a fault, which is not the case in developing countries. The MV network might experience a power outage, which potentially leads to frequent blackouts in LV networks even if their system components have been properly sized. Thus, we propose to design LV microgrids that rarely depend on MV networks. The proposed strategy is that the DSO invests in the PV and storage systems. Figure 1 presents four stages of the proposed method, which includes:

1) Build the optimal radial topology design to ensure the load balancing and to minimize the total length of lines.
2) Find the maximum penetration of PV peak power without violating current or voltage constraints.
3) Optimally sit and size the decentralized BES (DeBES).
4) Optimally size the centralized BES (CeBES).

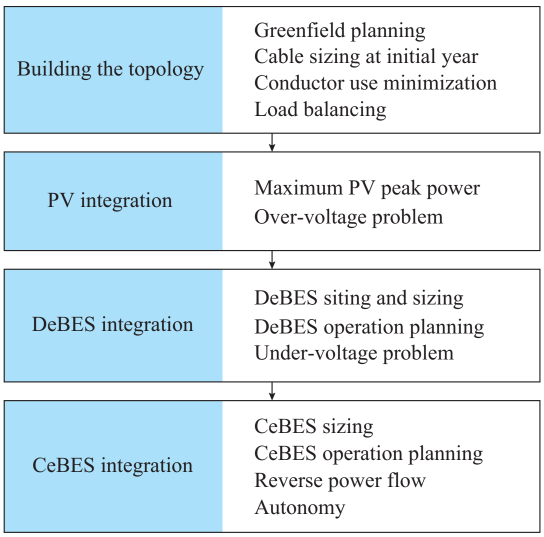

Fig. 1. Stages of novel planning method.

A. Building Topology

The LV network in Cambodia comprises of single-phase and 3-phase LV feeders for a 3-phase MV/LV transformer to several single-phase poles where LV customers are connected. In this subsection, an LV topology is planned for a non-electrified area by minimizing the total length of the distribution line and optimizing the load balance. To achieve this objective, the SPA and FFBPA algorithms are used. Based on graph theory, the problem of SPA is to search the path between two vertices in a graph in order to minimize the sum of the length of its segments. The problem of FFBPA is filling all pieces into a well-defined number of bins, while minimizing the total weight difference for each bin. In this paper, the pieces are load demand, i.e., active and reactive power, and phases of the power system correspond to bins. Firstly, the SPA is started to search for the nearest pole to which the load is connected, and then the FFBPA is applied to balance the power of the connected loads for each phase. Also, this method has been chosen because LV networks are short and simple (houses along roads), so classical algorithms from graph theory are well suited.

B. PV Integration

For this primary study in Cambodia, the renewable sources considered are PV, which have the highest potential in Cambodia. In the microgrid, the DSO is able to choose the location of the PV. The operation cost of a distribution system depends on power flows. The closer the generation and consumption are, the smaller the line losses will be. Hence, it is assumed that PV installation is located near high-consumption loads. The objective of this step is to determine the maximum peak power of PV that could be connected to the distribution system without violating the voltage and current constraints. Figure 2 presents the iterative algorithm implemented for that purpose, where I_{linepv} is line current from PV node; P_{pv} is the power of PV; N is the maximum number of iterations; PV_{peak} is the maximum power of PV; PV_{save} is the recoding vale of PV power; V_{pv} is the voltage at PV node; V_{limit}, I_{limit} are the voltage and current limits, respectively; ΔP_O is the increment power; and $V_{tolerance}$, $I_{tolerance}$ are the tolerances on the test for voltage and current, respectively.

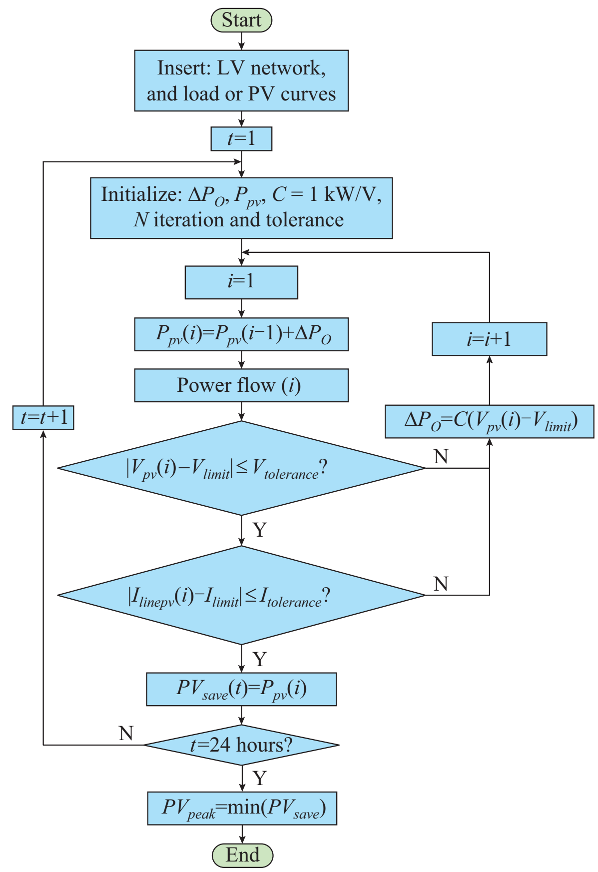

Fig. 2. Flowchart of maximum power of PV.

At the beginning, we input the network data such as the locations of MV/LV transformer and consumer, the line parameters, and the daily PV/load curves. Next, PVs are located at the customer side whose peak power is the highest. For every hour of the day, the PV power is incremented until an over-voltage, i.e., V_{max}=1.06 p.u., and/or an over-current appear. The highest penetration of PVs in the network is the smallest of the highest value, which is computed every hour.

C. Integration of DeBES

The problem of under-voltage almost always appears at the farthest household without/with the PV. Actually, the highest consumption generally happens when the production of PV is low, i.e., non-synchronized PV-load profile. Thus, the case of under-voltage constraint is not different without or with PV. The DeBES is placed in the network to eliminate the under-voltage constraint. Nevertheless, the integrated DeBES at the farthest household is not always the best place, especially if a producer is connected here. There are several techniques, e.g., particle swarm optimization (PSO), differential evolution (DE), GA, suitable for the siting and sizing problem of DeBES. The GA has been selected in this work because the computation time is shorter [32], [33], especially for mixed-integer problems with non-linear objectives and constraints. The GA here has been used to find the best DeBES location and power that can minimize the injected active power respected to voltage and current constraints at 7 p.m. (peak load) while the PV generation is not available. The objective function is expressed as:

$$\min Pbes_k^{\alpha}(t) \tag{1}$$

where $Pbes_k^{\alpha}(t)$ is the power injection of the battery for phase α at the k^{th} bus at t.

The objective function (1) is subject to the following constraints, i.e., voltage regulation of [–10%, 6%] [34]:

$$0.9 \leq V_{limit} \leq 1.06 \tag{2}$$

$$I_{line} \leq I_{limit} \tag{3}$$

where I_{line} is the line current.

Moreover, the fitness function for a given node p is defined as the sum of the objective and penalties of over-voltages, under-voltage and over-current. The value of the fitness function f for a given node p at t is expressed as:

$$f(p,t) = Pbes_k^{\alpha}(t) + C_1\delta_1 + C_2\delta_2 \tag{4}$$

where $\delta_1 = \max(0,\ I_{line} - I_{limit})$; $C_1 = 10^5$ is the penalty coefficient applied if the current is beyond the allowable line capacity I_{limit}; $\delta_2 = \max(0.9 - V_{node}, 0) + \max(V_{node} - 1.06,\ 0)$, and V_{node} is the voltage of the node; $C_2 = 10^5$ is the penalty coefficient if the voltage does not respect the permitted range; and δ_1, δ_2 are the coefficients of voltage and current constraints, respectively.

The penalty coefficients are used to measure the constrained violation. With numerous simulations, the adjustment parameters of the algorithm have been well-defined as a compromise between convergence and simulation time.

Once the location is obtained, the minimum DeBES capacity connected to the LV distribution network has to be computed to solve the problem of under-voltage. Firstly, as for PV in Fig. 2, the minimum charging and discharging of the DeBES have been found over 24 hours. The voltage at the node where the battery is connected remains equal to a fixed reference V_{set}. In Fig. 2, PV (the reference voltage V_{set}) is replaced by DeBES (the maximum voltage $V_{\max}$). In addition, the capacity of this DeBES will be extended to 25% larger to fulfill the minimum (20%) and maximum (95%) state of charge (SOC) of the battery to optimize its lifespan duration [35]. Finally, the capacity of DeBES results from the sum of the discharge values as expressed by (5).

$$C_{DeBES} = \sum_{t=1}^{24} \min(0,\ Pbes_k^{\alpha}(t)) \tag{5}$$

The maximum injected power by this battery has been calculated at 7 p.m. when the worst under-voltage constraint occurs. This reference voltage is estimated using a load flow at 7 p.m. considering the minimum discharging power of the battery, with which a constraint of under-voltage will occur in the system.

We propose a decentralized control strategy to manage the DeBES without expanding a large ICT network and devices. The DeBES will start to operate at 10 a.m. due to high PV generation and low consumption, as shown in Fig. 3. The simplest measurement of the voltage value at the connection node of the DeBES will be used to manage the charging/discharging for that battery storage, providing that the SOC stays between the minimum state of SOC $SOC_{\min}$ and the maximum state of SOC $SOC_{\max}$.

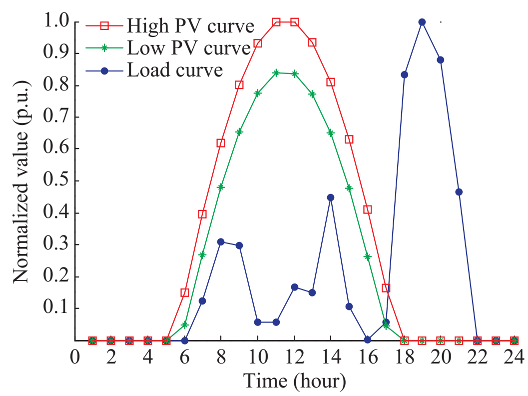

Fig. 3. Normalized daily PV/load curves.

D. Integration of CeBES

The CeBES is installed to store energy when reversed power goes from the LV network to the MV network, and to discharge when the network has to supply the LV consumers. It ensures that the SOC of the battery stays between $SOC_{\min}$ and $SOC_{\max}$. The power is measured at the MV/LV transformer every hour. With a positive value, the battery storage will be discharged if the SOC of the battery storage remains inside the allowable boundaries. Otherwise, the battery storage will be charged. Such management aims to prioritize the use of the CeBES instead of the MV network.

E. Cost Computation

The discount cost method is used in this paper to assess different proposed strategies over N planning years. Capital expenditure (CAPEX) and operation expenditure (OPEX) for energy losses of the LV network have been taken into account in this method. The discount cost [36] is formulated by:

$$C_{discount} = \sum_{t=0}^{N} \frac{C_{invest}(t) + C_{elect} \cdot EN_{loss}(t)}{(1+i)^t} \tag{6}$$

where $C_{discount}$ is the total discount cost; $C_{invest}(t)$ is the cost of investment for year t; C_{elect} is the cost of electricity; $EN_{loss}(t)$ is the energy losses for year t; and i is the discount rate.

In addition, the DSO invests in PV/BES, so the investment of PV/BES has to be integrated into this discount cost.

The reduction of the energy consumed due to the CeBES is also considered in the discount cost. Consequently, the energy losses in (6) have been replaced by the energy used by households and energy losses. Thus, the total discount cost of the system can be formulated as:

$$C_{discount} = \sum_{t=0}^{N} \frac{C_{invest}(t) + C_{elect} \cdot EN_{use}(t)}{(1+i)^t} \quad (7)$$

where $EN_{use}(t)$ is the energy used for year t.

III. Real Case Study: A Cambodian Village

A. Description of Case Study

A non-electrified village in a rural area, located in Khum Sandek, Srok Batheay, Khet Kampong Cham, Cambodia, has been chosen as a case study in this paper, and PV is available in this area. There are 129 single-phase households located along the sides of the way. The consumers are powered by a 22 kV/0.4 kV substation. The active power P_{active} of the network is about 43 kW with a power factor of 0.95 at the initial planning year. The maximum power of each consumer has been randomly generated following a normal distribution with a mean of 0.4 kW and a standard deviation of 0.05 kW because of no available information. For rural villages, typical conductor is 50 mm^2 for main feeders and 4 mm^2 for every consumer to the electrical pole in Cambodia.

B. Input Parameters

Some input parameters are listed in Table I. The planning study is 30 years, which is a typical time horizon. Over this duration, the uncertainties are too high to draw realistic conclusions. Three single-phase PV units per phase, i.e., 9 PV units in total, have been assumed because it represents about 10% of the total households of the network. It is the mean value of households equipped with a solar home system (SHS). Only one DeBES per phase has been considered to minimize the investment cost. Also, a high growing rate of 3% has been chosen since Cambodia is a developing country. Load profiles are built based on real measurements and considering ±5% uncertainties. Moreover, as real data of solar radiation are presently not available, the National Aeronautics and Space Administrations (NASA) data [37] have been selected in this paper.

TABLE I
INPUT PARAMETERS

Input parameter	Studied case
Planning study	30 years
Load growth	3 %
Load profile uncertainty	±5%
Load curve	Local measurements
PV curve	NASA [37]
Number of PV	9 units (3 per phase)
Number of DeBES	3 units (1 per phase)

A normalized daily load curve is an average load profile taken from local measurements of three households. A PV curve taken from NASA is given in Fig. 3. A one-year simulation is performed with the same normalized load curve. This assumption is realistic since the customers do not use electric heaters, thus the electrical devices are used in the same way during the year.

We decide to place 3 PV units per phase where customers have the highest consumption to optimize the self-consumption. Typically, PV units are connected in single-phase up to 5 kW [38]. The total PV penetration can vary between 0 to 45 kW, i.e., about 105% of the consumption.

Furthermore, the parameters taken for the economic study are listed in Table II.

TABLE II
INPUT PARAMETERS FOR ECONOMIC STUDY IN SANDEK

Item	Capital and replacement	Operation and maintenance per year	Lifetime (year)
Discounted rate	12% [37]		
Cost of electricity	0.5 $/kWh [3]		
Cost of ABC-4×50 mm^2	3200 $/km [5]	50 $/km	40 [39]
Cost of ABC-4×150 mm^2	8200 $/km [5]	50 $/km	40 [39]
PV cost	1200 $/kW	10 $	25 [40]
Battery cost	158 $/kWh	10 $ [40]	5 [41]
Degradation cost		3 $/kWh [42]	
Inverter cost	500 $/kW	10 $	15 [40]

C. Simulation Results

1) Optimal Radial Topology

An optimal radial topology of the LV network is obtained using the SPA/FFBPA algorithms. An optimal radial balanced topology is presented in Fig. 4, where P_a=13.9 kW, P_b=14.3 kW and P_c=14.7 kW with the total consumption $P_{a,b,c}$ on phase A, B or C.

2) Maximum Peak Power of PV

The size of the nine PVs and the phase where they have been connected to the network are listed in Table III. Then, three PV inverters of 3.0 kW, 3.6 kW, and 4.0 kW are used with 90% [43] efficiency.

3) Siting and Sizing of DeBES

By applying the algorithms described in Section II-C, the optimal siting of DeBES is found and the maximum power is set to the minimum power discharged at 7 p.m. to avoid the constraint of under-voltage. The parameters of the GA are as follows: the number of individuals is 150, and the number of generations is 300. This algorithm is integrated into a Monte Carlo simulation to estimate the average V_{set} of each DeBES, as depicted in Fig. 5. Thus, V_{set} for each DeBES is 0.93 p.u., 0.92 p.u., and 0.93 p.u., respectively.
Also, the operation of the DeBES without the use of ICTs and only with a voltage sensor is shown in Fig. 6 for phase A. Furthermore, the capacity of the DeBES is set by the sum of the discharged power from 6 p.m. to 9 p.m. and is upgraded by 25%, i.e., 20% for $SOC_{\min}$ and 95% for $SOC_{\max}$, to prevent the battery against utmost operation conditions.

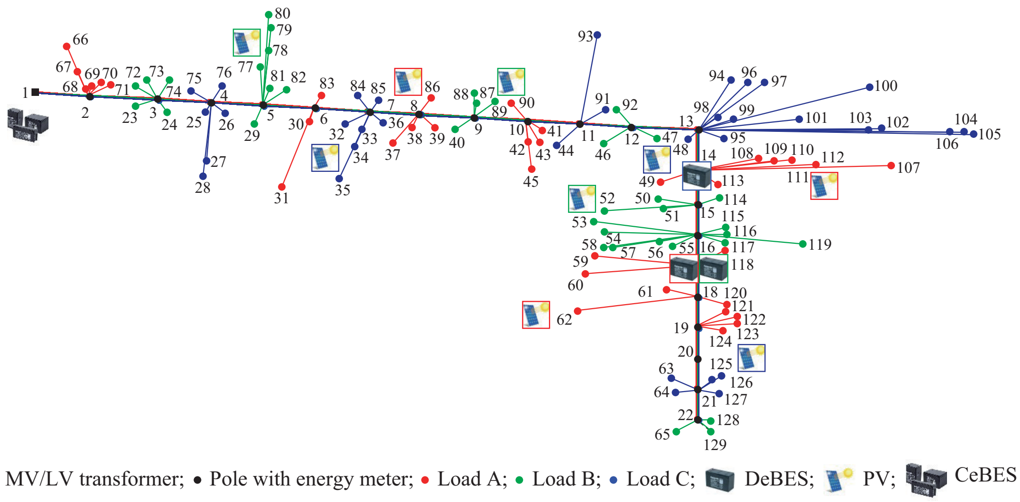

Fig. 4. Optimal topology including integrated PV/DeBES/CeBES in Cambodia.

TABLE III
SIMULATION RESULTS OF MAXIMUM PV PEAK POWER

Phase	Households with PV	Sizing (kWp)
A	62nd, 86th, 111th	2.40
B	52nd, 77th, 89th	3.28
C	32nd, 48th, 125th	3.06

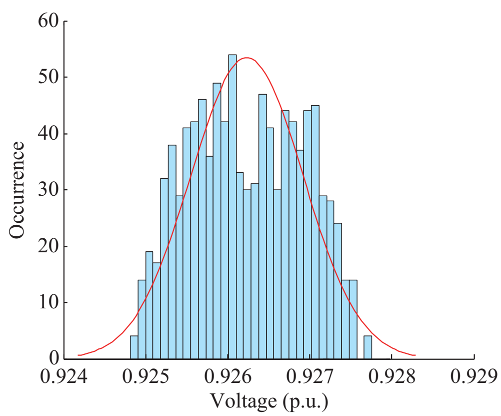

Fig. 5. V_{set} for DeBES of phase A at the end of planning period.

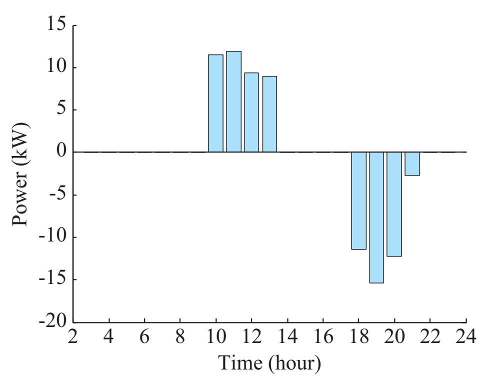

Fig. 6. Operation for DeBES of phase A at the end of planning year.

Thus, the size for each DeBES is 54.9 kWh, 48.8 kWh and 63 kWh, respectively. Their bi-directional inverters will be 18 kW, 18 kW and 20 kW with 90% efficiency [43], respectively.

4) Sizing of CeBES

According to the strategy described in Section II-D, the capacity of the CeBES is 162 kWh with a bi-directional inverter of 50 kW with 90% [43] efficiency.

As a result, the network can be operated as an isolated microgrid with an autonomy of 91% for the initial year and 52% at the end of the planning studies due to the growth of load demand.

IV. COMPARISON WITH TRADITIONAL MV PLANNING APPLIED TO LV PLANNING

A. Principles of MV Planning

The traditional planning of developed countries aims to supply all the consumers at the lowest cost with high service quality. This method sizes the system so that it can supply the load at the end of the equipment life (about 30 years) to avoid multiple investments. And large section cables need to be used in the method.

Table IV provides the minimum voltage and maximum current in the network as a function of cables currently used in Cambodia at 7 p.m. when the peak load appears for the last planning year. It can be concluded that the section used in the network must be 150 mm^2 to avoid under-voltage and over-current.

TABLE IV
MINIMUM VOLTAGE AND MAXIMUM CURRENT OF SEVERAL CABLE TYPES

Cable-ABC-overhead (mm^2)	Minimum voltage (p.u.)	Maximum current (%)	Decision
4×70	0.81	106.49	No
4×95	0.86	83.96	No
4×150	0.91	63.86	Yes

B. Impact of Uncertainties of Load Curve

As V_{set} for each DeBES has been statistically estimated, the values can be used as voltage references for the decentralized control considering the load curve uncertainty. Figures 7 and 8 present the histograms of daily minimum voltage with the decentralized control of DeBES for 1000 samplings of 50 mm^2 cable section of load curves. A ±5% uncertainty is considered, which occurs in the whole LV network without and with the integrated DeBES for phase A, respectively.

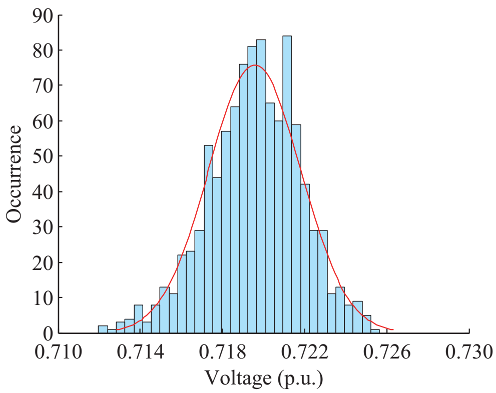

Fig. 7. Histogram of minimum voltage of network without DeBES for phase A at the end of planning year for 1000 samplings.

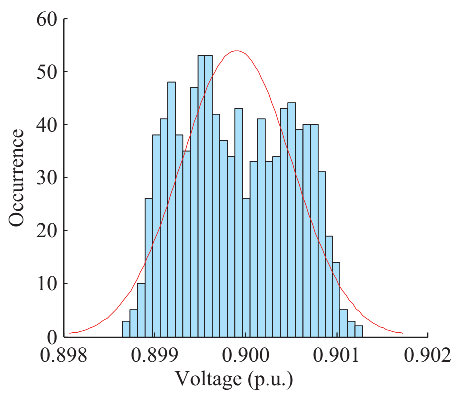

Fig. 8. Histogram of minimum voltage of network with DeBES for phase A at the end of planning year for 1000 samplings.

Note that the problem of under-voltage is absolutely eliminated by connecting the DeBES according to a selection of V_{set}. Hence, it can be concluded that this decentralized control without ICT infrastructure is suitable to solve under-voltage problems.

C. Cost Comparison

In this subsection, over the planning period of 30 years, the cumulative discount costs of the two different planning methods are depicted in Fig. 9.

The traditional planning solution is less expensive at the beginning because the CAPEX is lower than the novel planning solution. However, at year 12, the trend of the cumulative discount cost is reversed. The novel planning solution becomes more economical since the OPEX is always less expensive than the traditional planning solution. In the novel planning curve, we can see some discontinuities at years 5, 10, 15, 20 and 25 in comparison with the traditional planning curve. They are caused by additional investments for BES systems (every 5 years), inverters (every 15 years) and PV system (every 25 years). Thus, it can be concluded that the proposed solution is more economical than the traditional one.

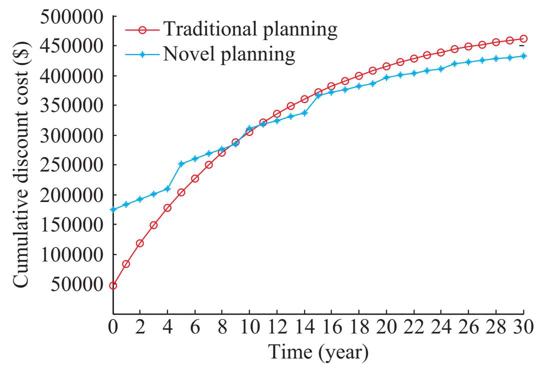

Fig. 9. Cumulative discount cost of two planning methods over 30 years.

D. Performance Indicators

The integration of PV/BES makes it possible to reduce the peak power flow coming from the MV network to supply loads at the end of the planning year from 116 kW to 94 kW, representing a reduction of about 19% as shown in Table V. Then, it is possible to size a smaller MV/LV transformer and reduce the section of the upstream MV distribution lines. The energy used per year is also reduced from 202 MWh to 146 MWh. Moreover, the autonomous operation of the system increases from 37 % to 52%, which corresponds to the situation when the consumption is equal to 0.

TABLE V
PERFORMANCE INDICATORS OF LV DISTRIBUTION

Parameter	Traditional planning at year 30	Novel planning at year 30
Active power from grid (kW)	116.94	94.60
Energy used (MWh/year)	202.50	146.83
Autonomous time (%/year)	37.5	52.53
Renewable penetration (%)	0	61

V. CONCLUSION

In this paper, a novel planning methodology for microgrid development has been studied for non-electrified areas of rural villages. The algorithm enables to find the optimal radial topology of LV distribution network as well as the siting and sizing of solar panels and batteries. The SPA and FFBPA have been applied to search for the optimal radial topology to ensure the load balancing. The maximum amount of installed PV has been determined considering the constraints of current and voltage. Besides, the siting and sizing of both decentralized and centralized BES systems have been carried out to resolve the problem of under-voltage and decrease the sizing of the MV/LV transformer. The integrated solar and battery storage into LV networks would be less expensive than that with traditional planning solutions for developing countries. Other benefits can be obtained such as the increasing autonomous operation of the network and the removal of reverse power flows. Additionally, the impact of the voltage reference values for the control of the decentralized BES has been investigated using Monte Carlo approach to consider the uncertainties of the load curve during the planning. A ±5% slight variation in the case study does not have an undesirable impact on the system.

Further works could investigate the use of wind turbines as they have high potential in mountainous and coastal regions of Cambodia. A comparison of several optimization techniques by considering the indicators such as the computation time and the accuracy will also be studied. The efficiency of the algorithms could be assessed by comparing the results obtained from other results of commercial software such as DIgSILENT PowerFactory. Finally, the development of models to tackle the intermittent behavior of both load demand and distributed generation will be investigated.

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