# Long-term Evaluation of DRES Penetration in LV Networks using Droop Control Techniques

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*Abstract*—**The main objective of this paper is to investigate the maximum penetration level of distributed renewable energy sources (DRESs) in a real radial low-voltage network. For this purpose, the business as usual (BAU) scenario, where no control scheme is applied to the installed DRESs, is compared with two conventional droop control techniques, namely the active power curtailment and the uniform power curtailment. Appropriate key performance indicators are introduced to evaluate the long-term performance of the examined control strategies. Simulation results show that, compared to the BAU scenario, a higher penetration level can be attained by exploiting the above-mentioned droop control schemes.**

*Index Terms*--**Active power curtailment, distributed generation, droop control, key performance indicators, overvoltage mitigation.**

## I. Introduction

Over the last decade, environmental concerns, regarding the reduction of carbon emissions as well as the market deregulation, have increased the penetration of distributed renewable energy sources (DRESs), which are mainly connected to the distribution network by means of electronic power inverters [1]. This advent has changed the conventional operation of the distribution network from a downstream unidirectional power flow to a bidirectional one, posing a series of technical challenges, which must be addressed by the distribution system operators (DSOs) [2].

One of the most substantial problems in low-voltage (LV) distribution networks is the overvoltages that occur due to the active power injection of the DRESs. Therefore, voltage rise is considered as an important limiting factor, concerning the further penetration of DRESs in the existing distribution networks [3]. Although classical approaches, such as the grid reinforcement and the use of transformer on-load tap changers, are the most straightforward solutions, they are not commonly preferred by the DSOs due to the high investment costs. On the other hand, techniques based on active power curtailment are the most promising methods for efficient voltage regulation [4].

The $P(V)$ droop characteristic is considered as the most typical decentralized active power curtailment (APC) method and is preferred over conventional centralized techniques, since no communication infrastructure is required [6]-[7]. The principal objective of the APC method is to mitigate overvoltages by curtailing part of the total injected active power of the installed DRESs. However, a significant drawback of the APC strategy is the non-uniform power curtailment among the DRESs [8]. To alleviate this problem, a number of coordinated APC techniques, known as fair power sharing (FPS) algorithms, has been proposed that reallocate the curtailed power among the DRESs [9]-[12] in a more uniform way.

In this paper, the conventional APC method and the most common FPS control scheme are thoroughly investigated to evaluate the maximum penetration level of DRESs in a radial LV network. Time-series simulations are performed for both short- and long-term periods and appropriate key performance indicators (KPIs) are proposed so as to quantify the performance of the examined methods, compared to the business as usual (BAU) scenario, where no DRES control scheme is considered.

The paper is organized as follows: In Section II, the examined control schemes are briefly described and appropriate KPIs are proposed. The system under study is discussed in Section III, while in Section IV the corresponding simulation results and the evaluation of the control schemes are presented. Finally, in Section V the conclusions are drawn and plans for future work are proposed.

## II. Description and Evaluation of the Proposed Controls

The most common approaches, regarding the voltage regulation in LV networks, are briefly presented and discussed. Furthermore, appropriate KPIs are introduced to assess the effectiveness of each approach.

### A. Active Power Curtailment Method

One of the most promising and effective solutions to the overvoltage problems in LV networks is the APC method

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applied to the DRESs. The active power injection $P_{inj}$ of each DRES depends on the voltage magnitude at the corresponding point of common coupling (PCC), as shown in Fig. 1. The control scheme is expressed mathematically by a piecewise function comprising of three regions, as expressed in (1),

$$P_{inj}=\begin{cases} P_{MPP}, & V_{min}<V_g\leq V_{cpb} \\ P_{MPP}-P_{MPP}\dfrac{\left(V_g-V_{cpb}\right)}{\left(V_{max}-V_{cpb}\right)}, & V_{cpb}<V_g<V_{max} \\ 0, & V_{min}\geq V_g \text{ or } V_g\geq V_{max} \end{cases} \quad (1)$$

where $V_{min}$ and $V_{max}$ represent the operational limits of the inverter-interfaced DRES, $V_{cpb}$ stands for the voltage threshold indicating the activation of the APC and $P_{MPP}$ is the maximum power point (MPP) that the DRES unit can deliver at a specific time instant, defined from the available power of the primary source. In the first region, the active power injection is kept constant to $P_{MPP}$ regardless of the grid voltage. In the second region, droop control is activated, while in the third one, the power injection is zeroed.

The droop-based curtailment of (1) leads to overvoltage mitigation in LV networks, while it also avoids the repeated tripping of overvoltage relays implemented in typical step-wise approaches of APC [13]. However, without proper modifications, the APC method generally results in non-uniform power curtailment among inverter-based DRESs connected along a feeder. This occurs due to the different voltage at the PCC of each inverter along the radial network, caused by the varying grid impedance.

### B. Fair Power Sharing Algorithm

The main objective of the FPS algorithm is to ensure a uniform power curtailment among the DRESs, by employing the sensitivity matrix and resetting the droop characteristics of each inverter. The sensitivity matrix is obtained by conducting a power flow analysis for the LV feeder under study. The sensitivity analysis is used to quantify the impact of the active and reactive power variations with respect to the voltage at the radial distribution feeder. Thus, the voltage magnitude $\Delta V$ and angle $\Delta\theta$ variations are calculated according to (2),

$$\begin{bmatrix}\Delta\theta \\ \Delta V\end{bmatrix}=S\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix}=\begin{bmatrix}S_P^{\theta} & S_Q^{\theta} \\ S_P^{V} & S_Q^{V}\end{bmatrix}\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \quad (2)$$

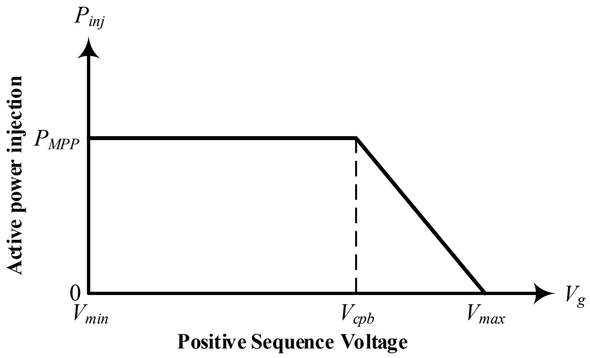

Figure 1. Droop curve of controllable DRES.

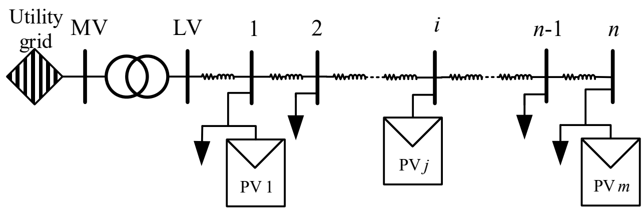

Figure 2. Typical radial LV feeder.

where $S$ denotes the sensitivity matrix, consisting of four submatrices that refer to the partial derivatives of node voltage magnitude and angle against active and reactive power.

A simple implementation of the FPS method is demonstrated on the radial LV network of Fig. 2. Since active power curtailment techniques are adopted in this paper, only the sub-matrix $S_P^V$ is considered for the implementation of the FPS control strategy. Therefore, the curtailed active power $\Delta P_{curt}$ of the DRES with the minimum $P_{MPP}$ is given by (3), while the vector of the active power curtailments $\boldsymbol{P}_{curt}$ of the other $m$-1 DRESs in the feeder are given in a percentage-based fair way by (4).

$$\Delta P_{curt}=\frac{\Delta\left|V_{g,\max}\right|}{\sum_{i=1}^{m} w_i x_{ji}} \quad (3)$$

$$\boldsymbol{P}_{curt}=\Delta P\cdot\boldsymbol{w} \quad (4)$$

where $\Delta|V_{g,max}|$ is the voltage magnitude of the node with the maximum voltage, $x_{ji}$ are the corresponding elements of the sub-matrix $S_P^V$, and $\boldsymbol{w}$ is the weighting vector related to the MPP conditions.

### C. Combination of the Proposed Controls

The combined operation of the above-mentioned control schemes is presented in Fig. 3 by means of a flowchart. For each time instant $t$, the APC algorithm mitigates the possible voltage rise along the examined network. Then, if different amount of active power curtailment is detected, the FPS algorithm is enabled and the percentage-based power curtailment of each inverter is calculated using (3) and (4). The calculated active power injections result in new operating voltages. Therefore, to achieve these new settings, reconstruction of the droop characteristics is required. The reconstruction is performed as shown in Fig. 4 based on the new operating conditions defined by the FPS method. In this way, the curtailed power is reallocated among the installed inverters of the network.

### D. Evaluation of the Proposed Controls

In order to investigate the effectiveness of the proposed control strategies, two KPIs are introduced. The first one is used to assess the maximum DRES penetration and is defined as follows:

$$\text{KPI}_\text{P}=\frac{\text{Total Injected Energy (Proposed)}}{\text{Total Injected Energy (BAU)}} \quad (5)$$

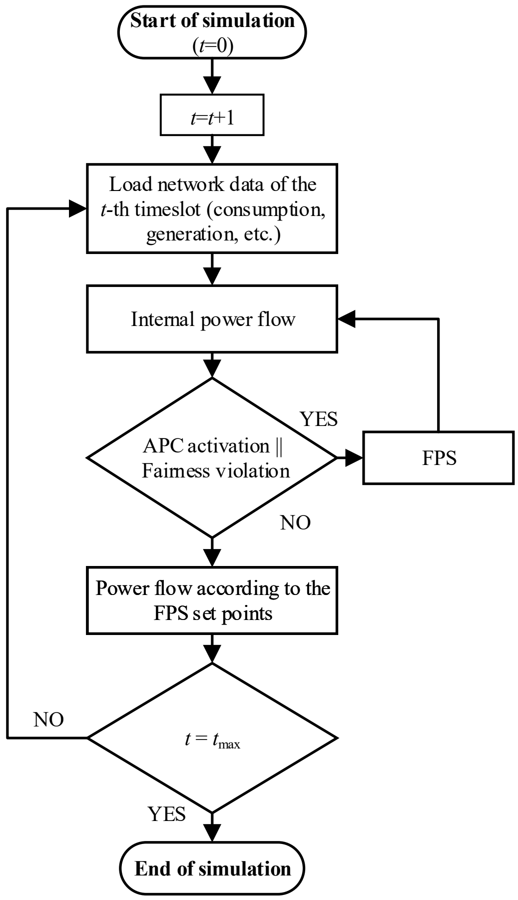

Figure 3. Simulation flowchart.

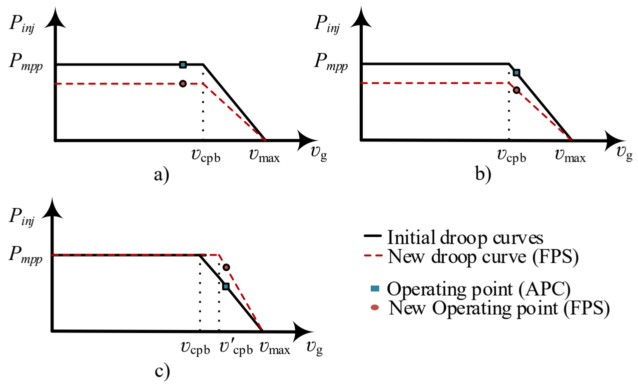

Figure 4. Reconfiguration of inverter droop curves.

A $KPI_P$ factor greater than 1 indicates that the total produced energy is increased by the proposed control strategies, compared to the BAU scenario. On the other hand, a $KPI_P$ factor lower than 1 denotes that the proposed control has an adverse effect on the total produced energy.

The second KPI evaluates the uniformity of power curtailment among a group of DRESs and is introduced as,

$$KPI_F = \frac{\text{Power of the DRES}_i \text{ injecting minimum}/\text{MPP}_i}{\text{Power of the DRES}_j \text{ injecting maximum}/\text{MPP}_j} \quad (6)$$

where both terms denote normalized injected power to the corresponding MPP. A $KPI_F$ factor close to 1 shows an almost uniform active power curtailment among the examined DRESs.

## III. SYSTEM UNDER STUDY

The proposed control strategies are investigated for a single feeder, which is part of a real Slovenian LV network. In this network, only one type of DRESs is considered, namely PV units. The network topology is depicted in Fig. 5, where the examined feeder is highlighted by the blue line. The feeder consists of 11 nodes and the corresponding line characteristics are presented in Table I. The transformer connection is Dyn5 and has a nominal power of 250 kVA, short-circuit voltage of 4%, while the no-load losses and on-load losses are 325 W and 3250 W, respectively.

Scope of the analysis is to investigate the impact of the examined controls on the maximum penetration level and the fairness of the power curtailment. For this purpose, three distinct cases are considered and examined: In the first case, which is considered as the BAU scenario, no control is applied to the PV units which inject their MPP at each time instant. In the second one, the APC method is incorporated to the PV

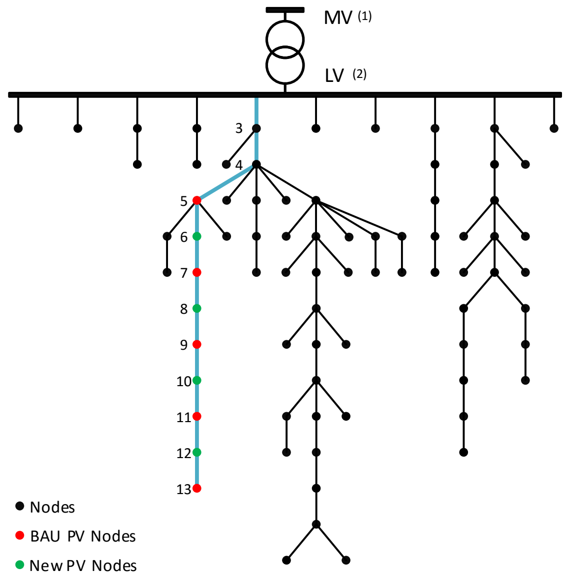

Figure 5. Network topology.

TABLE I. LINE CHARACTERISTICS

| Line | $I_{max}$ (A) | $R_1$ (Ω) | $X_1$ (Ω) | $R_0$ (Ω) | $X_0$ (Ω) | C (μF) |
|---|---|---|---|---|---|---|
| 2-3 | 275 | 0.018 | 0.006 | 0.324 | 0.2997 | 0.0243 |
| 3-4 | 275 | 0.012 | 0.004 | 0.224 | 0.2072 | 0.0168 |
| 4-5 | 120 | 0.061 | 0.005 | 0.264 | 0.2706 | 0.0132 |
| 5-6 | 145 | 0.034 | 0.004 | 0.208 | 0.1976 | 0.013 |
| 6-7 | 120 | 0.033 | 0.003 | 0.144 | 0.1476 | 0.0072 |
| 7-8 | 120 | 0.027 | 0.002 | 0.116 | 0.1189 | 0.0058 |
| 8-9 | 120 | 0.035 | 0.003 | 0.152 | 0.1558 | 0.0076 |
| 9-10 | 120 | 0.05 | 0.004 | 0.216 | 0.2214 | 0.0108 |
| 10-11 | 120 | 0.032 | 0.003 | 0.136 | 0.1394 | 0.0068 |
| 11-12 | 120 | 0.047 | 0.004 | 0.204 | 0.2091 | 0.0102 |
| 12-13 | 120 | 0.027 | 0.002 | 0.116 | 0.1189 | 0.0058 |

units, whereas in the third approach, the FPS algorithm is employed.

## IV. Simulation Results

To effectively compare the above-mentioned control strategies, time-series simulations are conducted for one day, using the simulation tool developed in [14], and taking into consideration the daily generation and consumption profiles provided by the DSO. The normalized generation profile which is applied to all PV units is depicted in Fig. 6, whereas the aggregated active and reactive power consumption profiles of the feeder for each phase are shown in Figs. 7 and 8, respectively. Considering the BAU scenario, voltage rise

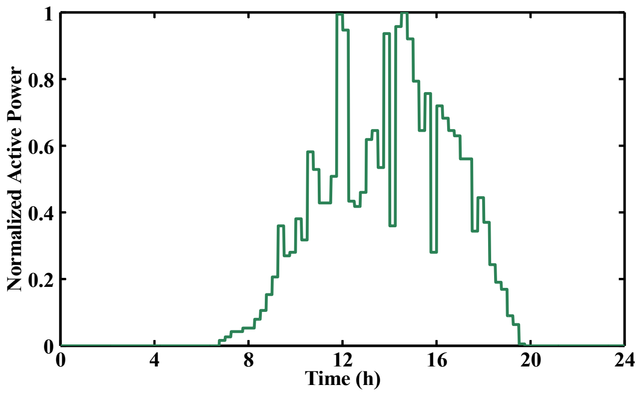


Figure 6. Normalized active power generation profile.

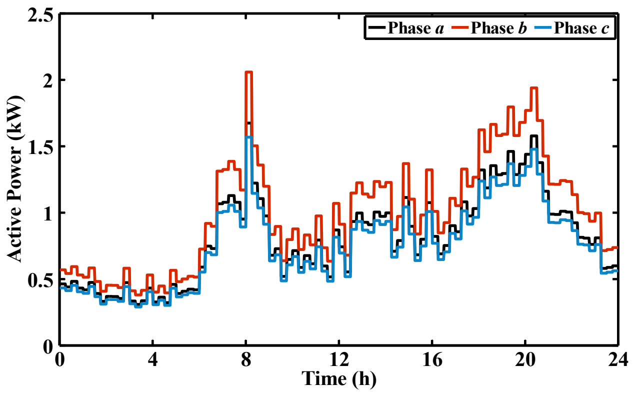


Figure 7. Active power of the aggregated load.

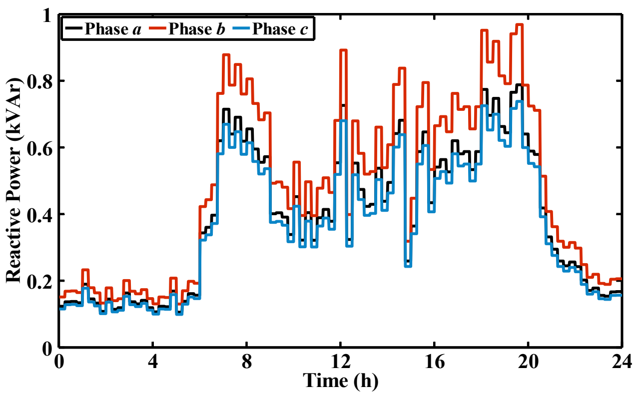


Figure 8. Reactive power of the aggregated load.

TABLE II. Maximum Rated Power (BAU Scenario)

| PV name | Node | Nominal Power (kW) |
|---|---|---|
| PV 5 | 5 | 11.65 |
| PV 7 | 7 | 9.31 |
| PV 9 | 9 | 13.98 |
| PV 11 | 11 | 18.65 |
| PV 13 | 13 | 16.3 |
| **Total** | | 69.89 |

along the feeder is the first met limiting factor of PV penetration, since no control is applied to the PV units. On the other hand, this limiting factor is effectively addressed by the APC and FPS methods. In these cases, the penetration can be further increased, until reaching the thermal limit of the lines.

### *A. Business as Usual Scenario*

In the BAU scenario 5 PV units are connected along the feeder. Their names and the corresponding connection nodes are presented in Table II. Initially, referring to the time instant with the minimum load and the maximum generation, the rated power of the PV units is arbitrarily chosen and is increased until one of the nodes reaches the maximum permissible voltage, defined at 1.1 pu according to EN 50160 [15]. Then, the final nominal power of the PV units for the BAU scenario is shown in Table II.

The PV units of the BAU scenario remain in the network and the droop control is incorporated into them, while 4 additional PV units are connected along the feeder. Since the overvoltage problem is fully addressed by the APC method, the thermal current is the limiting factor of the PV penetration. The rated power of the new PV units is arbitrarily chosen and is increased, until reaching the line thermal limit.

Three different cases of the APC scheme are considered and examined. More specifically, in the first case, $V_{cpb}$ is considered equal to 1.06 pu, whereas in the second one $V_{cpb}$ equals to 1.08 pu. In the third case, the voltage threshold for the preinstalled PV units of the BAU scenario is considered equal to 1.08 pu, while the voltage threshold of the new PV units is equal to 1.06 pu, i.e. the mixed case. The corresponding calculated maximum rated power for the above-mentioned cases are presented in Table III. As shown, the total installed rated power is significantly increased, when the APC is activated.

TABLE III. Maximum Rated Power

| | | Rated Power (kW) | | |
|---|---|---|---|---|
| | | $V_{cpb}$ | | |
| **PV name** | **Node** | **1.06** | **1.08** | **1.06/1.08** |
| PV 5 | 5 | 11.65 | 11.65 | 11.65 |
| PV 6 | 6 | 32.97 | 20.87 | 29.85 |
| PV 7 | 7 | 9.31 | 9.31 | 9.31 |
| PV 8 | 8 | 57.7 | 36.21 | 52.24 |
| PV 9 | 9 | 13.98 | 13.98 | 13.98 |
| PV 10 | 10 | 65.95 | 41.73 | 59.7 |
| PV 11 | 11 | 18.65 | 18.65 | 18.65 |
| PV 12 | 12 | 49.46 | 31.3 | 44.77 |
| PV 13 | 13 | 16.3 | 16.3 | 16.3 |
| **Total** | | 275.97 | 200 | 256.45 |

## B. The FPS Control Scheme

In this scenario, the FPS algorithm is integrated to the APC method in order to reallocate the curtailed power, while the combined operation of the APC and FPS control schemes is examined. The penetration level for each examined case is considered equal to the one presented in Table III. These values are selected as the corresponding limits since the maximum penetration level has been already defined by the APC method.

## C. Control Strategies Evaluation

The daily produced energy of all PV units is depicted in Fig. 9, where the examined control strategies are compared with the BAU scenario. The incorporation of the APC method to the PV units of the BAU scenario results to a reduced power injection for these units. However, in all the examined cases, the total installed PV capacity and thus the overall produced energy is significantly increased. The maximum captured energy is observed for the case where only the APC control scheme is enabled and the $V_{cpb}$ is considered equal to 1.06 pu. Furthermore, it can be concluded that the $V_{cpb}$ affects significantly the total penetration level. Based on the results depicted in Fig. 9, it seems that $V_{cpb}$ does not substantially affect the total amount of the captured energy. However, according to Table III, it is evident that a greater $V_{cpb}$ reduces the overall installed capacity, and thus the produced energy per installed capacity is eventually increased. This is verified from Table III and Fig. 9, where the daily produced energy per installed capacity is 2.86 and 3.77 kWh/kW for $V_{cpb}$ equal to 1.06 and 1.08 pu, respectively. Moreover, simulation results show that the incorporation of the FPS strategy has an adverse effect on the total produced energy. However, it is worth noting that the overall captured energy is still higher than in the BAU case.

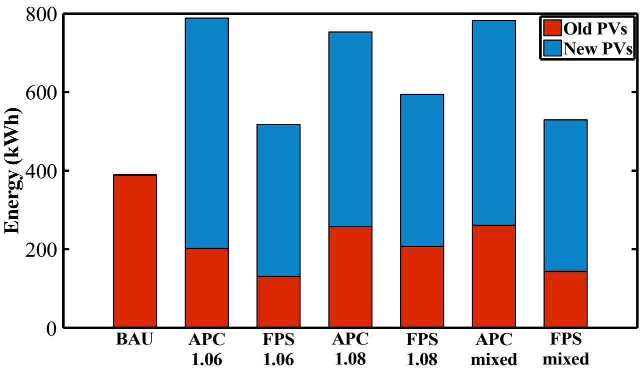

Figure 9. Daily produced energy.

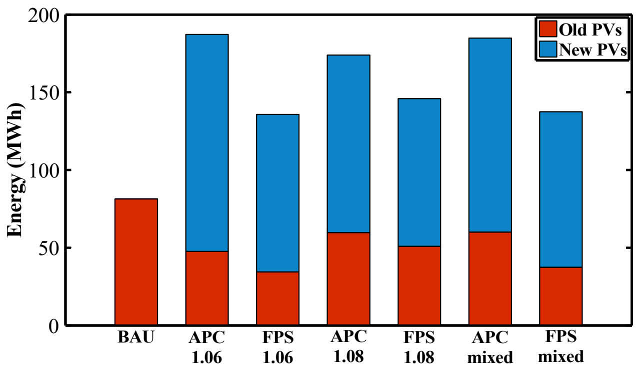

Figure 10. Yearly produced energy.

TABLE IV. KPI OF THE MAXIMUM PENETRATION LEVEL

| Control Strategy | $KPI_P$ | |
|---|---|---|
| | Daily | Yearly |
| APC (1.06) | 2.02 | 2.31 |
| FPS (1.06) | 1.33 | 1.67 |
| APC (1.08) | 1.93 | 2.14 |
| FPS (1.08) | 1.53 | 1.79 |
| APC (mixed) | 2.01 | 2.27 |
| FPS (mixed) | 1.36 | 1.69 |

TABLE V. KPI REGARDING THE FAIRNESS OF THE CURTAILMENT

| Control Strategy | $KPI_F$ | |
|---|---|---|
| | Daily | Yearly |
| APC (1.06) | 0.48 | 0.60 |
| FPS (1.06) | 0.99 | 0.99 |
| APC (1.08) | 0.59 | 0.72 |
| FPS (1.08) | 0.99 | 0.99 |
| APC (mixed) | 0.48 | 0.60 |
| FPS (mixed) | 0.99 | 0.99 |

The simulation time frame is extended to one year in order to thoroughly evaluate the performance of the examined control strategies on a long-term basis. For this purpose, representative generation and consumption profiles are employed for each season and the corresponding results are presented in Fig. 10, where similar conclusions can be drawn. The impact of these control strategies is quantified by employing the proposed KPIs. Both $KPI_P$ and $KPI_F$ are calculated on a minute basis and the corresponding average values are presented in Tables IV and V, respectively. The $KPI_P$ factor takes values close to 2 when only the APC method is considered, highlighting the significant increase of the captured energy compared to the BAU scenario. Considering the yearly $KPI_P$ factors, these values are further increased, ranging from 2.14 to 2.31. On the other hand, the activation of the FPS algorithm reduces the overall produced energy, and thus the corresponding $KPI_P$ factors range from 1.33 to 1.53 and from 1.67 to 1.79 for the daily and yearly scenario, respectively. Regarding both APC and FPS control strategies, the maximum $KPI_P$ factor is observed for the yearly scenario. This is due to the fact that low generation periods, i.e. autumn and winter, are also examined, during which the curtailed power is reduced and thus the overall produced energy is increased.

The $KPI_F$ factor for the cases, where only the APC method is implemented, is considered very low, ranging from 0.48 to 0.59 for the daily scenario and from 0.6 to 0.72 for the yearly case. These values indicate that the curtailed power is distributed among the inverters in a highly non-uniform way. The situation is significantly improved with the activation of the FPS control strategy, as highlighted by the corresponding $KPI_F$ factor. It should be noted that this increase in the overall injected power and energy has been accomplished without any investments in reinforcing the existing grid.

## V. Conclusions and Future Work

In this paper, two approaches regarding the voltage regulation in LV networks are presented and examined. More specifically, the APC and FPS control strategies are investigated in terms of maximum penetration level and uniform active power curtailment. For this purpose, appropriate KPIs are proposed as quantitative measures in order to systematically assess the performance of the examined control strategies. Daily and yearly simulation results reveal that both methods increase the total installed capacity and thus the injected RES energy compared to the BAU scenario. In addition, the FPS method manages to distribute the curtailed power in a more uniform but less efficient way, compared to the APC method. As a result, both control schemes can be considered as valuable tools for both DSOs and prosumers, towards the proliferation of the DRESs in the LV networks.

Future work will be carried out to extensively evaluate the performance of the above-mentioned control schemes. Further investigations will be conducted using different network topologies, load and generation profiles, different settings as well as the interference of the control schemes with other network components, such as the on-load tap changer of the transformer.

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