Optimal Topology with Improved Phase Balancing and PV Hosting Capacity in a Low Voltage Distribution System

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***Abstract*—There are many technical problems in Low-Voltage (LV) distribution systems caused by grid infrastructure and system operators. Phase unbalance is one of the major problems that can result in increasing the voltage drop, energy loss, heating the equipment, and reducing system capacity. Due to load variation, this becomes a difficult task to balance the loads in the three phases of LV distribution systems throughout the time. In this paper, to find the optimal solution for phase balancing in the system, Mixed Integer Linear Programming (MILP) and load profile as the necessary data are applied for the proposed method. After implementing the technique based on the load profile, a new topology with a minimum unbalanced factor is obtained. Then, Photovoltaic Hosting Capacity (PVHC) is performed and validated with the improved topology. The stochastic method is applied to assess the PVHC with limiting factors such as overvoltage, line capacity and reverse power. The simulations are conducted with an interval of 10 min and include variable PV profiles, location, irradiance, and load profile. The load profile is based on survey data and generated by the bottom-up algorithm. Next, Volt-Var Control (VVC) and Battery Energy Storage (BES) are also investigated to enhance the PVHC. To validate the proposed method, the modified IEEE-116 test feeder is selected as the case study. The simulations show that comprising improved phase balancing, VVC, and BES operation can dramatically increase PV penetration without grid violations.**

***Index Terms*—mixed integer linear programming, phase balancing, bottom-up algorithm, PV hosting capacity, stochastic analysis, battery energy storage, optimization**

I. Introduction

In this century, electricity is very important to people as food and water. Because of economic and population growth, the world's electricity consumption is increasing dramatically. To fulfill human needs, many energy resources are extracted and converted into electrical energy. However, some energy resources such as coal, oil, and natural gas are the major contributors to greenhouse gas emissions. For this reason, renewable energy has become a crucial resource to produce energy for addressing environmental challenges. Solar energy is one of the alternative renewable energy resources with a high potential for electricity generation in Cambodia according to the Electricity Authority of Cambodia (EAC) [1]. Both owners and consumers are interested in installing PV in their systems to reduce energy consumption. However, a large amount of PV installation on the network can harm not only the technical but also the economic point of view. Therefore, knowing the maximum PVHC of a network will be beneficial for the owners and consumers in their PV installation decisions. In the LV distribution system, the three-phase power is mostly unbalanced due to the combination of three-phase and single-phase load connections along the network [2]. Furthermore, this unbalance can be caused by the behavior and activity of users, even if the type, quantity, and rated power consumption of all the user appliances are the same. An unbalanced system can result in a variety of effects on the system and electrical equipment. Moreover, it will increase the voltage drop, energy loss, heating, or even damage the equipment and reduce system capacity. Typically, the PV hosting capacity is determined by several factors such as overvoltage, reverse power, and line capacity. In this case, optimal phase balancing can be one of the other ways to improve system performance and also to increase PV penetration without violations.

Many researchers have studied to find the technique for optimal three-phase balancing in the distribution system. According to the authors in [2], the radial topology of the LV distribution system was constructed by a repeated phase sequence ABC for phase balancing purposes. In the paper [3], the authors have implemented the First Fit Bin Packing algorithm to find the load phase connection in the rural village. However, the authors have chosen only peak load as input data. According to the authors in [4] and [5], phase balancing has been implemented by Mixed-Integer Quadratic Programming (MIQP) and Genetic Algorithm (GA) with only peak time, respectively. In the study in reference [6], the authors proposed a metaheuristic approach to find the optimal phase balancing in LV distribution networks using a

Manuscript received March 1, 2024; revised May 17, 2024; accepted May 23, 2024.
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hybrid differential evolutionary particle swarm optimization (DEEPSO) algorithm for single-phase load allocation. Also, to perform phase balancing of the LV distribution system in Romania, GA was used as an optimization tool to minimize the active power losses over 24 h [7]. Furthermore, the results of [8] showed an optimal phase balancing by using MILP. However, in this study only a specific time was considered. The authors in [9] presented the technique to find the optimal phase balancing by using the smart metering system, the consumers' characteristics and the power load profile were integrated into smart meters. The study in [10] showed the design of a microgrid system by using the shortest path algorithm and First Fit Bin Packing to find the optimal connection between loads and phases. On the other hand, the study in [11] applied GA and the Water Cycle Algorithm (WCA) during the peak load to achieve the load and pole balancing.

For PV hosting capacity determination, several constraints are investigated such as reverse power, overvoltage, line, and transformer capacity. Typically, there is no unique solution or technique to find the PVHC as it depends on many input parameters. The type of grid, characteristics of the load, and the standard limits of the constraint can cause different HC [12]. However, Umoh *et al.* [13] have reviewed four commonly used methods for determining HC including deterministic, stochastic, time series and optimization methods. The deterministic method used the fixed location and size of the PV system to identify its impact on the grid [14]. This method is also used to determine the HC by considering the worst-case scenarios due to variable parameters [15]. The stochastic method is used to obtain the HC by taking into account uncertainties of PV size, location, number, and other variables [16–18]. In this method, the uncertainties are classified into two types such as epistemic and aleatory uncertainties [13]. Epistemic uncertainties are unknown variables due to a lack of information and aleatory uncertainties are unknown variables related to variations in PV power generation and load power consumption [18, 19]. On the other hand, the time series calculation method is an improvement of the deterministic method by using the actual data of PV and load power. Moreover, the actual or synthetic data is presented as a time series profile to determine the HC based on its variation. Chitacapa *et al*. [20] used the quasi-static time series analysis method considering scenarios of PV system penetration to capture its effects on LV distribution networks. Another method for determining HC is the optimization method. This method is generally applied to find the maximum PV integration within the constraints [13]. In one part of the studies in [21], the optimal PV base capacity to maximize the hosting capacity for PVs in an unbalanced distribution network was determined based on a heuristic optimization method.

In many research works, not only PV hosting assessment has been considered, but also the method to enhance it [22]. As previously mentioned, overvoltage is the most common index to limit the amount of PV penetration in the distribution system. There are several ways to mitigate overvoltage in LV distribution systems with high PV penetration. Reactive power control from a smart inverter is one of the effective ways to coordinate voltage violations. Aboshady *et al*. [23] used a smart inverter to limit active power and compensate reactive power for voltage improvement. Moreover, there are many control strategies for reactive power, including fixed power factor, volt-watt, volt-var, constant active current, and constant peak current based on the review [24]. Aboshady *et al*. [25] also used a reactive power control approach for PV inverters to control the injection and absorption of reactive power to solve the overvoltage problem and reduce the active power loss of the system.

Nowadays, BES is also an option for PVHC enhancement in the LV network. In Cambodia, excess power from the PV system is not encouraged to be injected into the Medium Voltage (MV) grid due to system instability. Most of the LV system in Cambodia is in conventional infrastructure, thus utilities need more time to modernize it before allowing power injection with limited capacity and preparing for a net metering policy in the near future. For this reason, BES is the best way to absorb the excess power from PV canceling the reversed power into the grid. The work in [26] applied the BES system by controlling the discharge/charging operation of the energy storage to maintain the rate of power output variation from PV or wind while voltage variations are within acceptable limits. According to the study [27], customers with high PV exports experienced large overvoltage, which could be resolved by the BES. In the reference [28], BES was used as the central storage with high PV penetration; the optimal BES sitting was determined for minimizing a voltage rise and network losses using multi-objective genetic algorithm optimization. Furthermore, Pompern *et al.* [29] studied the optimal placement and capacity of a battery energy storage system (BESS) in a distribution system integrated with PV and electric vehicles to minimize the installation, replacement operation, and maintenance costs of the BESS using metaheuristic algorithms.

According to the previous literature, it shows that there is still a need to study more on the technique to find the optimal phase balancing. Especially, not only considering the peak load time but also considering load variations to get more accuracy. In this paper, the optimal phase balancing is investigated and the MILP technique is applied to this method. Load profiles from all consumers are used as input data for phase balancing implementation. Three scenarios will be observed to find the best option for phase balancing in the test system. Moreover, PV hosting capacity will be studied in this work. Normally, knowing the HC level is very important for utilities and distribution system operators in terms of both technical constraints and financial impact. The stochastic analysis method is used to evaluate PVHC in this paper. PV and load profile are taken from historical data and modeling, respectively. The topology achieved by the phase balancing technique in the first study will be used as a test system for PVHC evaluation. Different scenarios are applied to observe the HC such as without control, inverter volt-var control, reverse power limit, and centralized battery energy storage.

This paper is organized as follows: Section II presents the method for phase balancing in the LV distribution system. In Section III, the PV hosting methodology is presented. Simulation results and discussion are presented in section IV. Section V is the conclusion.

II. METHODOLOGY

A. Phase Balancing in LV Distribution System

1) Load profile modeling

In this work, a load profile of each customer is generated using a bottom-up algorithm [30] and all the input data was collected from the real power consumption through the people interviewed in one village in Cambodia. The reason for this survey is to identify the impact of load profile in the real situation on the proposed method. The power consumption, quantity, frequency, and time of use of all electrical appliances were collected during the interview. The procedure of the bottom-up algorithm is illustrated in Fig. 1.

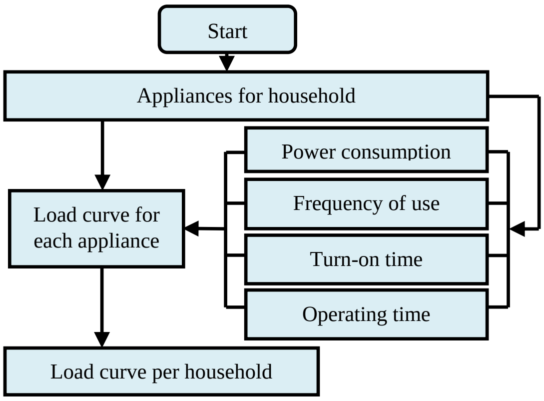

Fig. 1. Procedure of load profile simulation.

To generate the load profile of each household, the following necessary data and steps are needed for the mathematical model:

1) The electrical appliances in each household were informed by the owner during the survey. The different types of appliances will show the different patterns of each household.

2) The power consumption was determined by the type and size of the appliances. In this work, the power consumption of each appliance is based on its nameplate.

3) The used frequency indicates the number of utilizations of each appliance [31], and the turn-on and operating time represent the starting time and how long an appliance is operated, respectively. In this simulation, the normal distribution is used to estimate the turn on time of each appliance based on the deviation and average data from the interview with villagers. Otherwise, refrigerators and freezers are implemented with uniform distribution based on assumed information in [32]. Moreover, the uniform distribution is also applied to estimate the variation of washing machine use based on the minimum and maximum values from the survey. The frequency of use and operating time were estimated using a normal distribution based on the survey information

4) After getting all the inputs, a bottom-up algorithm is used to generate a load profile for each household by combining all the load curves of all appliances. Fig. 2 represents the daily load profile of one household in one village using the bottom-up algorithm.

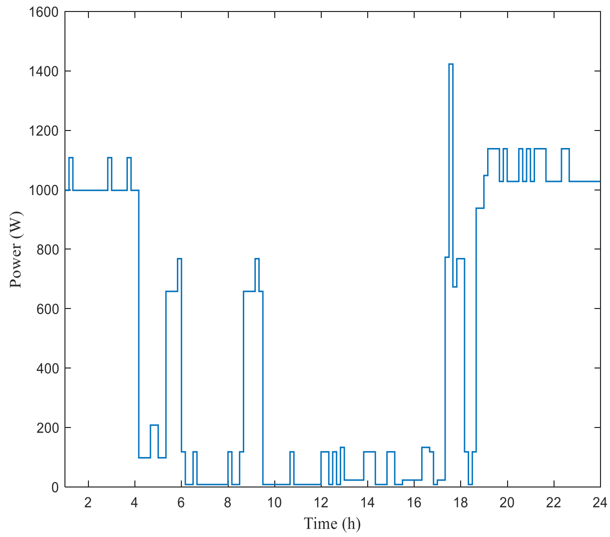

Fig. 2. Daily load profile of one household.

2) Load balancing technique

To minimize the unbalanced power ratio of each phase to the total load power, MILP is used in this work. Unlike other works, this proposed technique will define load connection to any phase of the electrical pole to achieve load balancing improvement throughout the time by employing the modeled load profile and there is no additional switching control to operate [33]. The most important information to apply this technique is the load profile characteristics of each customer to identify power consumption in each period.

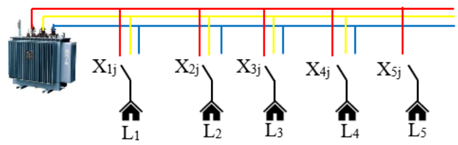

Fig. 3. Load connection to any phase by switch *X*.

Fig. 3 shows the load connection to any phase by switch X_{ij}. Thus, the total power of load L is the summation of all loads connected to the line by switches X_{ij}. X_{ij} represents the connection of switch i to phase j. The total load power consumption is illustrated below:

$$L_1X_{1j} + L_2X_{2j} + L_3X_{3j} + ... + L_nX_{nj} = L \quad (1)$$

$$X_{ij} \in \{0,1\} \quad (2)$$

In this work, all loads are considered to be single phase loads so one load can only connect to one phase. Where 1 indicates connection and 0 indicates no connection to the specified load. The summation of X_{ij} is determined by Eq. (3):

$$\sum_{j=1}^{3} X_{ij} = 1 \quad (3)$$

Normally, the ideal balanced phase means that the total load powers of each phase are equal or equal one-third of the total load power:

$$\alpha_1 L = \alpha_2 L = \alpha_3 L \tag{4}$$

$$\alpha_1 = \alpha_2 = \alpha_3 = \frac{1}{3} \tag{5}$$

where α_j is the fraction of the total load power. Actually, in the real operation α_j is not equal all the time due to the uncertainty of individual load demand. However, the summation of α_j every time still equals one as in Eq. (6). The total power consumption from the load is different all the time and it is shown in Eq. (7).

$$\sum_{j=1}^{3} \alpha_j = 1 \tag{6}$$

$$\sum_{j=1}^{n} L_{it} X_{ijt} = L_{jt} \tag{7}$$

To define which loads are connected to any phase, values of X_{ij} are needed and calculated to improve phase balancing in the system. The maximal function of the sum X_{ij} for all the load connections to phase j has been expressed as

$$\max\left(\sum_{j=1}^{3}\sum_{i=1}^{n} X_{ij}\right) \tag{8}$$

subject to

$$\sum_{i=1}^{n} L_{it} X_{ij} \le \alpha_j L_t \ , \ 0 \le t \le h, 1 \le j \le 3, X_{ij} \in \{0,1\} \tag{9}$$

$$\sum_{j=1}^{3} X_{ij} = 1 \tag{10}$$

where L_{it} represents the power from load i in time t, L_t is the total power from load in time t, α_j is the maximum percentage of the total power of phase j to total power during all periods, n *is* the number of loads, and h is the number of periods.

Eq. (9) shows that the total power of each phase has to be smaller than or equal to $\alpha_j L_t$. Normally, the total load power L_t varies every time interval due to different individual power load consumption, thus the connection between every load and every phase also changes if α_j is fixed to any value. The purpose of this work is to balance the loads of three phases and keep the same connections all the time. Therefore, the value of α_j has to change until getting the value of X_{ij} subjected to the constraint during the whole analysis time. In the ideal phase balancing, α_j has to equal 1/3. It is recommended that the minimum value of α_j should be 1/3. Actually, the value of X_{ij} depends on the value of α_j. In this way, Eq. (11) is used to define α_j in order to minimize the unbalanced factor throughout the analysis time.

$$\alpha_j = min\left(\sum_{j=1}^{3}\sum_{t=0}^{h}\left(\frac{1}{3} - \frac{L_{jt}}{L_t}\right)^2\right) \tag{11}$$

3) Simulation scenarios

Different scenarios have been described in this section to evaluate the proposed technique for phase balancing in the system.

- Scenario 1: Original phase connection

All load connections to each phase have been kept at their initial location.

- Scenario 2: Phase balancing based on peak load

In this scenario, one consumer is connected to any phase by following the procedure of the phase balancing technique. However, the only peak load of the individual user has been applied with the MILP method.

- Scenario 3: Phase Balancing Based on Load Profile

In this arrangement, the electrical poles have three single phases and one household has to connect only one phase of the electrical pole, as in Scenario 2. The difference is that all the phase connections between the electrical pole and households are defined by the proposed technique considering load variation for optimal phase balancing through all the time steps.

B. PV Hosting Capacity

1) Method for PV hosting capacity

Regarding to [34], the PV penetration level is determined by the ratio of peak PV power to peak load apparent power on the feeder:

$$\mathrm{PV_{Pentration}} = \frac{\mathrm{PV_{Peak}}}{S_{\mathrm{Peak}}} \times 100\% \tag{12}$$

However, the PV penetration level can be different depending on the method of determination. Normally, the optimization method is used to define the maximum PV hosting capacity after getting the optimal location and size of PV. In the real situation, this PV level is hard to achieve, since PV location and size are determined by a random process based on customer needs. The authors in [35], also used a multiple random variables process to estimate the failure rate of the transmission line from a low probability of occurrence, such as extreme weather or natural disasters. In this paper, the PV penetration level will be defined by a stochastic method with the uncertainty of PV location, size, and load profile in the test feeder without causing violations.

Typically, in radial LV distribution, undervoltage always occurs at the peak load time. As the PV system can reduce the load power consumption from the grid, the voltage amplitude will be improved as well. Conversely, if a large amount of PV is connected to the grid, it can cause overvoltage and overline capacity as well. Moreover, not only the amount of PV connection but also the location of PV can affect the HC calculation.

Currently, based on EAC regulation in Cambodia [36], PV grid-connected systems in LV systems are not encouraged to reverse power to the MV grid due to stability, security, and reliability problems. Thus, overvoltage, line capacity, and reverse power are considered as the factors limiting PV hosting capacity in this paper.

The proposed method to determine the PVHC is shown in Fig. 4. However, to keep it replicable and simple in the simulation process, some assumptions and definitions have been made.

- Load and PV profiles are based on real data in Cambodia.
- Define the maximum of scenario numbers N =1000

- The minimum and maximum of PV rated capacity are based on CB rated capacity of each consumer.
- Backward forward power flow is used to show output results for violation observation.

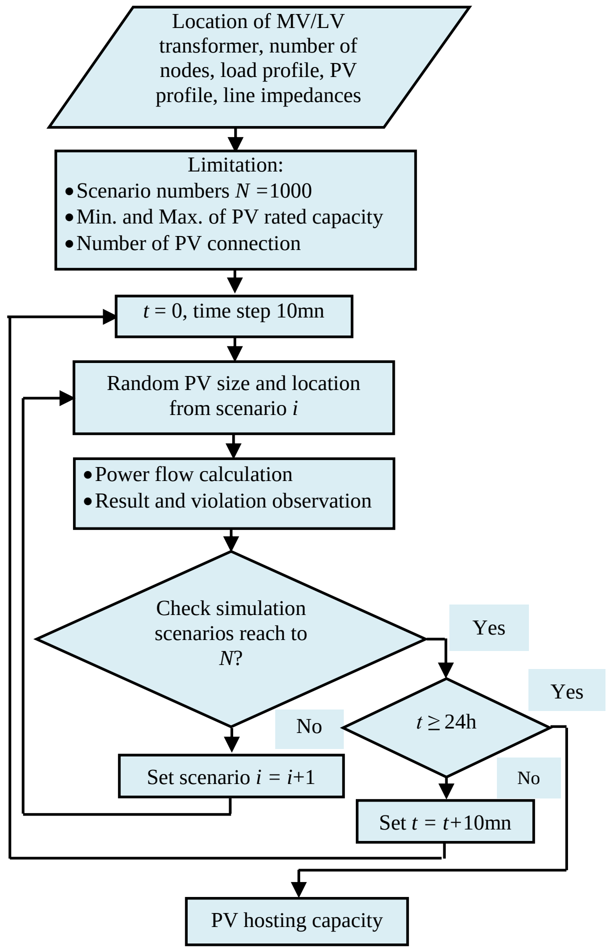

Fig. 4. Flow chart of PV hosting determination.

2) PV system

In this work, the irradiance profile is simulated in 10 mn resolution the same as the load profile. This resolution makes this work more realistic due to the variation of irradiance every time. Unfortunately, there is no actual data on solar irradiance with 10 mn resolution in Cambodia, thus daily solar irradiance from NASA is used to implement this simulation [37]. Moreover, the highest daily solar irradiance over 1 year is chosen since this period is considered the worst case where PV can generate the greatest power to inject into the grid.

Typically, PV system DC output depends on irradiance, temperature, dirt, and DC cable loss [38]. To connect the PV system to the grid, it needs to convert from DC to AC through a solar on-grid inverter.

Therefore, AC output from the PV system is illustrated as follows:

$$P_{\text{PV\_ac}} = P_{\text{PV\_stc}} \times I_{\text{irr}} \times \eta_{\text{temp}} \times \eta_{\text{dirt}} \times \eta_{\text{cable}} \times \eta_{\text{inv}} \quad (13)$$

where $P_{\text{PV\_stc}}$ is the PV rated power, I_{irr} is solar irradiance, η_{temp} is a de-rating factor due to temperature (82%), η_{dirt} is a de-rating factor due to dirt (95%), η_{cable} is the cable loss (97%) and η_{inv} is the inverter efficiency (97%) [38].

3) Voltage constraint

The voltage magnitude of each bus and customer connection after PV installation must stay within the acceptable limits as follows:

$$V_{\min} \le V_{b,t} \le V_{\max} \quad (14)$$

where $V_{b,t}$ is the voltage magnitude at bus b and time t, $V_{\min,}$ and $V_{\max}$ are the minimum and maximum voltage magnitude limits respectively. This work has adapted to $V_{\min}$ =0.90 p.u and $V_{\max}$ =1.1 p.u [36].

4) Reverse power constraint

Normally, all protection, regulation devices, and system elements in the power system are designed to transfer power or protect the system from the transmission line to the distribution network, thus reverse power from PV injection may interrupt such devices. However, some amount of power from PV is still acceptable to reverse to the grid based on technical criteria.

$$P_{\text{RP},t} = \sum_{l=1}^{n} P_{\text{PV},b,t} - \sum_{k=1}^{m} P_{\text{lossPV},m,t} - \sum_{b=1}^{v} P_{L,b,t} \quad (15)$$

where $P_{\text{RP},t}$ is the reverse power at time t, $P_{\text{PV},b,t}$ is the PV power output of bus b at time t, $P_{\text{lossPV},m,t}$ is the power loss for each line m in the system at time t, and $P_{L,b,t}$ is the load power at bus b and time t. Positive $P_{\text{RP},t}$ means that power flows from LV to MV distribution system, and negative $P_{\text{RP},t}$ means power flows from MV to LV system.

5) Line current constraint

Before and after PV installation, overloaded lines in the system must not occur all the time t.

$$\left|I_{l,t}\right| \le I_{l,\max} \quad (16)$$

where $I_{l,t}$ is the current flowing in line l at time t and $I_{l,\max}$ is the maximum allowed current in line l. In this paper, $I_{l,\max}$ is supposed to be the same as the rated capacity of protection devices at the connection point of each customer.

6) Reactive power control from inverter

In power system planning, overvoltage is the main concern for grid-connected PV systems [39]. This problem can occur due to sudden changes in load demand or weather conditions that cause excessive PV power output over the load demand. A voltage regulator is one of the alternative choices to mitigate the risk of this issue. In this work, a smart inverter is used as a voltage regulator through volt-var control to increase PV hosting capacity. The idea of this control is to provide or absorb reactive power from the inverter to reduce overvoltage at the point of the PV connection to determine the maximum PV power integration. The reactive power output varies according to the voltage and active power varies depending on the solar irradiance. The volt-var curve for VVC is shown in Fig. 5. The voltage between V_2 and V_3 is the dead band, no reactive power is injected or absorbed into the system which means the PV inverter operates at the unity power factor. If the voltage is over $V_{3,}$ the inverter will absorb reactive power to reduce the voltage, whereas the inverter will inject reactive power if the voltage is lower than V_2. Typically, the amount of reactive power support depends on the inverter capacity. The maximum reactive power that can be extracted from an inverter is determined by:

$$|Q_{PV,max}| = \sqrt{(S_{PV,max})^2 - (P_{PV})^2} \quad (17)$$

In fact, an inverter is capable of generating power over 20% of its rated capacity so that $S_{max} = 1.2\ P_{PV,max}$ [39]. Thus, even at maximum active power generation, the inverter still can change reactive power within 66% of its capacity.

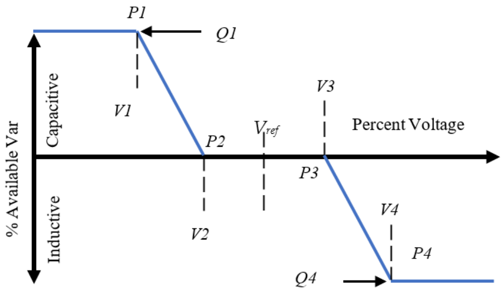

Fig. 5. Inverter volt-var control.

7) Battery placement and sizing

Typically, rural residential consumers have a slightly high-power consumption in the early morning, high power consumption in the evening, and low power consumption during the rest of the day. Consequently, most of the PV power will exceed demand and inject its energy into the grid at around noon. Conversely, consumers will consume the energy from the grid in the evening. In this case, battery energy storage has become the most attractive way to store the excess energy and discharge it when it is needed [22].

To examine the impact of BESS on PV hosting capacity in the system, centralized BES placement is considered in this paper. Based on previous analysis of PV hosting capacity, the voltage sensitivity index has been concerned. The main objective of BES placement is to minimize voltage deviation in the system when there is no PV injection. To solve this problem statement, genetic algorithm is used and the objective function is expressed as:

$$\min\left(\sum_{b=1}^{v}(V_b - V_{nom})^2\right) \quad (18)$$

where V_b is the voltage magnitude of each bus in p.u, V_{nom} is the nominal voltage assumed as 1 p.u.

The main purpose of BES utilization is to absorb excess energy and discharge energy when there is no PV injection into the grid. The optimal BES capacity is to keep the balance between charge and discharge energy. In this simulation, the charge energy has to be lower or equal to the discharge energy to avoid over BES sizing. Ideally, all the excess energy from the PV system is absorbed by the BES and discharges 100% of the stored energy to the grid. However, in real practice, not all the excess energy from the PV system can be stored in the BES and BES also cannot discharge all its energy to the grid. There are some main factors affecting these issues such as battery charging and discharging efficiency, depth of discharge, and battery converter efficiency. Battery charging/discharging power is obtained from Eqs. (19) and (20) and used to calculate the BES capacity with those variables [40].

$$P_{charge} = (P_{PV} - P_{demand} - P_{loss})\eta_{charging} \quad (19)$$

$$P_{discharge} = (P_{demand} - P_{PV} - P_{loss})\eta_{discharge} \quad (20)$$

where P_{charge} is the battery charging power in kW, $P_{discharge}$ is the battery discharging power in kW, P_{PV} is the power from PV in kW, P_{demand} is the power demand in kW, P_{loss} is the total power loss of the system in kW, $\eta_{charging}$ is the battery charging efficiency (90%) and $\eta_{disharging}$ is the battery discharging efficiency (90%) [38]. To obtain the BES capacity without oversizing, BES capacity was defined in Eq. (21).

$$E_{battery} = \sum_{t=0}^{h} P_{charge,t} \le \sum_{t=0}^{h} P_{discharge,t} \quad (21)$$

where $E_{battery}$ is the battery energy storage in kWh.

Normally, BES has a limit of discharge energy in order to prolong its life span and it is called the depth of discharge (DOD) (70%) [38]. Therefore, the final BES capacity will increase by the percentage of DOD.

III. Simulation Results and Discussion

A. Test System Description

In this research work, the modified IEEE 116 test feeder is used to evaluate the HC in the LV distribution system [41]. There are 55 consumers which are connected to the line as shown in Fig. 6. This feeder consists of 21 consumers in phase A, 19 consumers in phase B, and 15 consumers in phase C. The load pattern of each consumer is based on load modeling which used real data from the survey in one village in Cambodia. The total active power during the peak load time is 29 kW with a power factor of 0.95. In the simulation, all consumers have the potential to connect to the PV system and PV random allocation has been applied to define HC.

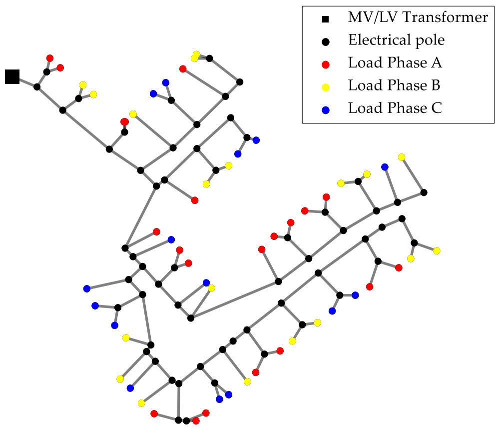

Fig. 6. Original topology of test system.

B. Optimal Topology with Phase Balancing

1) Scenario 1: Original topology

Fig. 6 depicts the topology of the original phase load connection which the red, yellow, and blue colors represent the load connection to phase A, B, and C, respectively. This topology is not generated by the proposed method for phase balancing, all the phase load connections are the same as the modified IEEE 116 test feeder. The active power of each phase is shown in Fig. 7 in 10 mn resolution. It has been seen that the load power between the three phases is slightly unbalanced since the optimal phase balancing was not implemented.

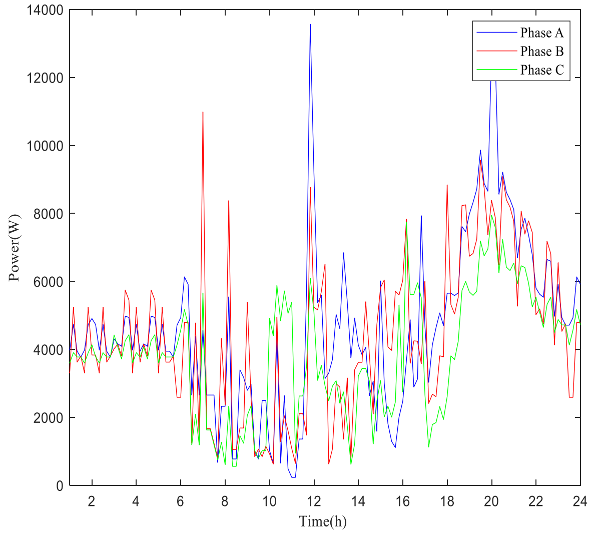

Fig. 7. Load profile of each phase of scenario 1.

2) Scenario 2: peak load balancing

Fig. 8 shows the topology of the system after phase balancing implementation using the proposed method. In this scenario, only the peak power of each household has been considered to apply for phase balancing in the system. There are three different colors of the line, which indicates that the connections between consumers and electrical poles are separated in different phases. Fig. 9 shows the power variation at every time step. It has been investigated that the different active powers between phases are small for only short periods but big differences for most of the time. The reason for this problem is that all households have not consumed peak power all the time.

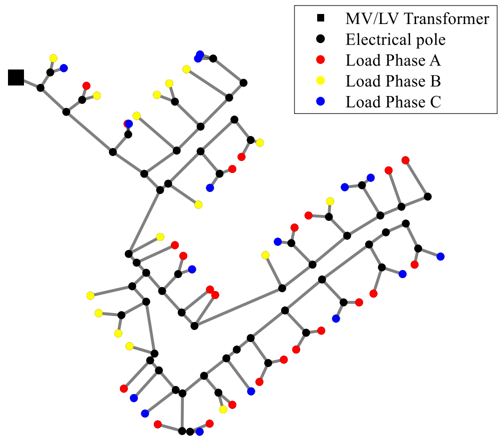

Fig. 8. Topology of test system by phase balancing on peak power.

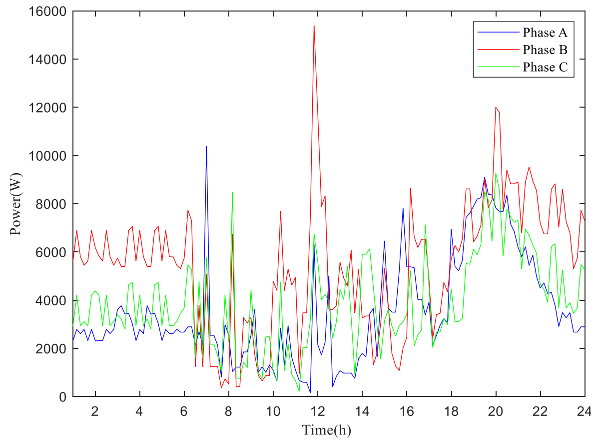

Fig. 9. Load profile of each phase of scenario 2.

3) Scenario 3: Load Profile Balancing

The topology of the three-phase arrangement in Fig. 10 is generated by the phase balancing improvement algorithm based on the load profile. First, the power consumptions of every household are generated by the load profile modeling simulation, then the proposed method is applied to define the phase connection to each consumer with the minimum unbalance factor. In this scenario, the optimal unbalance factor depends on the load power at every time step, as seen in Eq. (11). Based on Fig. 11, it illustrates that even for most of the period, the system is in good balance but it still dramatically increases in some periods due to the behavior of users with high power appliances such as motor pumps, air conditioners, and welding machines.

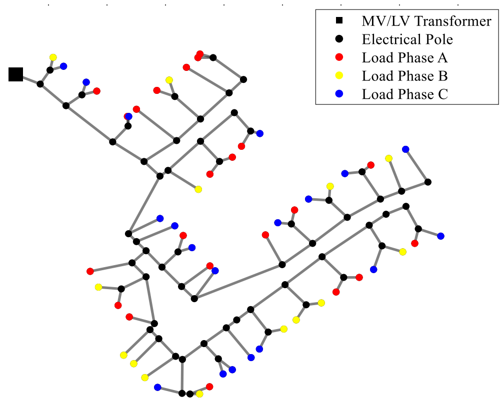

Fig. 10. Topology of test system by phase balancing on load profile.

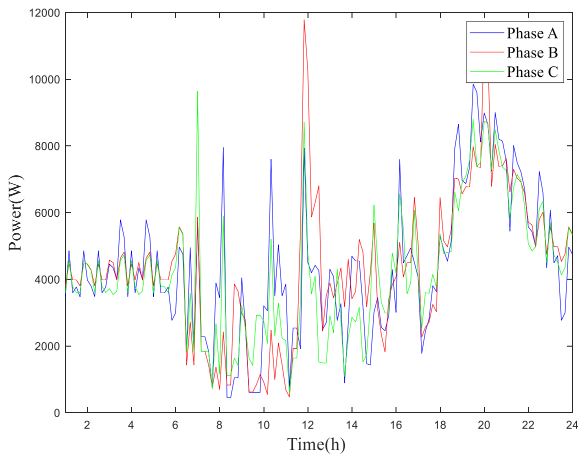

Fig. 11. Load profile of each phase of scenario 3.

Table I depicts the summary results of all the scenarios to define the optimal one for phase balancing. It shows that Scenario 3 is better than others based on criteria such as the maximum unbalanced factor, voltage deviation, and energy loss. It can be seen that the maximum unbalanced factor of phase balancing by load profile consideration equals half if compared to Scenario 1 and Scenario 2. Nevertheless, voltage deviation and energy loss are similar to all scenarios since the load power demand is still small and will have a high impact on the system when the load grows year by year.

TABLE I: SUMMARY OF THE SCENARIOS

Scenarios	Max. Unbalanced factors	Voltage Deviation (%)	Energy Loss (kWh)
Scenario 1	0.2824	0.2980	2.6953
Scenario 2	0.2704	0.2980	2.8614
Scenario 3	0.1315	0.2970	2.2808

C. PV Hosting Capacity

1) Without control

In this part, the PVHC is evaluated under the condition without any control technique. As mentioned in Section 3.1, the PVHC will be defined by the stochastic method and subject to limiting constraints such as overvoltage, line capacity and reverse power to the MV grid. Based on the power consumption of each load, 20 A and 32 A rated capacities of CB are selected as the maximum sizings for PV installation. On the other hand, most PV inverters for small residential buildings are around 1.5 kW [42] hence, this value is set as the minimum PV rated capacity. In this work, the topologies from the three different scenarios above are used to implement the HC assessment with technical constraints and the results can be shown in Table II.

TABLE II: PV HOSTING WITHOUT CONTROL

Scenarios	Overvoltage constraint	Reverse power constraint
Scenario 1	320 %	8.96 %
Scenario 2	268 %	9.07 %
Scenario 3	388 %	9.07 %

Evaluating based on overvoltage constraint, the PVHC of Scenario 3 is the highest one if compared to other scenarios. The results indicate that the benefit of load balancing not only improves the system performance but also increases the PVHC. Scenario 2 has the lowest PVHC, which means the phase balancing by considering only the peak load cannot take advantage of PVHC raising. However, Scenario 1 of the original phase load connection from the test feeder, the PV system can be installed up to 320% of peak load power. Comparing the HC of the overvoltage and reverse power constraints, it is noted that the HC of the reverse power constraint is smaller and is not much affected by the phase load connection in the system. The reason is that the excess power from the PV system does not allow it to reverse to the MV grid, thus the PVHC will depend on the characteristic of load power demand and PV profile every time. Currently, to solve this problem, a zero-power injection device is popularly used to avoid reverse power when power demand is lower than PV power generation.

2) Volt-var control from inverter

In this section, Table III indicates the PVHC of the test feeder in the LV distribution system under volt-var control conditions. It shows that the PVHC of all scenarios is higher than the previous condition. Additionally, with volt-var control, the HC of Scenario 1 can increase to around 418%. An interesting note is that Scenario 3 is still the best option to implement for raising PVHC both with and without control. However, the PVHC based on the reverse power limit is still the same because its value depends on the excess power only.

TABLE III: PV HOSTING WITH VOLT-VAR CONTROL

Scenarios	Overvoltage Constraint	Reverse Power Constraint
Scenario 1	418 %	8.96 %
Scenario 2	343 %	9.05 %
Scenario 3	447 %	9.07 %

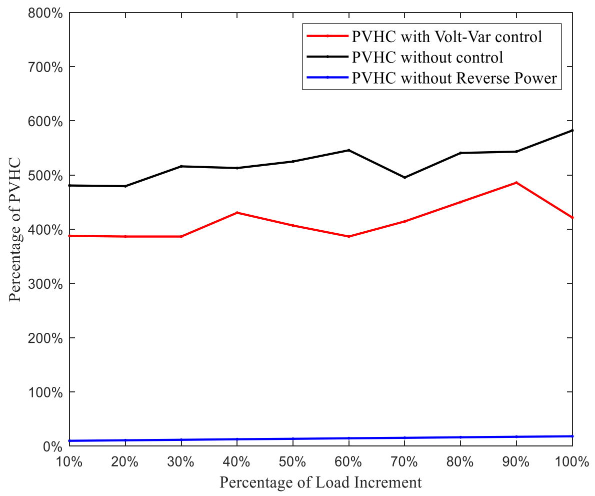

Fig. 12. Variation of PVHC based on load increment.

Generally, the level of PVHC is caused by the characteristics of load power and the performance of the system. The variations of PVHC associated with load power increasing under 3 scenarios are shown in Fig. 12. The black line illustrates that PVHC under volt-var control is still highest compared to other lines. Nevertheless, the percentage of PVHC does not increase linearly due to uncertainty in the random process. As stated in the without control section, the HC based on reverse power limitation will vary depending on the load power consumption and PV output.

3) Centralized battery placement and sizing

In this case, the optimal topology of Scenario 3 is chosen as the test system to find the maximum PV hosting capacity when BES is installed in the system. Based on the obtained result from Equation (19), the optimal BES location is placed on the middle location of the lines and the BES capacity is 248 kWh as shown in Fig. 13 and Table IV, respectively. The benefits of BES in this work are to improve system performance related to voltage deviation and to increase PVHC by absorbing the excess energy from the PV system to avoid reverse power to the MV line. Moreover, BES can operate as a Distributed Generation (DG) source to generate power for the grid when there is no PV injection or load power is higher than PV output power. In the previous section without BES, the PVHC based on reverse power constraint is very low because power injection into the MV grid is not allowed. For this reason, BES is the best choice to enhance the HC of PV installation in the LV distribution system. However, this value is still lower than the HC of voltage constraint because BES capacity is designed to support only one day of energy consumption. If BES is installed with more capacity, surely HC will enhance as well. Table IV demonstrates the comparison of PV penetration levels before and after BES installation without control in Scenario 3.

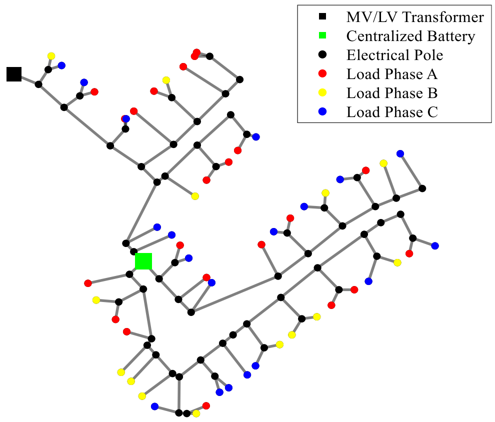

Fig. 13. BES placement.

TABLE IV: PV HOSTING WITH THE BES PLACEMENT

PV Hosting before BES Installation	PV Hosting after BES Installation	BES Capacity
9.07 %	196%	248 kWh

IV. CONCLUSION

There are two main contributions to this paper. First, a tool for phase balancing is provided by employing the different load profiles of consumers which were generated by the bottom-up algorithm. The input data for load profile modeling was collected from the survey in one village to observe the real variation of power consumption in the Cambodian electricity context. MIPL was used as the proposed technique for phase balancing in the test system. The results showed the appropriate connections between load and phases for optimal phase balancing throughout the time without swapping. The modified IEEE 116 test feeder was used to apply the method, and then the maximum unbalance factor, voltage deviation, and energy loss of the system were calculated to evaluate the benefit of the proposed method. Therefore, this method may be used as a planning tool to minimize phase unbalance in the distribution system.

Another main contribution is PVHC evaluation and stochastic analysis was used as the proposed method to investigate the maximum PVHC level. To make it more realistic, the variation of PV location, size, load profile, and solar irradiance were employed to examine the range of PV penetration. Three different topologies were tested to observe their effects on the PVHC with and without control. In this work, the volt-var control and centralized BES operation were used to enhance HC in the system. It can be seen that the HC of all scenarios will vary associated with load variation. When the power load increases, HC also increases. Based on the results, it is concluded that the optimal topology with phase balancing using the proposed method can inject more PV penetration both with/without control and BES installation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The original draft preparation, software simulation, visualization, validation and formal analysis have been done by Oudaya Eth. The paper conceptualization, methodology and investigation have been done by all authors. The supervision, review-editing and project administration have been provided by Vannak Vai and Long Bun. All authors had approved the final version.

FUNDING

This work was funded by Cambodia Higher Education Improvement Project (Credit No. 6221-KH) for the sub-project of HEIP-ITC-SGA#07 at the Institute of Technology of Cambodia (ITC).

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