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Non-uniform Rooftop PVs Distribution Effect to Improve Voltage Profile in Residential Feeder

Zamzami, Nelly Safitri*, Fauzi
Department of Electrical Engineering, Politeknik Negeri Lhokseumawe
Jl. Banda Aceh-Medan Km. 280,3 Buketrata Lhokseumawe 24301, Indonesia
*Corresponding author, e-mail: nellysafitri@pnl.ac.id

Abstract

This paper presents the simple design of a grid-tied single-phase with distributed rooftop photovoltaic (PV) non-uniformly location and ratings. All the inclusion components in the developed scheme are estimated and defined as the inevitability of low voltage (LV) residential network. This developed scheme is purposed for allocating AC and DC load, which are divided into four steps: the sized determination of PV inverter (1-5kW), the selection of PV array, the size determination of battery and the selection of other supporting components. The purposed configuration consists of modeling the system with non-uniform distributions of rooftop PVs, modeling the rooftop PVs based on their injected active and reactive power, and finally the inclusion of battery storage, based on its state of charge (SOC). Due to test the configuration, several cases are built in the MATLAB platform. Simulation results have been generated and analyzed for an unbalanced three-phase residential feeder which is populated with rooftop PVs and battery storage (BS). The simulation results show that the unbalanced reduction due to the coordinate of PVs and BS that provided educated energy storage when the unequal loadings are there, have significant effect toward the anxiety of the distribution network are successfully done.

Keywords: *grid-tied, rooftop PV, PV inverter, battery storage, residential feeder*

1. Introduction

Poor voltage regulation as one of power quality issues has become a significant problem in distribution systems around the world. In one hand, distribution networks were constructed a few decades ago and are reaching their capacity due to natural load growth. On the other hand, customer load demand and power quality expectations have increased considerably in recent decades along with a rapid growth in the digital technology. When the large single-phase loads and distributed generation (DG) units such rooftop PVs is used, although voltages are usually well balanced at the supply side, they can become unbalanced at the customer side due to the unequal system impedances, non-uniform distribution of single-phase loads and PV units [1]. The increasing demand for the installation of rooftop PVs can change the direction of power flow and lead to voltage regulation problems. Furthermore, most of the residential rooftop PVs are single-phase units. Their integrations into the three-phase networks might also cause unbalance issues due to their random location and rating. This might lead to an increased voltage beyond the standard value [2-3].

Many studies have been reported regarding the coordination of PVs and battery storage units to regulate network voltages, but they only discuss the control strategy of PV generators and battery storage units [4-6]. Reference [7] presents a battery-charging strategy, which is widely applied in PV systems and is based on directly connecting or disconnecting the solar array to the battery bank. Another method proposes a battery-charging algorithm based on the state of charge (SOC) estimation. However, the accurate estimation of the SOC remains very complex and is difficult to be implemented. In order to avoid this complexity, specific regulation algorithms have been proposed such as maximum power point tracking (MPPT) approaches [8] and fuzzy logic-based methods [9]. However, these regulation algorithms cannot operate with a grid-connected inverter and grid power references from a grid operator. Thus, a coordination of single rooftop PVs with battery storage units is proposed to regulate the network voltage by using the droop control approach.

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This paper presents an enlargement of a single-phase rooftop photovoltaic (PV) with battery storage (BS) scheme that installed in the low voltage (LV) residential feeder due to overcoming the raised issue of voltage regulation in the distribution system. The developed scheme is assigned to meet the single-phase rooftop PV for the purpose of AC and DC load. The five requirements steps are; i) the estimation of total loads and energy, ii) the assortment of PV inverter iii) the selection of PV array iv) the determination of battery size, and v) the determination of other supporting components. Each step comes with the proper configuration. The contribution of this paper is designated as the proper student practice material for laboratory purposes at the renewable energy plant laboratory in the Department of Electrical Engineering of Lhokseumawe State Polytechnic in Aceh, Indonesia.

The rest of the paper is organized as follows Section 2 is discussed the problem formulation and proposed approach which involving the PV system with BS. In Section 3 the configuration of the included components of the developed scheme are described independently. Several study cases, which have been built in the MATLAB platform is described in Section 4. Finally, section 5 is concluded the whole scenario of the developed scheme.

2. Research Method

There are basically two main problems with the application of rooftop PVs in distribution networks: i) during the day, PVs inject active power while most household loads are at their nominal levels which could result in active power flow in the opposite direction toward the grid causing voltage increase at some nodes, ii) in the evenings and during peak load hours, power output of PVs vanish that could result in voltage drops.

Droop control approach is commonly applied for lowering the frequency and voltage amplitude whenever increases in active and reactive powers are sensed. When rooftop PVs are deployed in single-phase residential feeders, the normal electric power demand pattern will change and the three-phase power system might not be capable of handling the new operating conditions and demands. Based on the recent study [10], rooftop PVs, typically with power levels ranging from 1-5 kW installed by the householders is gaining popularity due to their financial benefits. They will be soon expected to support the network as small DG units, which are able to transfer the energy stored in their battery into the grid. On the contrary, by deploying PVs at residential houses, the voltage unbalance in the network will be increased due to the uncertainties in the random locations and ratings of PVs. This proposal takes the following four steps to mitigate the impacts of rooftop PVs on the grid using numerical and droop control approaches in MATLAB software platform. A detailed droop control approach, rooftop PVs and battery storage units including their coordination will be performed in this section.

2.1. Modeling the system with non-uniform distributions of rooftop PVs

The unbalanced low voltage 415 V residential feeders of Figure 1 connected to the medium voltage system 11 kV and populated with PVs will be simulated to test the performance of the coded load flow algorithm. In this proposal, rooftop PVs are accurately modeled based on the injected active and reactive powers (P_{PV}, Q_{PV}) and their terminal voltages $(|V_{PV}|, \delta_{PV})$ as shown in Figure 2 [10]. Furthermore, a constant power factor of 0.95 is assumed for each household with an average house peak demand of 2.0 kW. An unbalance load flow algorithm will be coded in MATLAB that will be to implement the proposed coordination algorithm. Since the distribution system under consideration is a radial network consisting of single-phase, two-phase, and un-transposed three-phase lines serving balanced and unbalanced loads, it is necessary to carefully calculate the values of rows and columns of the Y_{bus} matrix. The nodal approach will be the model for the distribution systems:

$$I = Y_{bus}.V \quad (1)$$

Sometimes it is desirable to reduce the matrix size by eliminating the nodes in which the current do not enter or leave. The Kron's reduction approach will be used in this proposal to eliminate the unwanted values of row and column [11].

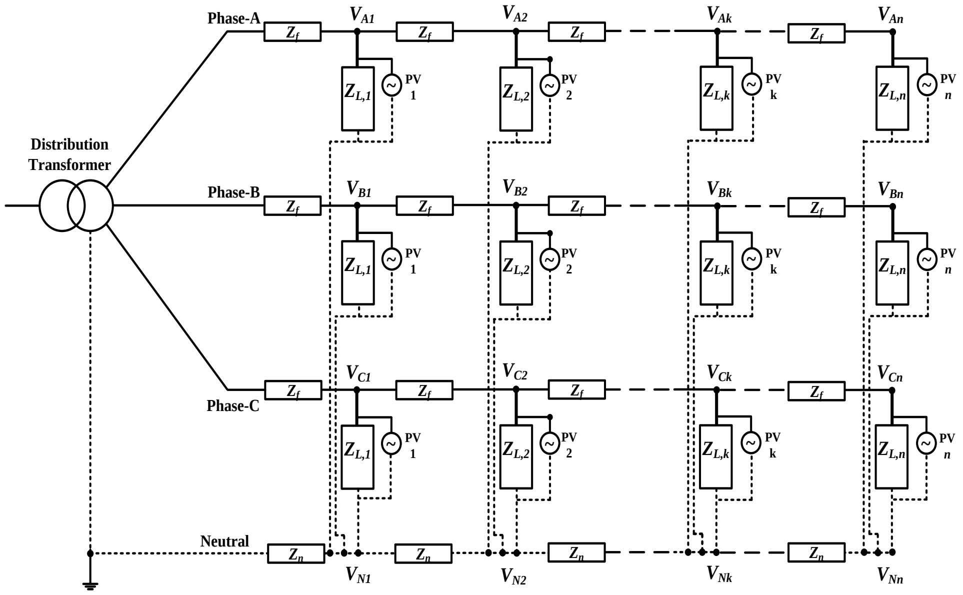


Figure 1. The unbalanced residential network used for simulations

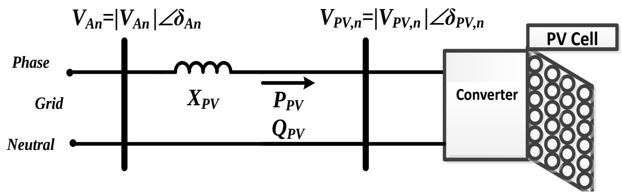


Figure 2. Details diagram of the rooftop PV

2.2. Modeling rooftop PVs based on the injected active and reactive power

The rooftop PV voltage magnitude and phase angle ($|\boldsymbol{V_{An}}|$, $\boldsymbol{\delta_{An}}$), as shown in Figure 1 can be computed based on its injected power ($\boldsymbol{P_{PV}}, \boldsymbol{Q_{PV}}$) and terminal voltage ($|\boldsymbol{V_{PV}}|$, $\boldsymbol{\delta_{PV}}$), as shown in Figure 1 as follows:

$$P_{PV} = \frac{|V_{An}||V_{PV}|sin(\delta_{An}-\delta_{PV})}{X_{PV}}, \quad Q_{PV} = \frac{|V_{An}||V_{PV}|cos(\delta_{An}-\delta_{PV})-|V_{PV}|^2}{X_{PV}} \qquad (2)$$

From (2), then $\boldsymbol{\delta_1}$ and $|\boldsymbol{V_1}|$ can be computed.

$$\delta_{An} = \delta_{PV} + atan\left(\frac{P_{PV}.X_{PV}}{Q_{PV}.X_{PV}+|V_{PV}|^2}\right), \quad |V_{An}| = \frac{P_{PV}X_{PV}}{|V_{PV}|sin(\delta_{PV})} \qquad (3)$$

Droop control through active and reactive power injection as shown in Figure 3 can be performed with rooftop PVs based on their equivalent circuit as shown in Figure 2 and power characteristics highlighted by (2) and (3). To mitigate the impacts of rooftop PVs, a droop control approach is implemented by updating the PV bus voltages as the locations and ratings of rooftop PVs are defined. These PV buses are the nodes where generators are connected. Therefore, the power generation and terminal voltage of PV buses are controlled through the droop control approach. By keeping the input power of PV buses constant and maintaining their voltage levels constant using voltage regulators, the constant power and absolute voltage values for these buses can be specified. Clearly, the reactive powers of the generator connected to PV buses depend on the system configuration and cannot be specified in advance. Furthermore, the unknown phase angles of the bus voltages need to be completed through load flow calculations. Therefore, to update the voltage of a PV bus, firstly the reactive power of the bus must be estimated [12]:

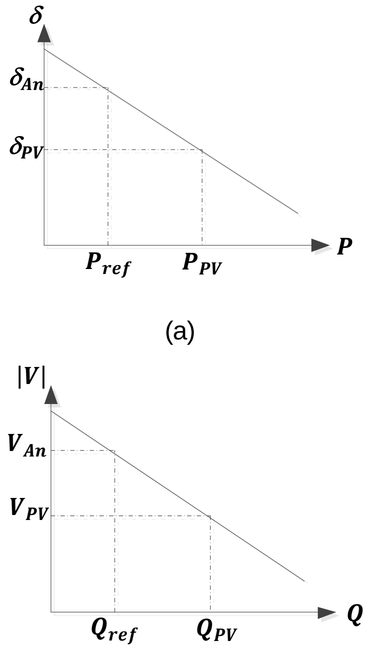
$$Q_{i,inj} = -Im\left[V_i^* \sum_{k=1}^{n} Y_{ik} V_k\right] = -Im\left[V_i^* \{Y_{i1}V_1 + Y_{12}V_2 + \cdots + Y_{ii}V_i + \cdots + Y_{in}V_n\}\right], \quad (4)$$

hence the Q value at the k^{th} iteration can be written as

$$Q_{i,inj}^{(k)} = -Im\left[V_i^{*(k-1)}\left\{Y_{i1}V_1 + Y_{i2}V_2^{(k)} + \cdots + Y_{ii}V_i^{(k-1)} + \cdots + Y_{in}V_n^{(k-1)}\right\}\right], \quad (5)$$

and the bus voltage can be completed as:

$$Vbus_{new}1 = \frac{1}{Ybus_{new}} \times \left[\frac{P-jQ}{Vbus_{new}} - Ybus_{new} \times Vbus_{new} - Ybus_{new}' \times Vbus_{new}'\right] \quad (6)$$



(b)

Figure 3. The droop concept; (a) δ-P characteristics, (b) V-P characteristics

2.3. Inclusion of battery storage

Voltage improvement and regulation through droop control of the rooftop PV's inverters will only be effective up to a certain level of loading. Furthermore, it is only possible to perform voltage regulations during the day while most of the large smart appliances such as PEVs are usually activated in the evening and/or early morning hours when the price of the electricity is expected to be inexpensive. Therefore, distributed battery storage units are assumed to be available in the household with rooftop PVs. The flowchart of the proposed algorithm for the coordination of rooftop PVs and battery storage units to regulate network voltage profiles and reduce voltage unbalance is shown in Figure 4.

The battery can be assumed as a constant voltage source with a fixed amount of energy and modeled as a constant DC voltage source with series internal resistance. Since the battery has a limitation on the duration of its generated power depending on the amount of current, then it will be assumed that the battery will be charged at off-peak load periods. Battery storage units with appropriate will be included in the algorithm of Figure 3 and their charge/discharge strategies will be coordinated with rooftop PVs to further improve the network voltage profiles.

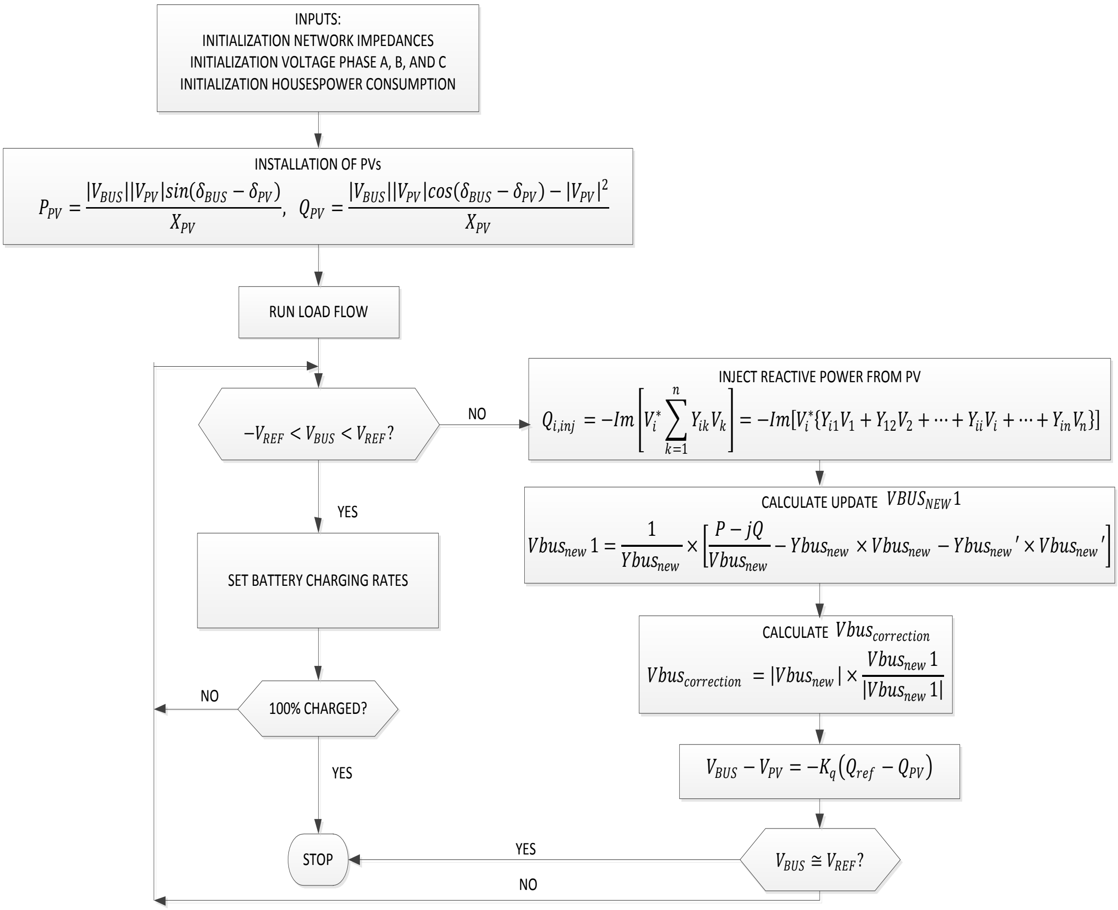


Figure 4. Flowchart of proposed algorithm for the coordination of rooftop PVs and battery storage

Firstly, we need to estimate the total loads and energy as the sum of the total AC and the total DC connected watts, then we calculate the AC average daily requirement. Thus, divide it by the inverter efficiency to obtain the DC energy required for the total AC load. Moreover, we need to calculate the total energy requirement due to DC loads, add the DC energies obtained and this quantity is the total of DC energy load on the battery bank. Additionally, Table 1 indicates the estimation of sizing the PV array, inverter, battery banks and other supporting components, respectively.

Table 1. Estimation size of PV system with BS components

PV array sizing	1. Average daily AH requirement from the battery ÷ battery columbic efficiency gives the AH to be put in by the PV array in a day 2. AH required from PV array ÷ average peak sun hours in a day of the site gives Amperes required from PV array 3. Amperes from array peak ÷ panel (or module) peak ampere gives number of PV panel strings required in parallel 4. Nominal system DC voltage ÷ nominal operating module voltage gives the number of SPV modules in one series string 5. Number of modules in one series string x number of parallel strings gives the total number of SPV modules in the pow er plant 6. Number of PV modules x PV module w attage is the total PV array w attage

Table 1. Estimation size of PV system with BS components

Selection of inverter	1.	The capacity of the inverter must be more than that of the total daily average AC loads, including their surge requirement
	2.	The nominal DC input voltage of the inverter will be the battery bank voltage and is decided by the design of the inverter
	3.	The output will be single phase or three phase, 230/440V & 50Hz, to be compatible with the AC loads requirement
	4.	The conversion efficiency at minimum load (10%) should be 80%
	5.	Total Harmonic Distortion (TDH) < 3%
	6.	The wave shape, crest factor, power factor etc, to be as per the load requirements
Battery bank sizing	1.	The total DC energy ÷ the nominal input voltage gives the daily Ampere Hour (AH) requirement from the battery bank
	2.	The daily AH hours x autonomy ÷ discharge limit provides the battery bank Ampere hour capacity
	3.	Battery bank AH capacity/Individual battery AH gives the number of batteries in parallel (generally it is 1)
	4.	DC system voltage ÷ the battery voltage gives number of batteries in series
Other supporting components	1.	Charge controller maximum current capacity should be one and half times that of total short circuit current of all parallel strings
	2.	The total open circuit voltage of all the modules in series should give the maximum voltage of the charge controller
	3.	The cables connecting the module to Junction boxes, to that of DC board and battery bank should be selected as per the standards
	4.	Cutouts, fuses and other control components should be as per the National standard of Electrical current ratings

3. Results and Analysis

A load flow algorithm is developed based on (1) to (8) and used to investigate the impacts of PV penetration on the LV distribution network of Figure 1. In this Section, the injected active and reactive powers by rooftop PVs (P_{PV},Q_{PV}) are assumed to be constant during the 24 hours period. Detailed preliminary simulations for the three-phase radial network of Figure 1 are performed to show the effectiveness of the proposed load flow algorithm as shown in Figure 5 with different penetrations, locations and rating of rooftop PVs. Detail of the developed cases is summarized in Table 2.

Table 2. The simulated case studies as shown in Figure 1

Locations of rooftop PVs (pf=0.95) with BS and PVs ratings are 1kW, 2 kW, 3 kW, 4 kW and 5 kW	Case of unbalanced three-phase system due to unequal residential loadings as recorded from a real system (Figure 1, n=13)
No PVs	Case 1, Figure 6(a)
All nodes	Case 2, Figure 6(b)
Beginning of feeder (nodes 1-5)	Case 3, Figure 6(c)
Middle of feeder (nodes 6-9)	Case 4, Figure 6(d)
End of feeder (nodes 10-13)	Case 5, Figure 6(e)

Five case studies (Cases 1-5) have been simulated with the using of actual recordings from a real system for the residential loads and rooftop PVs with BS during a 24 hours period. The system considered is the unbalanced three-phase LV networks with thirteen nodes and has unequal residential loadings. The location of rooftop PVs with the rating of 1-5kW is given differently for each case due to notice the voltage variation along the feeder.

As we can see from Figure 5(a), whereas no PVs have been installed along the feeder, the voltage variation shows significant imbalance phase-A, B, and C, respectively. On the contrary, as PVs are installed all along the feeder, the voltage variations of each phase are improving and indicate the unbalance reduction (Figure 5(b)). This is because the coordination of PV systems with BS improves the voltage profile and reduces voltage unbalance.

However, as PVs located randomly along the feeder, (Figure 5(c), (d) and (e)), the voltage profile for phase-A, B and C indicate several significant variations in the simulation cases. This is because of the rating of PVs along the feeder is random and uncertain residential loadings have been simulated for 24 hours period. It is proved that the unbalanced reduction due to the coordinate of PVs and BS that provided educated energy storage when the unequal loadings are there, have significant effect toward the anxiety of the distribution network.

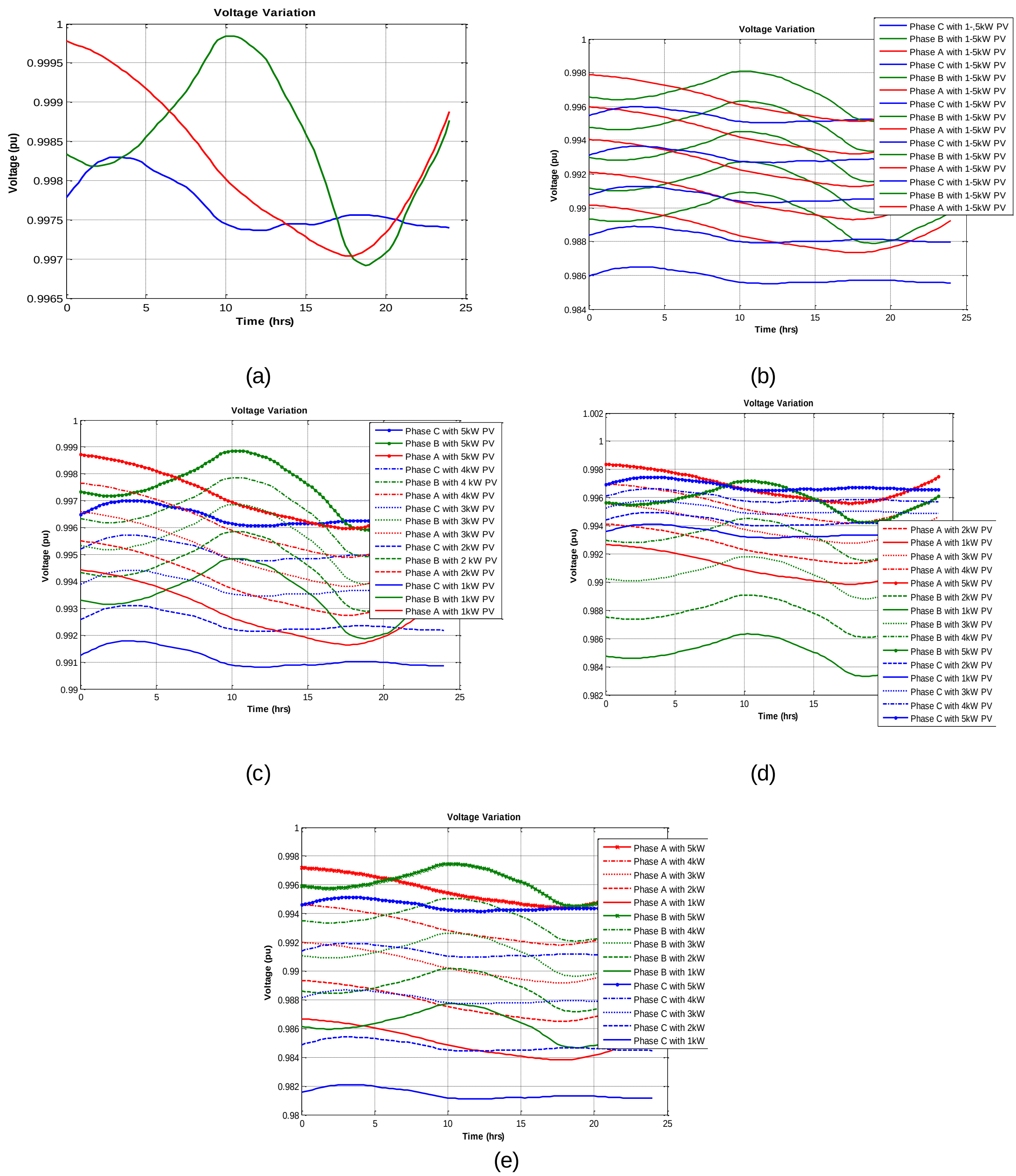


Figure 5. Simulations results showing the impact of rooftop PVs on a real system; (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4, (e) Case 5

4. Conclusion

Distributed PVs along the feeder that with reactive power control has the potential and possibility to improve the voltage profile and reduce the voltage unbalance of three-phase radial distribution networks. An algorithm based on the droop control has successfully been implemented to coordinate the reactive power injections of non-uniform single-phase rooftop PVs with the charge/discharge management of battery storage in order to regulate network voltages and reduce the voltage unbalance factor.

The load flow analysis is carried out to investigate the effects of non-uniform rooftop PVs distribution on the single- and three-phase network voltage profiles. First, the load flow simulates a voltage droop control that maintains the steady-state voltage profiles close to the reference values, up to a certain level of loading. Later, as the battery storage is included for further improvement of the voltage profiles and also the reduction of voltage unbalance that caused by the non-uniform distributions of rooftop PVs and unequal loadings conditions, is successfully done.

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