Increasing DER Hosting Capacity in LV Grids in the Czech Republic in Terms of European Project InterFlex

Stanislav Hes, Jan Kula, Jan Svec
Modeling and Analysis Department
CEZ Distribuce, a.s.
Prague, Czech Republic
jan.svec@cezdistribuce.cz

***Abstract*—The paper explains benefits of autonomous control functions Q (V) and P (V) implemented in smart PV inverters for increasing DER hosting capacity in LV grids. The functions are implemented and tested by CEZ Distribuce, the largest Distribution System Operator (DSO) in the Czech Republic, in terms of Horizon 2020 InterFlex project. A simple methodology is verified and used to quantify the control functions impact on DER hosting capacity. Further measurement data from real installations are used to prove previous theoretical calculations and to check that power quality limits are not exceeded. Thus a highly positive benefit of autonomous control functions for DER hosting capacity is verified.**

***Index Terms*--autonomous control functions, grid code, hosting capacity, power quality, smart PV inverters**

I. Introduction

The future development of DERs seems to be a great challenge for TSOs and DSOs in many European countries. The expected scenarios of DER development in the Czech Republic are described in the official document Czech National Action Plan for Smart Grids (NAP SG) [1] published by Czech Ministry of Industry and Trade. The major share of future DERs should be covered by PV generation on LV level. Many calculations proved that the main constraints for DER hosting capacity (HC) are voltage levels and changes.

Standard HC calculations use two voltage constraints. Firstly the voltage level which should be in the range ±10 % V_n (rated voltage), but mostly voltage change (increase) in all grid nodes. This voltage change mustn't exceed 3 % V_n when comparing load flow calculations without all generations in the particular LV grid and with these generations. This criterion is used not only in the Czech Republic but also in some other European countries (e.g. Germany, Austria, etc.). It results from the voltage control coordination going from HV/MV transformer tap changer through MV feeders up to LV feeders preventing the voltage to exceed 110 % V_n level.

As the voltage issue is usually the most critical one, CEZ Distribuce focuses on testing and integrating of new generation smart PV inverters equipped with Q (V) and P (V) control functions which should increase DER HC in LV grids. Both functions work autonomously without the need of communication towards DSO and are used for voltage stabilization in LV grids. In case voltage is higher than a threshold, PV inverter switches to the under-excited (inductive) mode thanks to Q (V) function as it is shown in Fig. 1, in case the voltage rise even more, PV inverter starts to curtail active power generation thanks to P (V) function – see Fig. 2. In case voltage is lower than a threshold, PV inverter switches to the over-excited (capacitive) mode thanks to Q (V) function. The figures show the control functions settings as they are required in CEZ Distribuce distribution area.

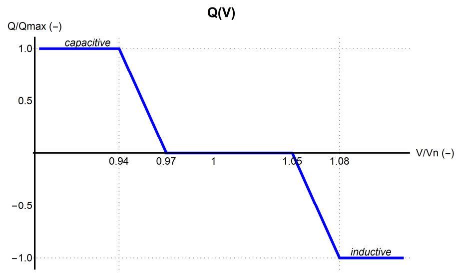

Figure 1. Autonomous Q (V) function of smart PV inverter

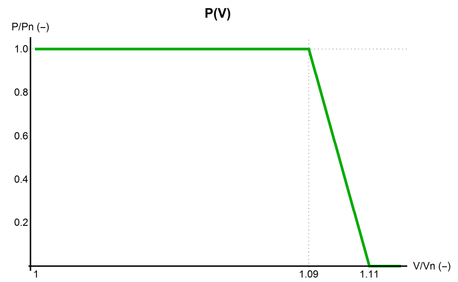

Figure 2. Autonomous P (V) function of smart PV inverter

Autonomous control functions and their impact on distribution grid operation and DER HC increase are under research of European project InterFlex [2], [3], [4]. Micro-generation plants are obliged to be equipped with Q (V) and P (V) control functions according to technical standards [5]

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and Distribution grid code in the Czech Republic. It means relevant prosumers have to provide this grid supporting control as a condition of connecting to the grid. Their benefit is higher generation power connectable to the grid without any intensive need to curtail their energy production. This paper introduces calculations and their results quantifying these benefits.

II. DER Hosting Capacity Analysis in LV Grids

There were carried out some previous theoretical studies [6], [7], [8] or practical tests [9] of smart PV inverters regarding their influence on DER hosting capacity increase in LV grids, different control strategies and impacts on operational electrical quantities. However the studies evaluate mostly overall benefits in project grids from different viewpoints or predict positive impacts on a state level. There is missing a technical analysis respecting standard evaluation process in LV distribution grid feeders which must respect current calculation steps used in DSO methods. If a new HC evaluation method is used, it must be long-term monitored and verified in real grid operation. That is included in this paper.

The present HC calculation considers only DER active power delivery with reactive power Q = 0. This results naturally in more or less significant voltage increase along a LV feeder. As mentioned, voltage increase 3 % V_n in any LV grid node is the most often constraint. The first analysis was carried out to show how Q can result in HC increase. The Czech grid code requires an obligatory grid support from a generation unit (without any remuneration from DSO side) up to the power factor 0.9 in both modes. Therefore it was decided to analyse HC changes if the generation unit operates with this limit power factor – in inductive (under-excited) mode to mitigate voltage increase.

Assuming only single generation unit at a feeder end, the voltage change (hence HC) is strongly dependent on R/X ratio of the whole supplying path. This ratio depends mainly on feeder length, power line type and MV/LV transformer parameters. If we compare the voltage increase caused by DER for modes with and without Q, we can get easily:

$$\frac{\Delta V_{PQ}}{\Delta V_P} \approx \frac{RP - XQ}{RP} = 1 - \frac{X}{R} \cdot \frac{Q}{P} \qquad (1)$$

where R (Ω) / X (Ω) are resistance / reactance of the supplying path, P (kW) / Q (kVAr) are DER active / reactive (inductive) power.

Let's mention the usual R/X ratios in LV grids are approximately in the range 1 to 3. The inverse value of voltage change ratio determines how HC can be increased by operating DER with power factor 0.9 instead of 1 (if voltage change is the constraint). So we define HCIC (hosting capacity increase coefficient):

$$HCIC = \left(1 - \frac{X}{R} \cdot \frac{Q}{P}\right)^{-1} \qquad (2)$$

It is obvious the HC increase is more significant for lower R/X ratios (higher reactances) as expected.

The mentioned theoretical expression was then applied on wide R/X set. There were used 98 representative feeders defined in NAP SG working groups as typical LV feeders in the Czech Republic. See blue squares in Fig. 3. Furthermore feeders from 3 tested real grids from InterFlex project were used (grid D, L, T) where smart PV inverters are tested. See green squares in Fig. 3.

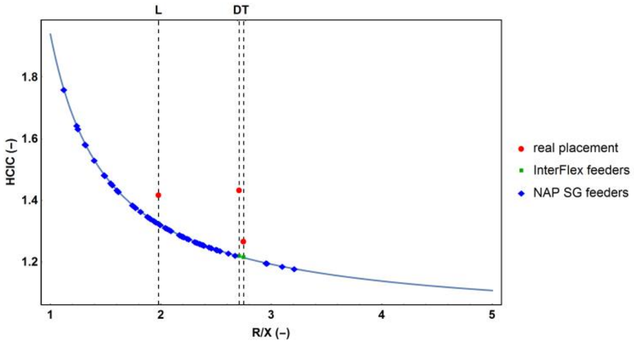

Figure 3. Hosting capacity increase by means of DER reactive power (power factor = 0.9, inductive mode)

We can see that HC increases by 20 to 60 % for a large set of feeders. It is necessary to add all the previous calculations were done for a single generation unit at the feeder end which is not an expected case in real grids (more generations are expected along feeders). Therefore other calculations were carried out for a different DER placement along the feeder. NAP SG working groups defined such a DER placement as 10-60-30 % of total DER power in a feeder for beginning-middle-end of the feeder. Then we obtain even more positive results (Fig. 4).

4 chosen representative feeders results and their extrapolation show that HC increase is higher than for a single DER at the feeder end. This is in accordance with specific results for 3 InterFlex grids (D, L, T) in Fig. 3 (red circles). DER placements in these grids are very different and dependent on available customers so HC increase over the single DER case differs a lot. The issue is that generally it is complicated to quantify HC increase for a specific DER placement, however it is always higher than for the simple case with a single DER at the feeder end.

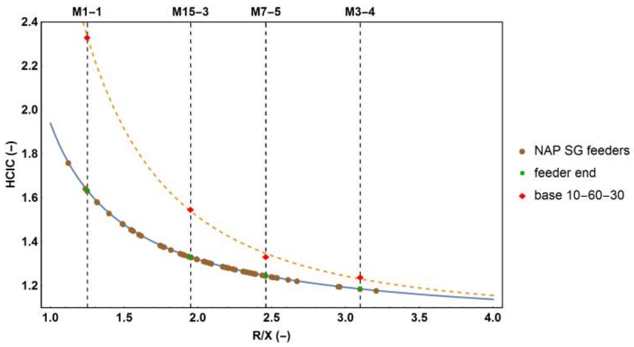

Figure 4. Hosting capacity increase by means of DER reactive power (power factor = 0.9, inductive mode) and DER placement

III. Impact of Autonomous Control Functions on DER Hosting Capacity

The described autonomous control functions, mainly Q (V), result in a variable DER power factor according to voltage level along the feeder. However the simple HC increase quantification described in the previous chapter is very important. Standard SW tools used for grid calculations are not currently able to respect real settings of autonomous functions. Moreover detailed particular settings in SW tools are relatively time-consuming and can be also confusing for technicians processing higher number of DER connection requests. Therefore there was a need for a simplified method for DER HC calculation respecting the control functions.

Hence the further necessary step is to compare the HC calculation results for the simplified approach with the fixed power factor and for the real Q (V) settings. There were compared hosting capacities for 4 representative feeders and 3 InterFlex grids with different topologies and types of LV feeders. The total installed PV power is between 30 kW and 50 kW for each grid and exceeds the standardly evaluated hosting capacity which was required for project purposes.

HC calculated for a fixed power factor doesn't depend on the voltage level given by MV grid very much. One percent change in voltage level results in about one percent HC change. On the other hand the Q (V) control reflects not only feeder parameters and PVs placement but also global voltage level given by MV grid and MV/LV transformer tap settings.

Therefore HC comparison was carried out for Q (V) control with MV grid voltage 100, 105 and 106 % V_n and for fixed power factor 0.9 inductive with 105 % V_n. To simulate real PV placements, InterFlex grids models contain PVs as they are in situ, reference feeders models contain PVs 10-60-30 as described. All simulations were done in a special SW DNCalc, representative feeders placement is e.g. in Fig. 5, the InterFlex grids complexity is shown in Fig. 6 for grid T case.

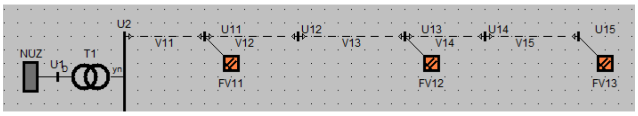

Figure 5. Representative feeder model (PVs are orange squares)

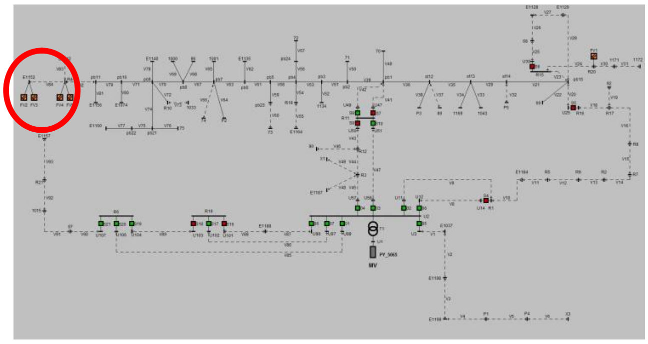

Figure 6. InterFlex grid T model (PVs are orange squares)

HC calculation reflecting Q (V) function setting is highly sensitive on voltage level. As the Czech grid code determines the voltage increase limit to 3 % V_n, this limit is met in all calculations. If the MV grid voltage is 100 % V_n and voltage increase is max. 3 %, Q (V) functions don't work (as they start for 105 % V_n), hence HC is the lowest. The maximal MV grid voltage is set to 106 % so that LV grid voltage in any point doesn't exceed 109 % V_n which is the start point for P (V) function. This function should be understood as an "emergency break" for voltage and its activation should not be required during standard grid operation because it reduces the produced power. The following Fig. 7 and Fig. 8 show the calculated HC for the mentioned topologies, voltage levels and control modes.

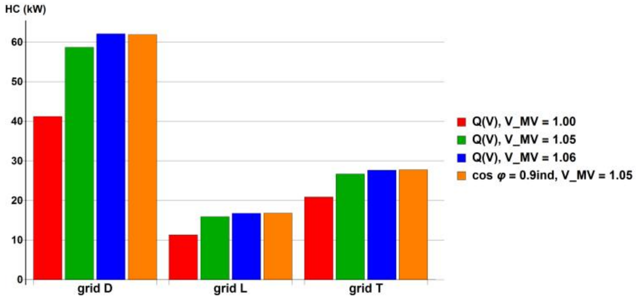

Figure 7. Hosting capacity results for InterFlex grids

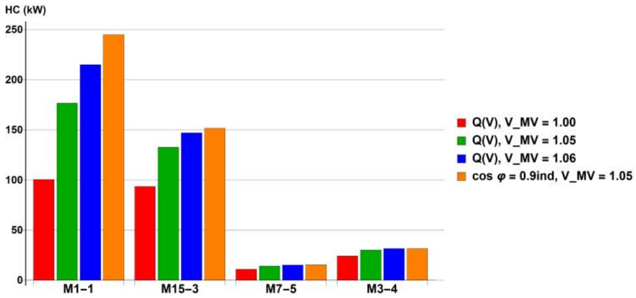

Figure 8. Hosting capacity results for representative feeders

To compare the simplified approach (fixed power factor) with the complex one (real Q (V) setting), it is necessary to compare blue and orange columns. It is obvious that both columns values are very similar. When respecting many additional factors in real grids (loading, voltage measurement, P (V) function, inverter installation, etc.) we can declare the simplified method as a very precise and sufficient one.

IV. Real Operation Evaluation

Very detailed long-term monitoring of voltage levels and power flows are carried out in all InterFlex grids by means of power quality analysers. Data from the grid T are used further. 4 PVs with smart inverters are installed near a feeder end (red circle in Fig. 6), about 600 m from the transformer. Their total rated power is 25.6 kW (2 x 9.6 kW + 2 x 3.2 kW). Standard HC evaluation for PF = 1 would allow only 14.6 kW. The proposed approach with PF = 0.9 inductive (respecting Q (V) setting) would allow 18.2 kW. That is increase by 25 % which is in accordance with Fig. 3. The real installed power is thus even higher – by 78 % against the standard approach, by 41 % against the proposed approach. This could indicate potential voltage limits [11] violation. However no issues with voltage have occurred which is presented further.

The most critical place from the voltage viewpoint seems to be naturally the feeder end. Based on the PVs measurement and the grid topology there was calculated voltage in PV connection point if there is no Q (V) control. Supplying path impedance is $(0.36 + j0.13)\ \Omega$, i.e $R/X = 2.75$. Fig. 9 shows a summer day 1-minute measurement in July 2018 for PV active power P (black), reactive power Q (orange), average voltage (blue) and hypothetical average voltage without Q (V) control (violet). Since HC increase due to Q (V) is not so high for grid T (about by 20 %), voltage change when neglecting Q control is not so significant.

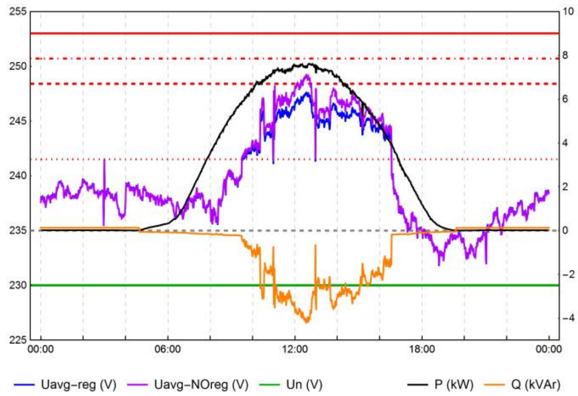

Figure 9. Daily course of PV powers and voltage

Another view at voltage issue can be done in Fig. 10 for voltage difference between MV/LV supplying transformer (blue) and voltage in PV connection point (violet). As the transformer loading is not very high, its voltage can be accepted as MV grid voltage and thus all feeder points voltage for the grid no-load state which is used during standard HC calculation process. Thus it is possible to define a "dynamic voltage limit" for any point in the feeder (brown) which is simply the transformer voltage + 3 % V_n. It is obvious that the real voltage exceeds this limit quite often and much. The maximal difference is about 5 % V_n. However it doesn't mean any power quality violation as the maximal average voltage doesn't exceed 108 % V_n (red dashed line). This is given by lower supplying voltage level (about 102 % V_n at the transformer), hence lower Q (V) activation at some PVs. The higher voltage increase doesn't represent any danger for power quality limit in such operation conditions.

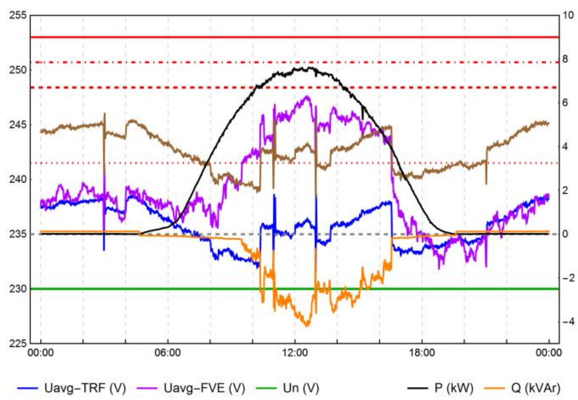

Figure 10. Daily course of voltages at TRF and PV

The mentioned voltage conditions can be evaluated also for one month statistics – July 2018. Fig. 11 shows the average voltage distribution function for MV/LV transformer bus. Almost all monthly values are under 103.5 % V_n. Fig. 12 shows the monthly voltage values in the PV connection point. The absolute 1-minute maximum reaches about 108.2 % V_n, 99th percentile is under 106.5 % V_n. Voltage quality is thus maintained - valid for all the other months in the year.

Fig. 13 shows voltage difference between the PV at the feeder end and the transformer similarly as in Fig. 10 but on the monthly statistics base. Negative values correspond to loading operational states, higher positive value are clearly connected with PV production. 12.6 % of samples exceed the standard 3 % limit.

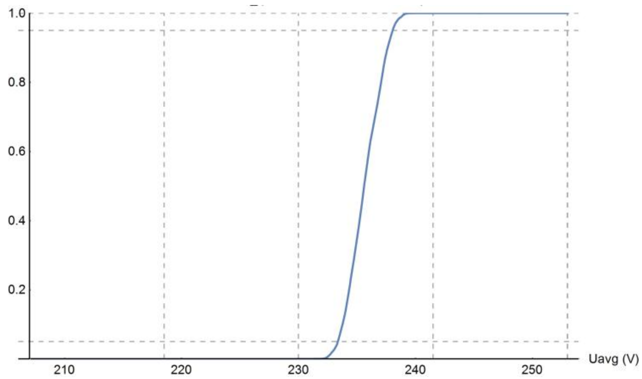

Figure 11. Monthly distribution function for transformer voltage

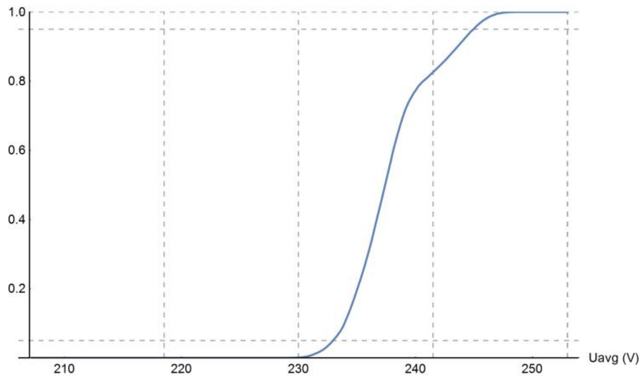

Figure 12. Monthly distribution function for PV voltage

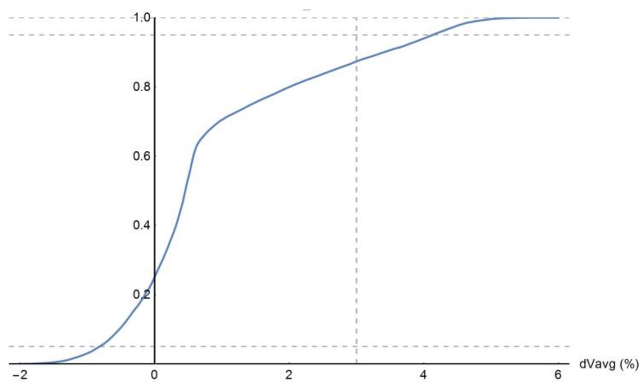

Figure 13. Monthly distribution function for voltage difference between transformer and PV (feeder end)

To reflect power quality standards requirements correctly, all three phase-to-ground voltages should be evaluated. Voltage at the MV/LV transformer bus is very symmetrical but voltage at the feeder end has a higher unbalance because of the feeder parameters and unbalanced load at customers. A monthly statistics for PV voltages is in Fig. 14. Some differences between phases are evident. Differences between maximal and minimal phases reach values up to 10 to 15 V (4 to 7 % V_n). The phase-to-ground maximum is here at the margin 110 % V_n. Fur such values P (V) control is active and significantly prevents from power quality limits violation. Only 2 minute values during the whole year 2018 exceeded this margin. However voltage level is evaluated in 10-minute period averages according to EN 50160 [10] so there was no limit exceeded. We must emphasize again that these high voltages occur for PV penetration highly over standardly allowed values.

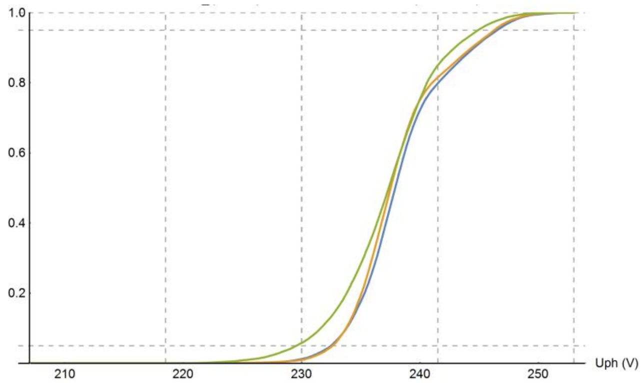

Figure 14. Monthly distribution function for PV phase-to-ground voltages

P (V) activation because of higher voltages prevents voltage levels to rise even more. This is benefit for DSO as well as for the customers. On the other hand prosumers can be worried of undesired reduction of their yearly PV production because of P (V) function. Summarizing data for the analysed PV we can see a usual yearly production course by months in Fig. 15. The total yearly production was 9.34 MWh.

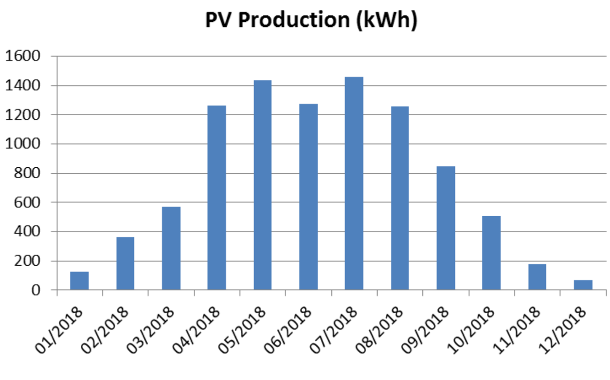

Figure 15. PV yearly production

The reduction of produced energy due to P (V) control function is not registered by the inverter so it must be calculated / estimated from the measured data. The reduced energy was obtained by calculating the reduced power for samples with voltage increasing 109 % V_n. Hence we get the maximal potential energy reduction. As expected P curtailment occurs only during spring and summer months. Comparing total energy produced and reduced, the result is that P (V) activation reduces the overall PV energy production by less than 0.4 %. This is the maximal value for PV penetration highly exceeding standard hosting capacity limit.

V. CONCLUSION

The paper describes a proposed methodology how to evaluate DER hosting capacity in LV grids from the voltage constraint viewpoint for smart inverters equipped with Q (V) and P (V) control functions. A theoretical analysis showed the potential of increasing DER HC by means of control functions. The minimal expected rise is 20 to 60 % depending on feeder electrical parameters and DER placement along the feeder. A complex HC evaluation respecting real control functions settings can be simply replaced by a fixed power factor approach with very precise results.

Implementation and long-term monitoring of smart PV inverters equipped with Q (V) and P (V) control functions are carried out in 3 LV grids in CEZ Distribuce area in European project InterFlex. Measured data analyses showed real benefits to DER HC without power quality limits violation.

Finally, after evaluation of InterFlex project activities, CEZ Distribuce would like to initialize grid code changes respecting the benefits of autonomous control functions to increase calculated DER hosting capacity in distribution grids.

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