IMPACT ASSESSMENT FRAMEWORK OF PV-BES SYSTEMS TO ACTIVE DISTRIBUTION NETWORKS

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Abstract

Passive distribution networks tend to become active, due to the high penetration of photovoltaic units, battery energy storage utilization and their combined active participation to distribution network operation. In this paper a framework for the assessment of the impact of PV and BES systems on voltage profiles and power losses of active distribution networks is proposed. Also, the utilization of the BES is evaluated. The proposed methodology is applied to statistically analyse results obtained from annual timeseries power flow calculations in a real 18-bus low-voltage network considering various operational scenarios; the obtained results are quantified using a set of probabilistic indices. The proposed framework can be a useful tool for system operators to identify operational challenges and ensure the optimal exploitation of network assets.

1 Introduction

The need for clean and sustainable power becomes more critical than ever due to the negative environmental impact of the conventional power plants. For this reason, in the last decades, the installation of distributed generation (DG), and especially photovoltaics (PVs) in the low-voltage (LV) distribution network has been significantly increased [1]. According to [2], in 2022 the European PV market growth is estimated to be around 210 GWp. DGs can also contribute to reduced network power losses, voltage profile improvement and participate to the distribution network operation by providing ancillary services [3], [4]. Nevertheless, the increasing penetration of DGs in active distribution networks (ADNs) poses unprecedented technical challenges to the network operators, jeopardizing the reliable operation of power systems, e.g. power fluctuations [5], voltage rise [6], [7] and network component overloading [8].
Therefore, the systematic evaluation of the impact of DG units on the performance of ADNs is very important. For this purpose, index-based approaches have been proposed to quantify the impact of DG units on voltage profiles, line losses and environmental reduction [9] as well as to correlate reverse power flow (RPF) to voltage limit violations [10]. Similarly, in [11], [12] a set of indices is proposed to evaluate the impact of net-zero energy buildings (NZEBs) on the performance of the electricity grid.

Moreover, the rapidly developing battery energy storage (BES) technology [13] at the residential level, alongside PV systems, can improve the household self-sufficiency and also provide a variety of ancillary services [14]. However, very few papers [15] can be found in the relevant literature, investigating the impact of PV-BES systems to the performance of ADNs.

In this paper a generalized framework for the impact assessment of PV-BES systems on the operation of ADNs is proposed. The proposed framework involves the statistical analysis of steady-state results obtained from timeseries power flow calculations on annual basis. A set of new probabilistic indices is also introduced to quantify the impact of PV-BES systems in terms of voltage profiles, power losses and BES utilization. This approach can constitute a useful tool to provide valuable information during the planning phase by identifying operational challenges and ensure the optimal exploitation of network assets by evaluating PV-BES system control strategies.

2. Methodology

The proposed framework is depicted in the flowchart of Fig. 1. This involves four main steps:
1) power flow simulations
2) voltage assessment
3) power losses evaluation
4) BES utilization investigation

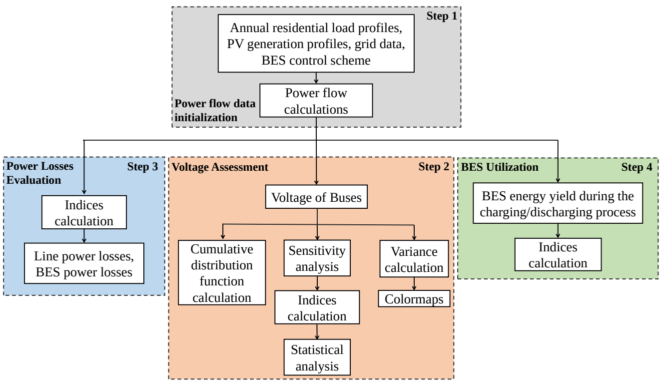

Fig. 1. Flowchart of the proposed methodology

In step 1, timeseries power flow analysis is conducted by using annual load and PV production timeseries; different scenarios are explored by statistically analyzing the obtained steady-state results. In the next step, voltage assessment is performed in terms of voltage magnitude results as well as a set of probabilistic indices. In the third step, the impact of PV-BES systems on the ADN power losses is investigated; the system power losses are decomposed to distribution line and BES losses. Finally, the performance of the BES system is evaluated, by introducing a new BES utilization indicator.

3. Simulation Model

In this section, the test network, the load and PV production data as well as the modelling of the BES are described.

3.1 System Under Study

Annual timeseries simulations of 1-h resolution (8760 samples) are conducted in the Open Distribution System Simulator (OpenDSS) software. The single-line diagram of the examined ADN is depicted in Fig. 2. Note that, the number in the brackets denotes the network bus number. The examined ADN is a radial three-phase LV network with base frequency 50 Hz, consisting of 18 buses and a 630 kVA, 20 kV / 0.69 kV delta-wye distribution transformer. The positive- and zero-sequence line impedances are: Z_1=0.215+j0.334 Ω/km and Z_0=0.363+j1.556 Ω/km, respectively. The ADN consists of 11 three-phase residential end-users classified into two main groups. Group #1 contains end-users L1-L5 (denoted with blue), each of 15.66 kVA rated apparent power (*S*) and power factor (*pf*) 0.96 lagging; Group #2 corresponds to L6-L11 (denoted with red), each of *S*=9.49 kVA and *pf*=0.95.

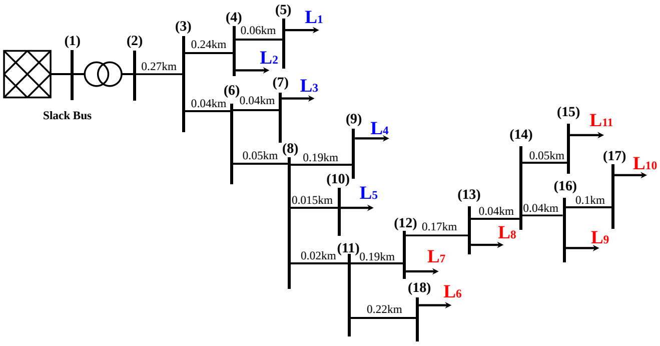

Fig. 2. Single-line diagram of the ADN

3.2 Load Timeseries

Annual residential electricity profiles from the National Renewable Energy Laboratory (NREL) dataset are used. Specifically, electricity data of the West Coast region of USA are selected, since this region presents high resemblance to the Mediterranean climate [16]. Load data of 2528 households are categorized into four main load classes, namely Res. 1-4. By averaging the annual profiles of the end-users belonging to the same load class, the representative (mean) annual profile (8760 samples) of the load class is obtained. Each of the load classes is then normalized based on the corresponding maximum power and the corresponding normalized timeseries is generated. For ease of simplicity, the daily profile (24 samples) of each load class, based on the normalized timeseries, is plotted in Fig. 3 as the average of the samples corresponding to the same time interval of the day.

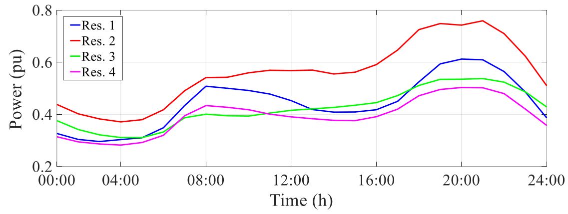

Fig. 3. Daily average profile patterns of each load class

3.3 PV Timeseries

The annual PV timeseries are obtained by the online simulation tool of [17], allowing to perform calculations of the hourly power output of PV systems. The PV model input is the hourly incident solar irradiation for 35° tilt and 180° azimuth of PV modules located in the region of Xanthi, Greece; the generated power is calculated, assuming 10 % PV system losses and PV size 1 kWp, corresponding to 1 p.u. base. In Fig. 4 the average daily profile of PV production in p.u. is presented.

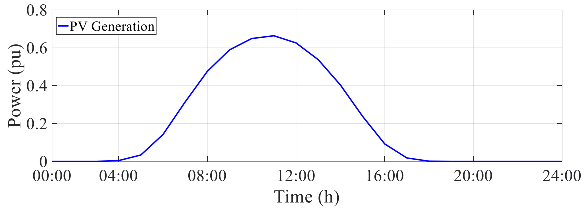

Fig. 4. Average daily production profile

3.4 BES Modelling

Each ADN prosumer can also employ a BES system. The BES modelling is described by the energy content (*E*) at each point time *t*, given in (1):

$$E(t) = E(t-1) + \eta_c \cdot P_c(t) \cdot \Delta t - \frac{1}{\eta_d} \cdot P_d(t) \cdot \Delta t, \qquad (1)$$

where Δt is the time step, P_c and P_d is the BES charging and discharging power, respectively, and η_c and η_d the corresponding charging and discharging BES efficiency. Among a variety of BES control strategies (CSs), two main CSs are examined, namely CS1 and CS2. In detail:

BES CS1: The BES charges when the load demand (P_{load}) is lower than the generated PV power (P_{PV}). Otherwise, the BES discharges. Algorithm 1 summarizes this procedure.

Algorithm 1: BES CS1

```
1: if P_load ≥ P_PV
2:     BES discharges
3: else
4:     BES charges
5: end if
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BES CS2: This strategy is designed by taking into account only the PV generated power. Specifically, when the generated power exceeds 70% of the nominal PV peak power ($P_{PVnominal}$), the BES starts charging. Otherwise, if there is no

PV production, the BES discharges. This process is described by Algorithm 2.

Algorithm 2: BES CS2

if $P_{PV} \geq 0.7 \cdot P_{PVnominal}$
  BES charges
else if $P_{PV} = 0$
  BES discharges
end if

The BES operation is constrained by its characteristics, depending on the technological type. The BES characteristics are also incorporated in the simulation model. Specifically, for Group #1 a 10 kWh BES is assumed with characteristics: P_c = P_d = 5 kW, $\eta_c = \eta_d$ = 95% and depth-of-discharge (*DoD*) 80%. Accordingly, for Group #2, a 6 kWh BES is used with P_c = P_d = 3 kW, $\eta_c = \eta_d$ = 95% and *DoD* = 80%. Note that, for both prosumer types, the BES power to energy ratio is 50%.

4 Simulation Procedure

Several scenarios are performed and the effect of various parameters to the ADN performance is evaluated. The examined network operating scenarios are:

- Passive network (reference): all network LV end-users consume energy.
- PV ADN: all LV end-users are PV prosumers.
- PV-BES ADN: all LV end-users are PV-BES prosumers.

At each scenario, the PV penetration level, i.e. the percentage of the PV size to the load nominal apparent power at each bus as well as BES characteristics, i.e. power and maximum energy content were assumed varying. The PV penetration ranges from 50% to 100%; the examined cases regarding the BES characteristics are described in Table 1. Note that, in all cases the same load and PV production timeseries is applied to all end-users.

Table 1 Examined Cases of BES Parameters

Case	**Description**	**Capacity (kWh)**		**Power (kW)**	
		Group #1	**Group #2**	**Group #1**	**Group #2**
1	Reference case	10	6	5	3
2	Power reduction (50%)	10	6	2.5	1.5
3	Power increase (50%)	10	6	7.5	4.5
4	Capacity and power increase (50%)	15	9	7.5	4.5
5	Capacity and power increase (100%)	20	12	10	6

5 Results

In this section, results obtained for the different network operating scenarios and cases are analyzed. The voltage profiles, power losses and BES utilization are investigated.

5.1 Voltage Assessment

5.1.1 Basic assessment

Initially, as a general assessment of the network voltage performance, the voltages at buses L1-L11 are statistically analysed by using cumulative distribution functions (CDFs), in order to identify general trends for each case. Note that, the CDF random variable is the voltage magnitude results of L1-L11. PV ADN and PV-BES ADN operation (Case 1) are compared, considering different PV penetration levels. In all simulations Res. 4 load pattern is employed. The resulting CDFs are summarized in Fig. 5. As expected, the voltage rise probability increases with PV penetration level due to the increased reverse power flow. However, BES utilization improves the ADN voltage profiles. This can be justified by the fact that the use of BES reduces the amount of the reverse power flowing to the grid during high generation periods. Similar remarks are also concluded for load patterns Res. 1 - 3.

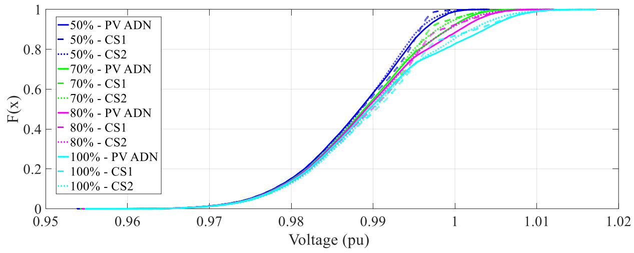

Fig. 5. CDF for varying PV penetration level

5.1.2 Systematic investigations

Next, to quantify systematically the network voltage performance, the voltage level quantification index (*VLQI*) is adopted. The *VLQI* was originally introduced in [9]. Nevertheless, the therein implementation assumes that all network nodes are of the same importance, which is not valid in real distribution networks. To consider the behaviour of the most critical network nodes, the *VLQI* is modified by introducing the sensitivity theory. Moreover, the *VLQI* is also extended to be applied for statistical analysis. The proposed probabilistic *VLQI* is defined in (2):

$$VLQI = \frac{1}{8760} \cdot \sum_{k=1}^{8760} \frac{\left(\sum_{n=1}^{N} v_n(k) w_n \right)_{\text{ADN (PV/PV-BESS)}}}{\left(\sum_{n=1}^{N} v_n(k) w_n \right)_{\text{Passive}}}, \tag{2}$$

where k is the discrete time step, N is the number of network buses (N=11), v_n is the normalized voltage at bus n and w the sensitivity (dV/dP) of bus n described by (3) [18]:

$$w_n = -\frac{1}{V_{\text{nom}}} \sum_{ab \in \left[TF^{sd}, n \right]} R_{ab}, \tag{3}$$

where V_{nom} is the nominal network voltage (0.69 kV) and R_{ab} is the total resistance of the path ab, connecting the secondary of the distribution transformer to bus n. It should be noted that, in (2) the numerator corresponds to ADN operation, while the denominator to passive operation.

The *VLQI* of the annual network voltages against PV penetration is evaluated in Fig. 6 considering different cases; results are plotted for the four load patterns. It is shown that for low penetration levels, *VLQI* acquires lower values for CS2 compared to CS1; as PV penetration increases, CS2 results into higher voltage rise. Additionally, for cases of decreased BES power, i.e. Case 2, *VLQI* becomes higher compared to reference Case 1. On the contrary, *VLQI* decreases with increasing BES capacity and power, i.e. Cases 3-5; this is evident for both BES strategies. This can be justified by the fact that the increased BES capacity and power provides an additional flexibility to the grid, leading to reduced network voltages, since the reverse power flow is decreased during high generation periods.

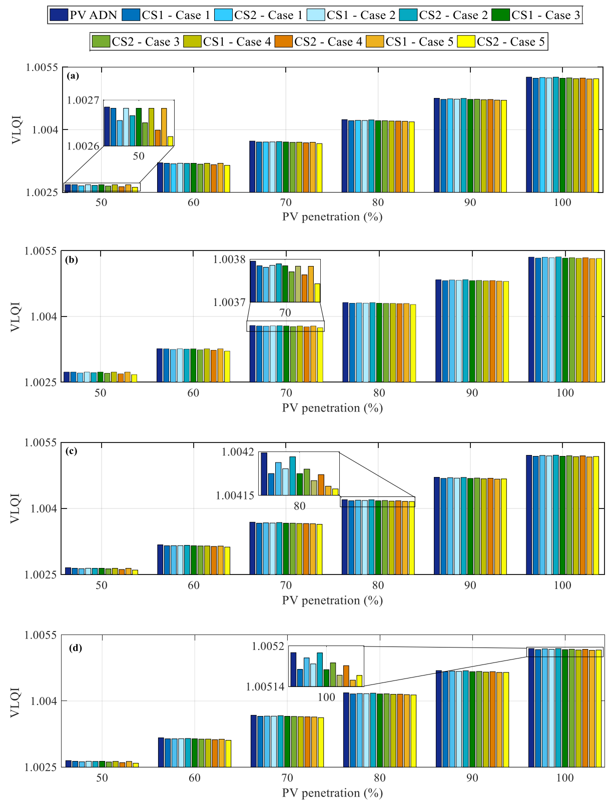

Fig. 6. Probabilistic *VLGI* against PV penetration for (a) Res. 1, (b) Res. 2, (c) Res. 3, (d) Res. 4

5.1.3 Voltage sensitivity analysis

Finally, in order to statistically analyse the impact of the PV-BES on voltage variations during the day, the mean voltage variance index is calculated in (4) for each network bus:

$$\sigma_{n,h}^{2}=\frac{1}{D-1}\sum_{d=1}^{D}\left|V_{n}\left(d,h\right)-\bar{V}_{n}\left(h\right)\right|^{2} \tag{4}$$

where D is the total number of days (365), V is the voltage magnitude of bus n and $\bar{V}$ is the annual mean voltage for hour h.

The $\sigma^2_{n,h}$ results for all network buses are visualized in Fig 7, by using colour maps. Results for PV-BES ADN (CS1 and CS2) as well as for PV ADN operation are presented, assuming Res. 4 load pattern and 50 %, 70 % and 100 % PV penetration. It is shown that the most distant bus of the feeder, i.e. No. 17, is the most sensitive (also verified by Eq. (3) calculations), since significant voltage variation is observed for all cases. It can be also realized that voltage variations are more often during the day for PV-BES ADN operation; this is more evident for CS2. Lower σ^2 is observed when CS1 applies, resulting into smoother voltage profiles compared to CS2.

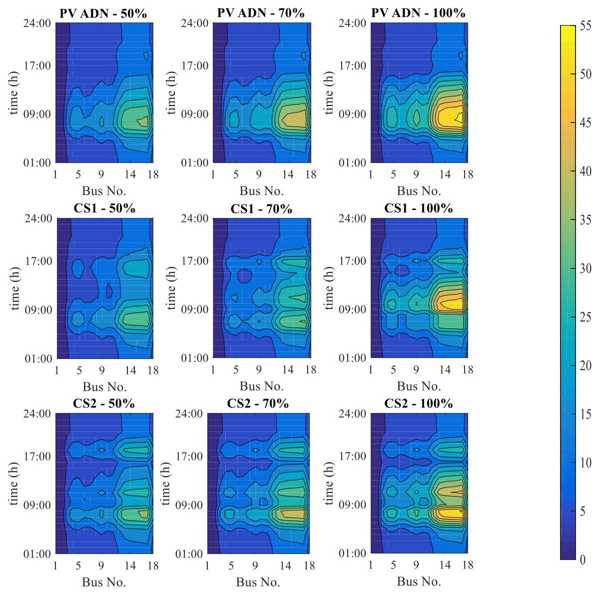

Fig. 7. Voltage variance of buses for Res. 4 (Case 1)

5.2 Power Losses Evaluation

In this section, the effect of the PV-BES operation on the total ADN power losses is systematically evaluated. For this purpose, the losses reduction index (*LRI*) and the losses to load ratio (*LLR*), defined in (5) and (6), respectively, are used.

$$LRI(\%)=\frac{\Sigma P_{\text{Losses(ADN)}}}{\Sigma P_{\text{Losses(Passive Network)}}} \tag{5}$$

$$LLR(\%)=\frac{\Sigma P_{\text{Losses(ADN)}}}{\Sigma P_{\text{Load}}} \tag{6}$$

where $\Sigma P_{\text{Losses(ADN)}}$ and $\Sigma P_{\text{Losses(Passsive Network)}}$ are the system losses (line and BES system losses) for ADN and passive network operation, respectively; ΣP_{Load} is the total load demand. Both indices can be used to determine the optimal PV penetration level in terms of minimum system losses. Note that, *LRI* and *LLR* were originally proposed to evaluate the impact of DGs on distribution networks [9], [19]. In this work, *LRI* and *LLR* are modified to analyse PV-BES prosumers, thus apart from line losses also BES losses (due to η_c, $\eta_d \neq 100\%$) are included in (5) and (6).

In Fig. 8 the *LRI* variation against PV penetration is presented for all cases and load patterns; both BES CS1 and CS2 are examined. Results generally reveal that system losses are mostly affected by CS1, since in this case system losses are an increasing function of PV penetration. On the other hand, regarding CS2 LRI results are practically unaffected. For low penetration levels, the LRI acquires higher values for CS2 than CS1. This is due to the more often use of the BES system in CS2, resulting consequently into higher BES losses. The opposite behavior is observed for higher penetration levels, e.g. >80 %. Regarding the effect of BES characteristics, it is shown that for Cases 2 and 3, i.e. the BES power modification from the reference Case 1, the LRI is similar to that of Case 1; this is evident for both BES

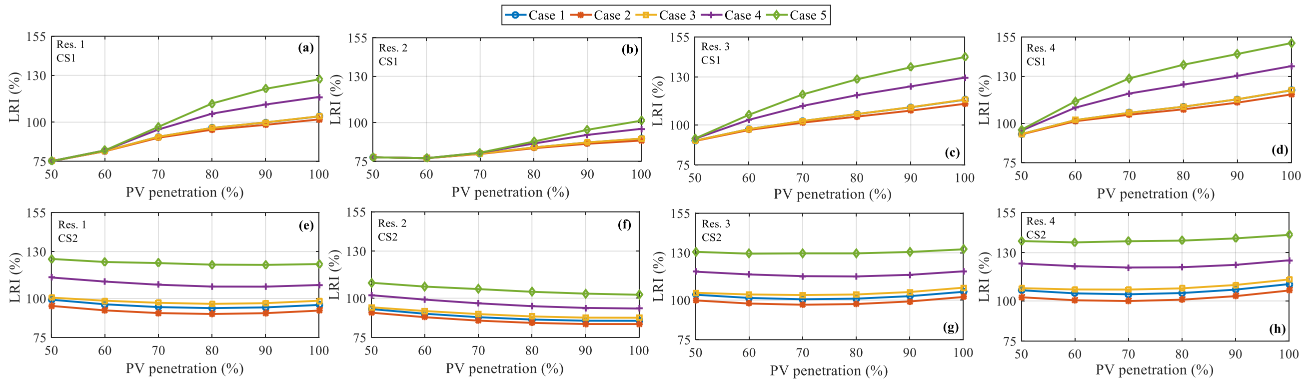

Fig. 8. LRI against PV penetration for different cases

strategies. However, for Cases 4 and 5 the LRI acquires higher values, especially with increasing PV penetration. This reason behind this lies on the use of a BES with increased installed capacity and maximum output power. More specifically, this type of BES can handle larger amounts of energy during the day. Thus, the corresponding BES losses are significantly increased leading to higher values of the *LRI*. Similar results as above can be concluded for *LLR*, thus results are not presented.

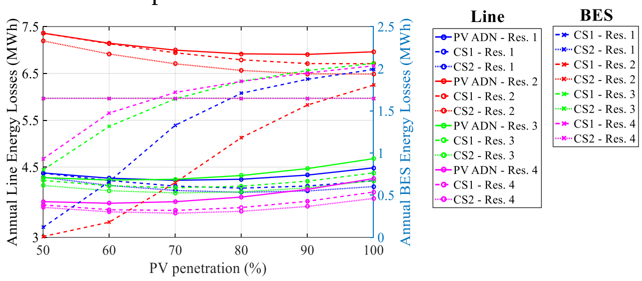

Fig. 9. Annual grid and BES energy losses with PV penetration (Case 1)

In Fig. 9 the total system losses are decomposed to distribution line (left *y*-axis) and BES (right *y*-axis) losses. Their variation against PV penetration is analysed for Case 1, assuming load patterns Res. 1 - 4. Line losses for patterns Res. 1, 3 and 4 decrease up to a certain value of the penetration level; above this value line losses start to increase, due to reverse power flows as a result of energy excess from prosumers. On the other hand, line losses for load pattern Res. 2 is a decreasing function of PV penetration. Comparing PV-BES ADN and PV ADN operation it can be observed, that PV-BES operation results into reduced line losses, especially when CS2 is applied. Contrary to CS1, in CS2, the BES charges only for high levels of PV production, absorbing the surplus energy and preventing it from being injected into the grid which causes additional losses. Finally, from Fig. 8 it can deduced that the annual line and the corresponding BES losses can be generally regarded comparable. For CS1, BES losses increase with PV penetration, while for CS2 the BES losses remain constant (curves for Res. 1-4 overlap).

5.3 BES Utilization

To evaluate the performance of the BES system, the battery utilization index (*BUI*) is proposed; *BUI* is the ratio of the annual energy yield ($E_{\text{ch/disch}}$) during BES charging/discharging process to the annual energy yield (E_{rated}) on the basis of BES rated characteristics, as shown in (7):

$$BUI\,(\%) = E_{\text{ch/disch}} / E_{\text{rated}} \tag{7}$$

where $E_{\text{ch/disch}}$ and E_{rated} are calculated by (8) and (9).

$$E_{\text{ch/disch}}\,(\text{kWh}) = \sum_{k=1}^{8760} E_{\text{oper}}^{\text{ch/disch}}(k) \tag{8}$$

$$E_{\text{rated}}\,(\text{kWh}) = 365 \cdot E_{\max} \cdot DoD \tag{9}$$

where E_{oper} is the charging/discharging energy during the BES operation and $E_{\max}$ is the maximum energy content (capacity) of the BES.

In Fig. 10, *BUI* variation of charging process against PV penetration is examined for different cases of CS1. Similar results are emerged for BUI variation of discharging process; thus, results are not presented. It is evident that *BUI* is generally an increasing function with PV penetration. Comparing the results of the four load patterns, it can be observed that as PV penetration increases *BUI* curves tend to 80 %, regarding Res. 1, 3 and 4; the corresponding *BUI* level for Res. 2 is 70 %. For low penetration levels the highest *BUI* value is observed for Res. 4. This occurs due to the relatively high misalignment between the load and generation profiles, leading to increased BES operation. *BUI* curves for Cases 1 - 3 overlap; for Cases 4 and 5, i.e. cases of increased BES capacity, lower values are calculated. This reveals that an increase of the BES power and/or capacity may result into unnecessary investment costs.

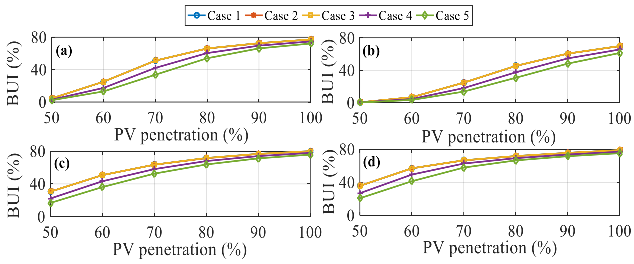

Fig. 10. *BUI* (charging) against PV penetration for (a) Res. 1 (b) Res. 2 (c) Res. 3 (d) Res. 4. BES CS 1

BUI variation with PV penetration for BES CS2 is depicted in Fig. 11. Similar results are obtained for all load patterns, since under CS2 the BES operation depends only on the PV production. It is shown that for cases 1 and 2, BUI remains constant against PV penetration, acquiring values equal to ~64 % and 59 %, respectively. Comparing these cases, it can be deduced that BES power reduction by 50% results only into a slight BUI decrease (5%). For Caseσ 3, 4 and 5, the same behavior is observed as for BES CS1.

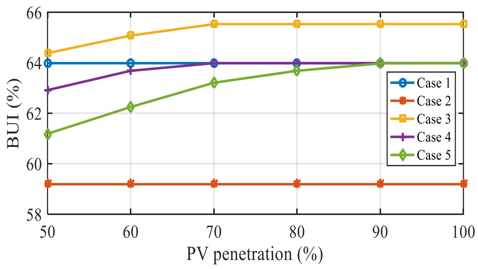

Fig. 11. BUI (charging process) against PV penetration for BES CS2

From the comparative assessment of the *BUI* results regarding BES CS1 and CS2, it can be concluded that for low penetration levels higher BES utilization is achieved under BES CS2; the opposite behavior is observed as PV penetration increases. Furthermore, it worth mentioning that *BUI* is strongly related to the BES losses. Thus, similar conclusions can be drawn when assessing these indices. For example, the BES losses of CS1 are greater than of CS2 when the *BUI* of CS1 is greater than of CS2.

6 Conclusion

This paper presents a generic framework for the assessment of the impact of PV-BES systems on the performance of ADNs. Timeseries power flow calculations are conducted on annual basis and the obtained results are statistically analyzed. Additionally, a set of new probabilistic indices is developed to quantify systematically the impact of different operating conditions on the ADN voltage profiles, power losses and BES system utilization. More specifically:

- The proposed statistical analysis framework regarding voltage assessment can assist the evaluation of the voltage levels and indicate the most proper operating scenario in terms of voltage profile improvement.
- The introduced voltage variance index can help DSOs to identify and verify the most sensitive buses to voltage variations; this enables them to take measures regarding the system limits.
- Annual BES losses can be comparable to distribution line losses. Therefore, they should be taken into account for the evaluation of the total system losses.
- Both *LRI* and *LLR* can be used to determine the optimal PV penetration level in order to achieve minimum system losses.
- The proposed *BUI* can constitute a useful tool for the assessment of the BES applicability under different operating conditions.

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8 References

[1] Olivares, D. E., Mehrizi-Sani, A., Etemadi, A. H., et al.: 'Trends in microgrid control,' IEEE Trans. Smart Grid, 2014, 5, (4), pp. 1905–1919

[2] Gaetan, M., Sinead, O., Manoel, R.: 'Global market outlook,' EPIA - European Photovoltaic Industry Association, 2018, pp. 1-60

[3] Chowdhury, B. H., Sawab, A. W.: 'Evaluating the value of distributed photovo1aic generations in radial distribution systems,' IEEE Trans. Energy Convers., 1996, 11, (3), pp. 595–600

[4] Srisaen, N., Sangswang, A.: 'Effects of PV grid-connected system location on a distribution system,' Proc. IEEE Asia Pac. Conf. Circuits Syst., December, 2006, pp. 852–855

[5] Sukumar, S., Mokhlis, H., Mekhilef, S., et al.: 'Ramp-rate control approach based on dynamic smoothing parameter to mitigate solar PV output fluctuations,' International Journal of Electrical Power and Energy Systems, 2018, 96, pp. 296–305

[6] Kryonidis, G. C., Kontis, E. O., Chrysochos, A. I., et al.: 'A Coordinated Droop Control Strategy for Overvoltage Mitigation in Active Distribution Networks,' IEEE Trans. Smart Grid, 2018, 9, (5), pp. 5260–5270

[7] Nousdilis, A. I., Christoforidis, G. C., Papagiannis, G. K.: 'Active power management in low voltage networks with high photovoltaics penetration based on prosumers’ self-consumption,' Applied Energy, 2018, 229, pp. 614–624

[8] Robak, S., MacHowski, J., Gryszpanowicz, K.: 'Automatic Alleviation of Overloads in Transmission Network by Generation Curtailment,' IEEE Trans. Power Syst., 2018, 33, (4), pp. 4424–4432

[9] Chiradeja, P., Ramakumar, R.: 'An approach to quantify the technical benefits of distributed generation,' IEEE Trans. Energy Convers., 2004, 19, (4), pp. 764–773

[10] Hasheminamin, M., Agelidis, V. G., Salehi, V., et al.: 'Index-Based Assessment of Voltage Rise and Reverse Power Flow Phenomena in a Distribution Feeder under High PV Penetration,' IEEE Journal of Photovoltaics, 2015, 5, (4), pp. 1158–1168

[11] Verbruggen, B., Driesen, J. 'Grid impact indicators for active building simulations,' IEEE Trans. Sustain. Energy, 2015, 6, (1), pp. 43–50

[12] Gjorgievski, V., Cundeva, S.: 'The effects of residential battery storage on grid impact indicators,' 2019 IEEE Milan PowerTech, PowerTech 2019, June, 2019

[13] Tan, X., Li, Q., Wang, H.: 'Advances and trends of energy storage technology in Microgrid,' International Journal of Electrical Power and Energy Systems, 2013, 44, (1), pp. 179–191

[14] Li, X., Wang, S.: 'A review on energy management, operation control and application methods for grid battery energy storage systems,' CSEE Journal of Power and Energy Systems, 2019

[15] Katsanevakis, M., Stewart, R. A., Junwei, L.: 'A novel voltage stability and quality index demonstrated on a low voltage distribution network with multifunctional energy storage systems,' Electric Power Systems Research, 2019, 171, pp. 264–282

[16] Nousdilis, A. I., Chrysochos, A. I., Papagiannis, G. K., et al.: 'The impact of Photovoltaic Self-Consumption Rate on voltage levels in LV distribution grids,' IEEE International Conference on Compatibility, Power Electronics and Power Engineering, 2017, pp. 650–655 .

[17] Pfenninger, S., Staffell, I., ‘Renewables.ninja’, Available: https://www.renewables.ninja/, accessed December 2019.

[18] Brenna, M., Berardinis, E. De, Carpini, L. D., et al.: 'Automatic Distributed Voltage Control Algorithm in Smart Grids Applications,' IEEE Trans. Smart Grid, 2013, 4, (2), pp. 877–885.

[19] Alam, M. J. E., Muttaqi, K. M., & Sutanto, D.: 'An approach for online assessment of rooftop solar PV impacts on low-voltage distribution networks,' IEEE Trans. Sustain. Energy, 2014, 5, (2), pp. 663–672