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Integrated Battery Energy Storage into an Optimal Low Voltage Distribution System with PV Production for an Urban Village

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***Abstract*—The feed-in tariff for rooftop photovoltaic (PV) systems has not yet been adopted in Cambodia. Thus, it does not purchase excess power by reverse power flows from PV production unidirectional energy meters are used even in the capital. The power distribution systems are expanded in recent years due to load demand increase, and this issue makes the distribution system designers perform the planning. The design of a low voltage distribution system and suitable solutions are proposed to handle these issues. This paper purposes of designing an optimal low voltage distribution topology with the integration of PV and three different proposed solutions of reverse power relay (RPR), solar hybrid inverter (SHI), and battery energy storage (BES) in an urban village, which consists of improving a balanced load and existing PV production usage. Firstly, the repeated phase ABC is applied to minimize the power loss and unbalanced load in the three-phase distribution system. Next, the integration of RPR, SHI, and BES into household grid-connected PV production systems have been proposed as solutions. The urban village in Phnom Penh, Borey Mungkul Phnom Penh, Sangkat Veal Spov, is chosen and modeled for a case study to confirm a proposed method. Simulation results allow concluding that the integrated battery energy storage into the optimal low voltage distribution topology provides the best solution to design the grid connection PV system.**

***Keywords*— energy storage; load balancing; repeated phase abc; reverse power relay; solar hybrid inverter.**

I. INTRODUCTION

The Feed-In tariff for rooftop PV systems has not yet been adopted in Cambodia. The utility thus does not purchase excess power by reverse power flows from PV production. Only unidirectional energy meters are used even in the capital. One solution is to size the PV system so that the peak generation from PV is below the baseload. However, this concept does not work well for small load households. The power distribution systems are expanded in recent years due to the load demand increase; these points compel the distribution operators to perform planning. The low voltage distribution systems are radially unbalanced due to consist of single-phase and three-phase loads. A radial distribution system optimization was developed to search for the optimal topology to handle these issues. The single-phase of the LV distribution system was described in a previous study [1] with the shortest-path algorithm; the authors focused on searching the radial topology with the shortest length of the conductor from energy meter to households. This shortest-path algorithm was also applied [2]; the authors combined this shortest-path algorithm with two different load balancing algorithms to find radial topologies in a rural village. The optimal radial topology with PV and energy storage has been investigated in [3]; the authors proposed a first-fit bin-packing (FFBP) to search for the topology and genetic algorithm for sitting and sizing of PV-energy storage.

Furthermore, the authors in [4] had focused on radial distribution topology development in an urban village. It is using two different algorithms, which are FFBP and mixed-integer quadratically constrained programming (MIQCP) [5],[6]; this paper aimed at searching for radial topology with the shortest cable length and load balancing improvement. Planning of local PV production for low voltage distribution grids was studied in previous research [7]. The authors proposed an analytical expression to consider the impact on load consumption. The PV production aggregations at the coupling point of a grid such as a peak power and line cross-section reduction. The impact of storage systems on low voltage distribution grids was investigated [8]; the authors applied a mathematical model to minimize losses with the storage system's penetration rate. The authors in [9] studied the issues of integrated storage uncertainty into low voltage distribution grids with a delay of PV production; an advanced automation algorithm is developed to figure an economy of storage compared to a traditional reinforcement concept. The voltage unbalance analysis by single-phase rooftop PV [10], its mitigation [11], and voltage rise impact in the LV distribution system have been studied. The utilization of energy storage with the highest PV penetration has been considered [12], [13]; these energy storages are installed at households to avoid voltage issues in the network. However, these authors had almost addressed optimal radial low voltage distribution topologies considering the conductor length to minimize and load balancing improvement and voltage problems. Therefore, this paper proposed the optimal radial distribution system topology and reversed power flow solutions in an urban village.

This paper aims at designing a radial distribution topology considering load balancing improvement. It reverses the power flow solution of the grid-connected PV system by using repeated phase ABC (RPABC) and reverse power relay (RPR), solar hybrid inverter (SHI), and battery energy storage (BES) for mitigating the reverse power flows. The rest of this paper is structured as follows. Section II describes the materials and proposed method of designing the radial topology and integrated RPR-SHI-BES. The pilot of the selected site and numerical simulation results, including discussion, is provided in section. Section IV gives conclusions and future work of the paper.

II. Material and Method

The proposed method aims to study a radial distribution topology of grid-connected PV system with different proposed solution (i.e., reverse power relay, solar hybrid inverter, and battery energy storage in the urban village, Phnom Penh. To achieve the purpose of the paper, several steps will be proposed as follows: 1) Insert the system data, i.e., peak load demand, location (X, Y) and line impedance (Z), 2) Getting an optimal topology by applying the repeated phase ABC, and 3) Impact study of deployment of the reverse power relay, solar hybrid inverter deployments and sizing battery energy storage with PV production. The flowchart of the proposed method of the paper is shown in Fig.1.

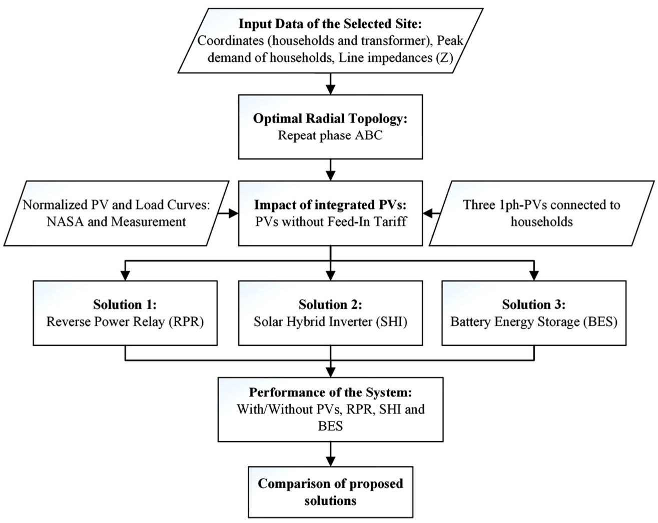

Fig. 1 Flowchart of the proposed method

A. *Repeated Phase ABC*

To cope with load balancing, the 1st algorithm of the proposed method to balance the loads is RPS-ABC. This algorithm is applied for the sum of demand at each electrical pole. The ABC phase sequence is repeated for every three connected poles to get the load balancing. Fig. 2 illustrates the RPS-ABC algorithm for this paper.

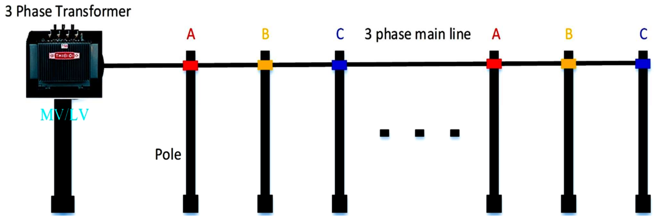

Fig. 2 Repeated phase ABC concept

The selected conductor process of radial topology design is provided in Fig. 3. The load flow is implemented at a time of 8 PM (i.e., peak load); the conductor size will be increase if there is voltage or current constraint.

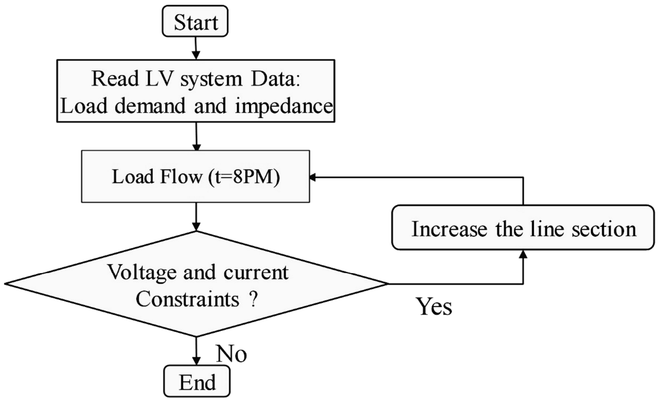

Fig. 3 Process of selected conductor size of the system

B. *Deployment of Reverse Power Relay*

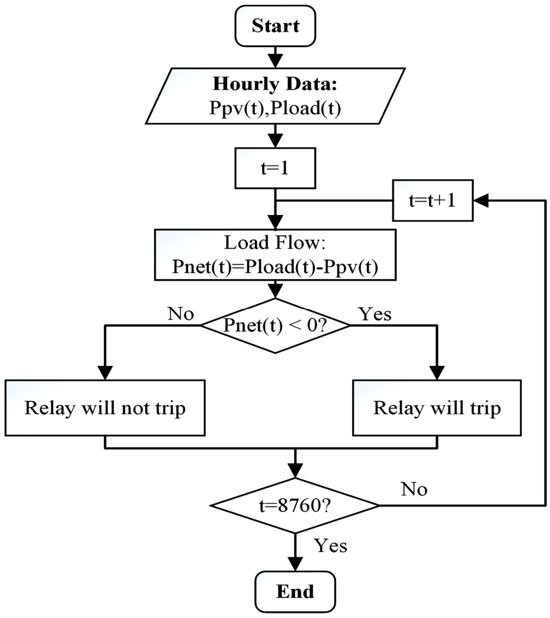

Fig. 4 Process of reverse power relay deployment

A reverse power relay is proposed to set up a household PV connection. This relay will trip the PV system from the grid if the net power (i.e., $P_{net}(t)=P_{load}(t)-P_{PV}(t)$) is a negative value, and it will not trip the PV otherwise. The strategy of the reverse power relay is provided in Fig. 4.

C. Deployment of Solar Hybrid Inverter

A solar hybrid inverter is proposed to replace the existing grid connection solar inverter. With this proposed system, the rooftop PV panels will not be able to inject the excess power into the grid, which is called zero export. This inverter is proposed to set up a household PV connection. This system will regulate the power injection from the PV according to load consumption. The process of deployment of a solar hybrid inverter is provided in Fig. 5.

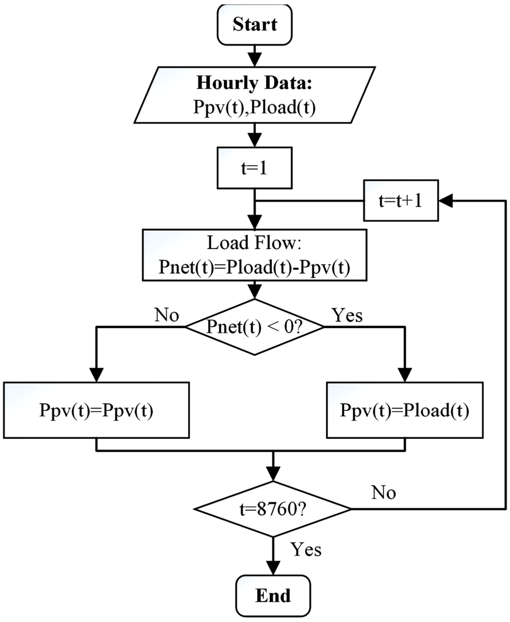

Fig. 5 Process of solar hybrid inverter deployment

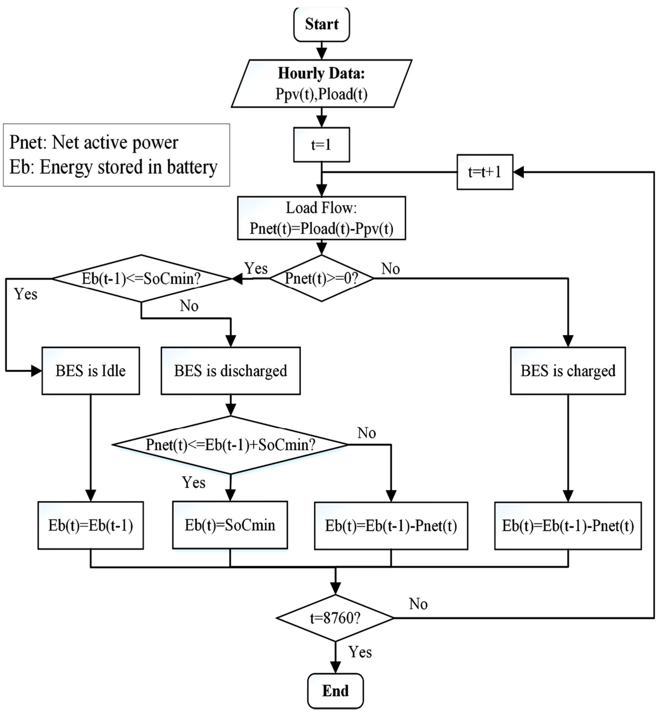

Fig. 6 Process for sizing and deployment of battery energy storage

D. Deployment of Battery Energy Storage

Battery storage is proposed to install at a household grid connection PV system. This storage is to charge the energy when reverse power (i.e., $P_{load}(t)-P_{PV}(t)<0$) flows to the grid and to discharge when the grid is required to supply (i.e., $P_{load}(t)-P_{PV}(t)>0$) and state of charge (SoC) is higher than a minimum state of charge (SoCmin). Fig. 6 provides an algorithm for the sizing of energy storage, and we assume that these normalized curves are repeated over a year as a preliminary study.

III. Results and Discussion

A. The Pilot of the Selected Site and Optimal Topology

The low residential voltage distribution system has been selected, and the model of the system has been developed based on the specification of the pilot of the selected site, where is situated in Borey Mungkul Phnom Penh, Sangkat Veal Sbov, Phnom Penh as shown in Fig.7. Due to only one household's power consumption has been measured, the normal distribution for energy meter (i.e. five households) with a mean of 7 kW and STD of 0.5 KW has been applied. The system's total active power is about 250 kW, with a power factor of 0.9 pf. The households are supplied by a 400 V main source from the 1st bus to 41st buses. Classical conductor size is 4x70 mm^2 from mainline and 4 mm^2 from energy meter to households. Fig. 8 provides a site with existing PV production and optimal radial topology by using repeated phase ABC.

Fig. 7 Pilot of the selected site in Borey Mungkul Phnom Penh [11°32'04" N, 104°58'06" E]

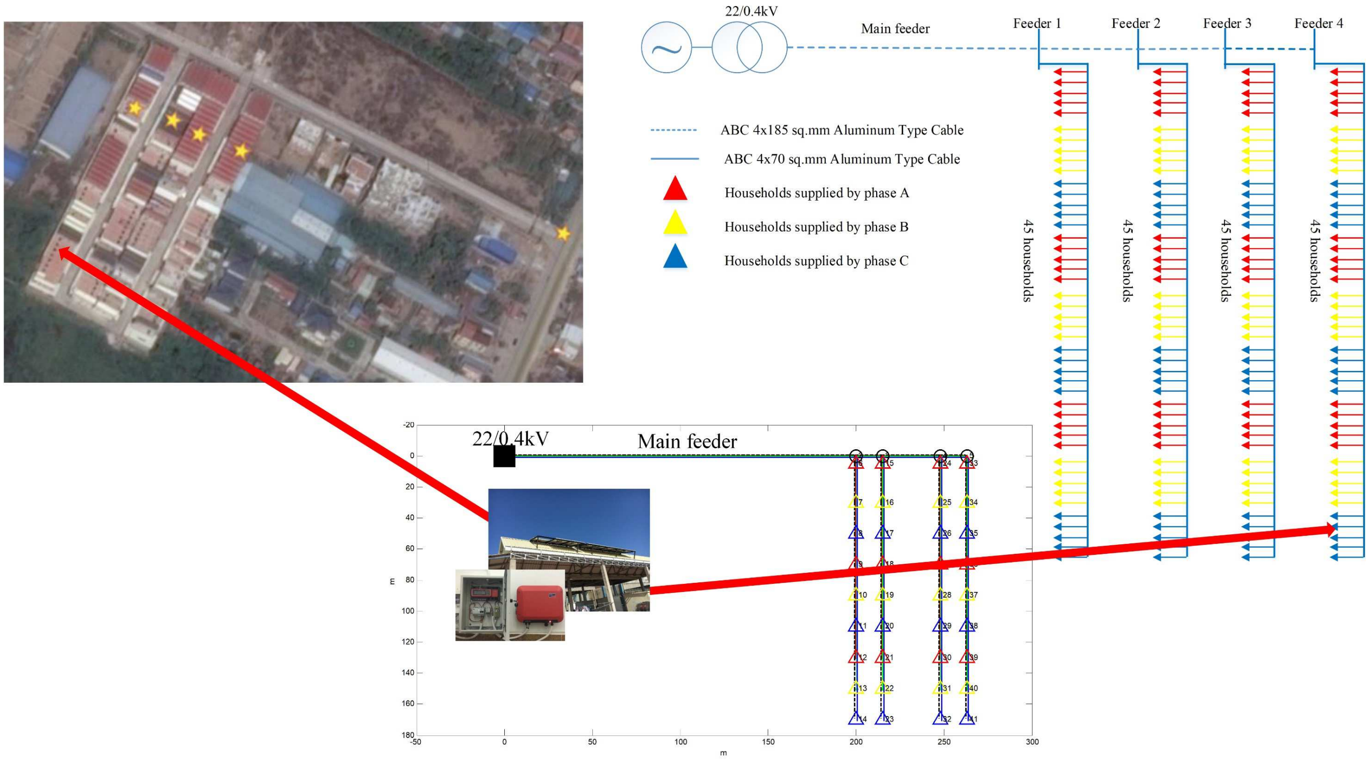

Fig. 8 Selected site with existing PV production and optimal radial topology using repeated phase ABC

Also, the system's performance is computed by backward/forward load flow over a year with MATLAB software. The system's voltage profile is the most important to identify that the system is operated within the voltage regulation (i.e. 0.9 pu ≤ V_m ≤ 1.06 pu) in Cambodia. Fig. 9 shows a voltage profile of the system at 8 PM; according to that figure, the system has no voltage problems even if the PV system does not support the system.

B. PV Production and Load Consumption

In this paper, three 1ph households' grid-connected PVs with 1.5 kWp located at bus 32, 40, and 41. The load curve is from local measurement at the selected site and is used as

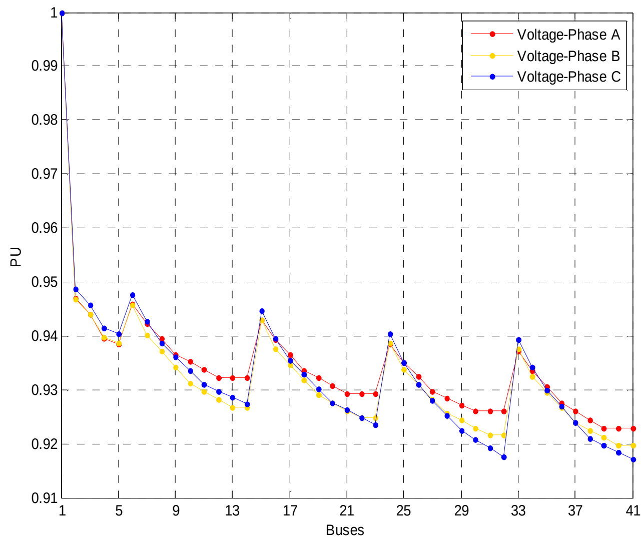

Fig. 9 Minimum voltage profile for each phase (Peak load at 8PM)

the normalized curve, and the NASA source is used for solar radiation at the site, as shown in Fig. 11. The load measurement set-up and normalized daily PV and load curves are provided in Fig. 10, and Fig. 12. As we have seen in the figure, the peak leak appeared at a different time with peak solar radiation. Thus, the PV system's power supply is not available for households' peak consumption, and it is almost available at the lowest power consumption (i.e. worst case).

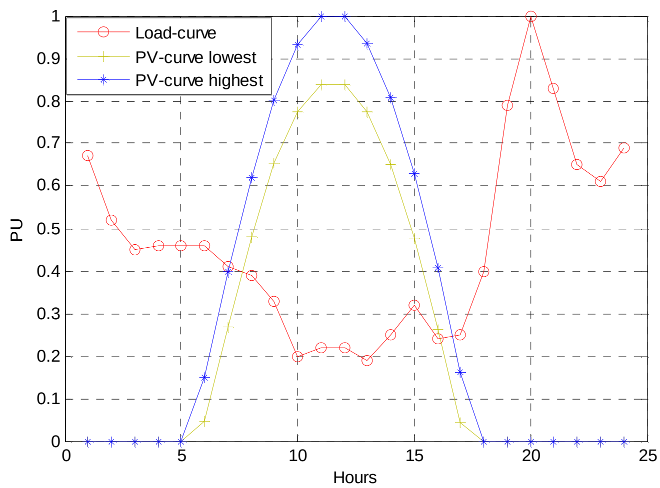

Fig. 10 Normalized daily PV-load curves

C. Impact of Proposed Solutions in the System

A net load profile for each household (i.e., 32, 40, and 41) without/with photovoltaic (PV) and integration of reverse power relay (RPR), solar hybrid inverter (SHI), and battery energy storage (BES) are provided in Fig. 13 to Fig. 15. As given in the figures, a reverse power flow has occurred at the

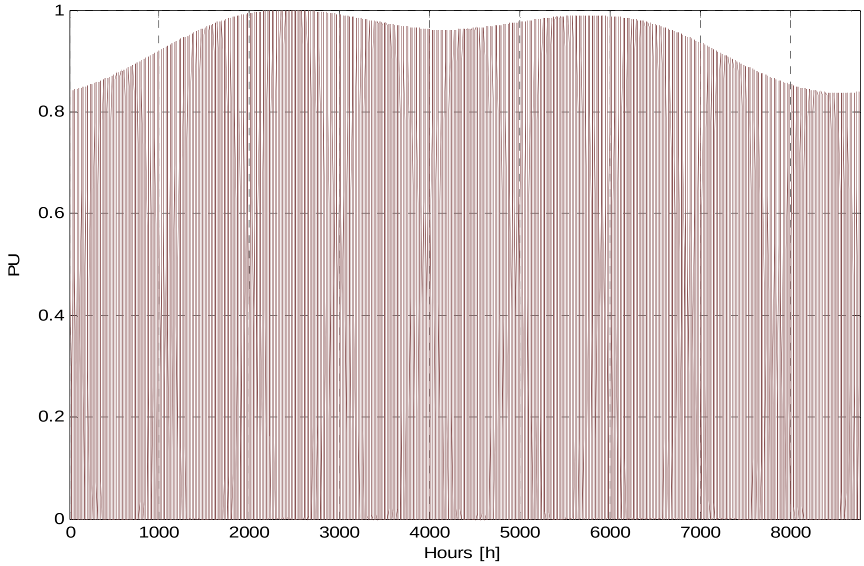

Fig. 11 Annual solar irridiance by NASA in Cambodia

time the PV system is connected to the grid. Without a bi-directional energy meter and feed-in-tariff, that reverse power means that each household's power consumption has increased with excess PV production. However, these unused power consumptions (i.e., bill of electricity) have been completely removed from the household with the deployment of reverse power relay as the first solution. Those relays have tripped the PVs from the grid. Also, the solar hybrid inverter's deployment as the second solution can remove the reverse power flow with PV power curtailment means, which operates as zero export to the grid.

Moreover, each household's power consumption has decreased notably, thanks to battery energy storage used as the third solution. Besides, the indicators of the impacts in the system over a year are given in Table 1. With these three proposed solutions, integrating BES into the household grid-connected PV is more interesting in terms of energy losses and energy used in the whole system.

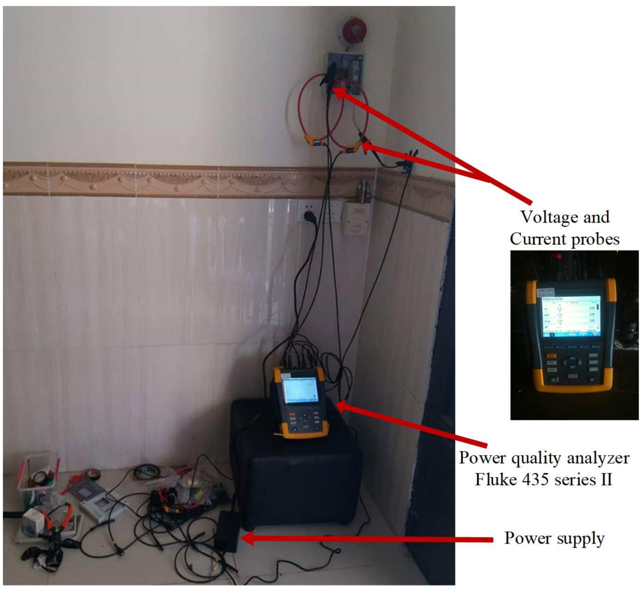

Fig. 12 Set-up of load measurment with Fluke 435 series II

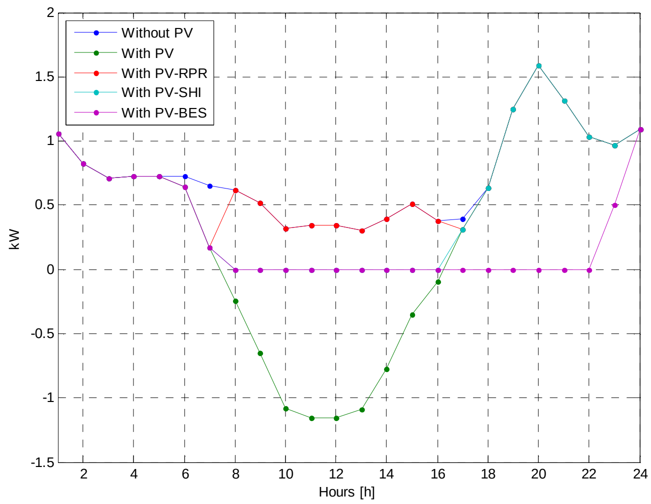

Fig. 13 Load profiles of hoursehold (at bus 32) at lowest solar radiation

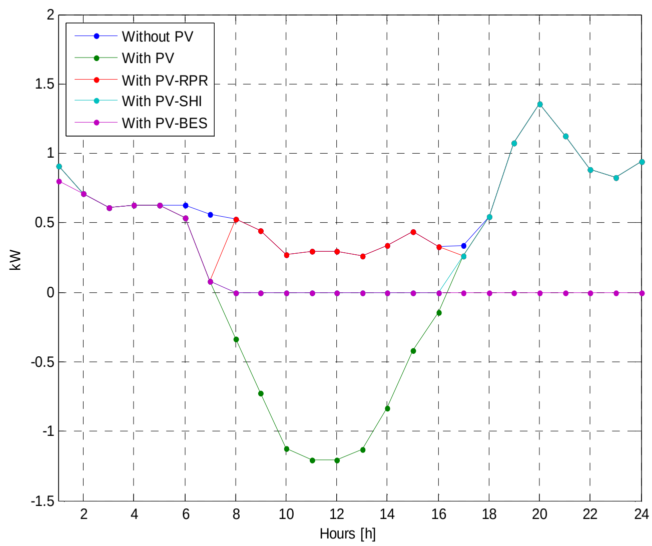

Fig. 14 Load profiles of hoursehold (at bus 40) at lowest solar radiation

TABLE I
INDICATOR OF THE SYSTEM PERFORMANCE

Items	**Scenarios**				
	Without PV	**With PV**	**PV-RPR**	**PV-SHI**	**PV-BES**
Sizing of PV [32,40,41] (kWp)	0	[1.5, 1.5, 1.5]	[1.5, 1.5, 1.5]	[1.5, 1.5, 1.5]	[1.5, 1.5, 1.5]
Sizing of BES [32, 40,41] (kWh)	0	0	0	0	[8.25, 8.92, 9.15]
Energy used (MWh/year)	1125.35	1114.53	1124.55	1120.58	1110.78
Energy losses (MWh/year)	107.59	106.79	107.49	107.16	105.05
Energy bill [32,40,41] (MWh/year)	[6.37, 5.47, 5.14]	[7.18, 6.66, 6.48]	[6.14, 5.23, 4.90]	[4.77, 4.06, 3.80]	[2.36, 1.45, 1.13]

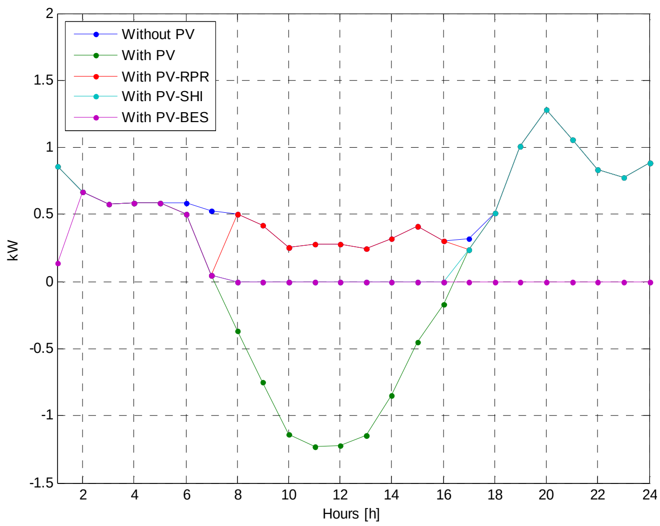

Fig. 15 Load profiles of hourséhold (at bus 41) at lowest solar radiation

Moreover, the daily active power at MV/LV substation and active power losses with/without PV and three proposed solutions are provided in Fig. 16 and Fig. 17. As seen in the figures, the peak power at MV/LV has appeared at 8 PM during the peak load without PV production. Also, there is no reverse power flow at the substation level and slightly different between these scenarios due to only three single-phase PVs with RPR, SHI, and BES connected into the system. However, that reverse power flow has occurred at the household as described in the previous section.

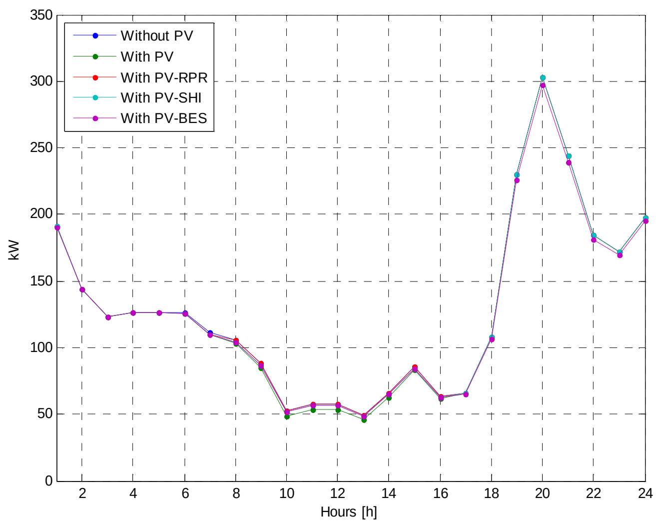

Fig. 16 Daily active power at MV/LV substation

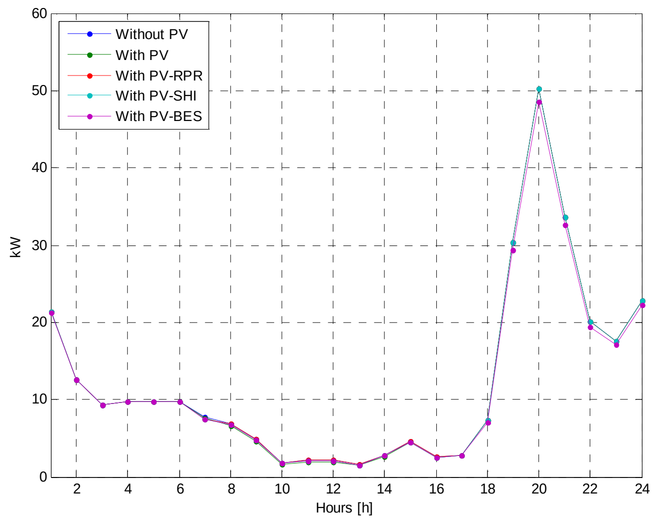

Fig. 17 Daily active power loss of the system

IV. CONCLUSION

The optimal and modelling of low voltage distribution with different proposed solutions. It is coped with reverse power flow. Without feed-in-tariff in the pilot of the selected site, Borey Mungkul Phnom Penh, Sangkat Veal Sbov has been developed, not only for simulation but also for visualization in MATLAB software. Three proposed solutions are using reverse power relay (RPR), solar hybrid inverter (SHI). The battery energy storage (BES) has been submitted to solve household grid-connected PV, which is currently faced with a one-directional energy meter and non-feed-in-tariff of the system. These devices are proposed to be installed at households to avoid the reverse power flow from the PV system. Also, the deployment of RPR has reduced not much energy consumption for household compared with SHI and BES used. Moreover, BES's integration is more appealing compared to the other two proposed solutions (i.e., RPR and SHI) in terms of energy usage, energy losses, and electricity bill of each household. However, to be a more concrete result, forecasting PV and load profiles, including economic analysis, will be investigated to get more indicators for the system design decisions.

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