IMPACT OF THE CORRECT MODELING OF LOW VOLTAGE GRID WITH HIGH DG SHARE ON THE MEDIUM VOLTAGE GRID CALCULATIONS

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ABSTRACT

The penetration of distributed generators are effecting the operation of power grids. They, especially photovoltaics, are commonly connected via an inverter to low voltage grids and equipped with a local Volt/var control schema. Usually, when calculating medium voltage grids, low voltage grids are modelled using lumped loads. In the case of Q(U) controlled PV systems, this modelling approach does not correctly reflect the reactive power behaviour of low voltage grids. This work analyses the impact of the correct modelling of low voltage grids with high PV share on the voltage and reactive power behaviour of the superordinate voltage levels. Results show that a more realistic modelling of the there do exist discrepancies between the lumped load modelling approach and the real reactive power behaviour of low voltage grids. The reactive power consumption of the whole low voltage grid increases with the rising of low voltage bus bar voltage on the secondary side of the distribution transformer. It is shown that this changed reactive power behaviour of low voltage grids has significant impacts on the voltage levels in the high and medium voltage grids.

INTRODUCTION

Many studies have shown that the penetration of distributed generators, DGs, provokes an uncontrolled reactive power flow in the superordinate grids, which unpredictably changes their voltage landscape [1] [2] [3] [7] [8]. This behaviour is being caused by the local Volt / var control of the DGs, which are not properly taken into account in power calculation models.

Typically photovoltaics, PVs, are connected via an inverter at the low voltage grid, LVG, and equipped with local control schemas, e.g. *Q(U)* or *cosφ(P)*, to alleviate the violation of upper voltage limit [10].

Usually, when calculating medium voltage grids, MVG, LVGs are modelled using lumped loads (ZIP load model) and an infeed (*P*, *Q* constant) for MVG calculations [4] [5] [6].

This paper investigates the impact of the correct modelling of LVGs with high DG share on the MVG power flow calculations. Firstly, the real MVG and DGs are described, Secondly, the studied load / injection scenarios are defined followed by the discussion of different LVG modelling approaches. Finally, the impact of different LVG modelling approaches on the MVG calculation is evaluated and conclusions are drown.

GRID DESCRIPTION

All simulation are performed in a real European distribution grid, which includes the sub-transmission grid (110kV), MVG (30kV and 10kV) LVG (0.4kV). This paper considers the MVG and five LVG types: industrial, rural and small rural, and urban and large urban.

Medium Voltage Grid

The analysed MVG is modelled in detail, **Figure 1**. The 110 kV / 30 kV substation has two parallel transformers with an apparent power of 32 MVA each. Each of them has an on load tap changer, OLTC, with 25 steps each with a step size of 1.667 %, The local control of the transformers have normally a voltage set point on the MV bus bar between 99 % and 102 %. In normal conditions, each transformer supplies 6 feeders through the bus bars 1 and 2, creating two MVGs; MVG_1 and MVG_2. The MVG has a share of 7,41 % of PVs, which are connected directly to LVGs, and 92,59 % "Run Of River" (DG_{RoR}) power plants, which are connected to the medium voltage feeders. The feeder SS 2_1 of MVG_2 supplies a subordinated 10 kV grid connected at the end of the feeder using two 30 kV / 10 kV transformers. Both transformers are equipped with an OLTC to regulate the voltage of the 10 kV bus bar.
The longest feeder is about 45 km long, while the shortest 22 km.

The MVG has a high share on distributed generation from PVs and DG_{RoR}, and a different structure of the individual feeders. DGs are dispersed along 12 feeders. The total DG_{ROR} installed power is about 25 MVA. Additional 2 MVA are fed back flows from the LVG, where PV installations are fitted with local *Q(U)*-control. The maximal load situation of the MVG is about 32 MVA.

The MVG consists of 38,84 % underground cable and 61,16 % overhead line. Feeder 2_1 and 2_4 have sharply decreasing load profiles because there is a high load installed at the end of the feeders. To reduce this issue, the feeder 2_4 and 2_5 are meshed in normal switching state, which is rather uncommon in MV grids due to more sophisticated protection engineering. The Feeder 1_4 is very long and only has small loads distributed along the feeder. Also feeder 1_6 has DG_{RoR} with a capacity of 13 MW connected to its end of the feeder.

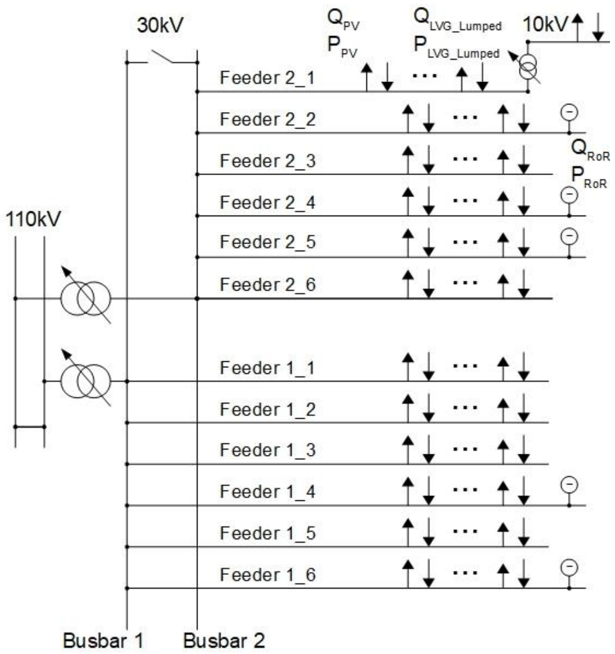

Figure 1: Structure of the MVG

In this study the MVG, is modelled in detail. 26 Power Units, mostly Run of River power plants are installed in the MVG. The rated apparent power of the power units varies from 0,03 MVA to 13 MVA and in the maximum generation scenario a total amount of active power of 25,05 MW is fed into the MVG.

Low Voltage Grid

Five typical real LVGs are selected and investigated in detail: Large and Small-Urban, Large and Small-Rural and Industrial. Figure 2 depicts schematics of the different investigated LVGs.

The Large-Urban LVG, with a 96% cable share and 175 connected residential consumers/prosumers, consists of 9 feeders, the longest of them is 1.27 km, while the shortest is 0.305 km long. It is connected to the MVG through a 30 kV / 0.4 kV, 630 kVA Distribution Transformer, DTR.

The Small-Urban LVG consists of 6 cable-feeders with 81% cable share and 87 connected residential consumers/prosumers.

The Large and Small Rural LVG are overhead line dominated with a share of 41% and 100%, respectively. Both LVGs are connected to the MVG through a 30 kV / 0.4 kV, 160 kVA DTR and have 59 respectively 5 consumers/prosumers connected to it.

Additionally a typical industrial LVG with mainly industrial customers is analysed. It consists of 3 cable-feeders while the longest is 0.65 km.

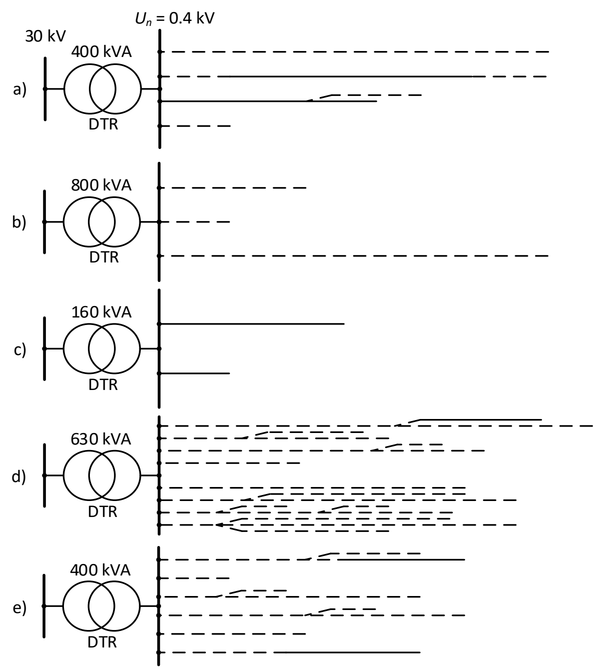

Figure 2: Schematic presentation of different real LVGs: a) large rural, b) industrial, c) small rural, d) large urban, e) small urban

The PVs are equipped with a local *Q(U)* controller with the purpose to influence the voltage at the grid connection point to keep the voltage within the allowed limits [8] [9]. Figure 3 shows the characteristic of the *Q(U)* local controller.

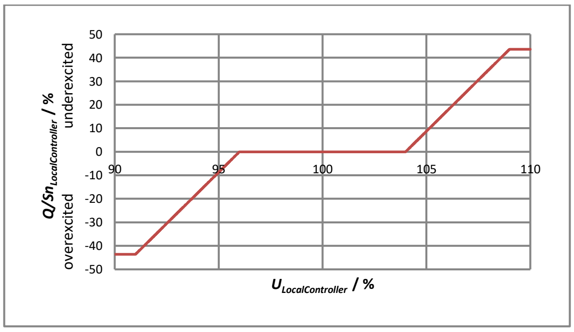

Figure 3: *Q(U)* reactive power control characteristic

SIMULATION SCENARIO DEFINITION

Medium Voltage Grid

To analyse the effects of different LVG models on the voltage levels of the MVG different grid situations are considered and evaluated in various simulation scenarios. Particularly interesting are the times when the power grid is heavily loaded, namely the time of high DG_{RoR} generation and simultaneously low load, spring scenario, and the time of low DG_{RoR} generation and simultaneously maximum load, winter scenario. The winter grid situation is characterized by a high power consumption, due to heating systems and low generation from conventional hydro power plants, due to low water levels. Therefore the global factor for DG_{RoR} is being set to 0,2. In turn, the spring grid situation is characterized by high generation from DG_{RoR} (high water levels due to snow melting) and low load (global load factor of 0,2).

Low Voltage Grid

In LVGs are connected PV systems, which inject power into the grid and customer loads, as shown in Table 1. Different load and infeed cases are considered. A maximum and minimum load case combined with three different PV injections (deactivated PV, currently installed PV infeed → normal PV infeed, and tenfold PV infeed → highest PV share) resulted in six LVG-scenarios.

Table 1: Characteristic parameters LVGs

LVG type	P_{Load_max} / kW	P_{PV} / kW
Small Urban	235.8	101.0
Large Urban	343.0	168.0
Small Urban	12.0	5.0
Large Urban	83.0	20.0
Industrial	95.9	30.0

The loads, connected to the LVG are modelled according to the ZIP load model. For the high load simulation, a power factor of $\cos\varphi = 0{,}95$ is used and the low load simulation is calculated with $\cos\varphi = 0{,}98$ and a global load factor of 0,2. In total, 6 different characteristic *Q(U)* curves are recorded for the respective LVGs.

MODELLING APPROACH

Medium Voltage Grid

The traditional modelling approach of power systems is to analyse each voltage level grid by itself and to reduce the adjoining subordinated, super ordinated or adjacent grid and model them as a lumped load and/or injection. The MVG is fully modelled. The super ordinated HV grid is modelled as a slack injection where the voltage and the voltage angle is being set to a specific value. The lines in the grid are modelled using the pi-equivalent circuit diagram. DG_{ROR}, which operates with a constant power factor of one, are modelled using the constant power load model, which means the active power output is independent from the node voltage.

Low Voltage Grid

The subordinated LVGs are modelled using different approaches, Table 2.

Table 2: LVG model types

LVG Modelling Approach	Load Model	PV Model
LVG Model 1	*Q* according to 5 typical LVGs; *P* ZIP	
LVG Model 2	ZIP	*P*,*Q* constant
LVG Model 3	ZIP	*Q(U)* curve; *P* const.
LVG Model 4	*P*,*Q* constant	*P*,*Q* constant

Model Approach 1

In the LVG Model Approach 1, the reactive power behaviour of the individual LVGs, Q_{LVG}, with high PV share is considered in detail. It is calculated for each LVG type and LVG-scenario. The Small Urban and Large Rural LVG show the most distinct behaviour.

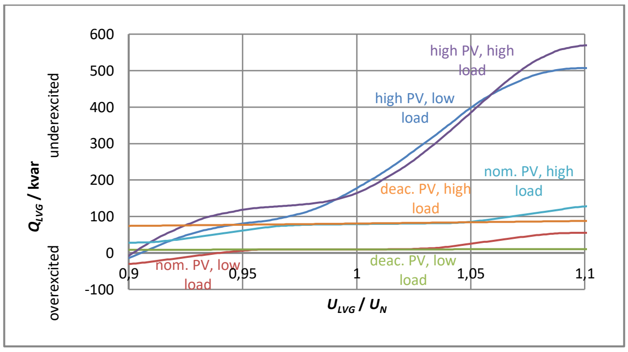

Figure 4: Q_{LVG} behaviour of the Small Urban LVG for different LVG-scenarios.

Figure 4 show the *Q* behaviour of the Small Urban LVG for different LVG-scenarios. In the case of high PV share, for both high and low load, the Q_{LVG} flow strongly depends on the voltage of the primary DTR side. The same trend is found also in the case of Large Rural LVG, Figure 5. The calculated Q_{LVG} are adapted to present the 389 LVGs connected to the MVG.

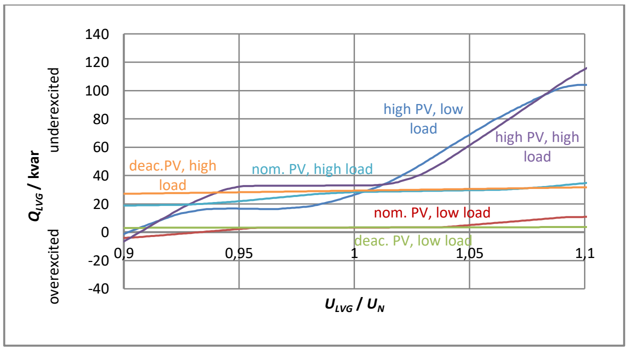

Figure 5: Q_{LVG} behaviour of the Large Rural LVG for different LVG-scenarios.

The calculated Q_{LVG} characteristics are correspondingly adjusted to the 389 LVGs connected in the MVG. This means that the factor of the installed power and installed DGs has been adjusted so that the *P* and *Q* reference at rated voltage corresponds to the measured maximum values at DTR level. The active power flowing through the DTR, P_{LVG}, which represent the sum of the active power consumed by the loads, P_{LVG}^{Load}, with the one produced by PVs, P_{LVG}^{PV}, is modelled through the ZIP model as in:

$$P_{LVG} = P_{init} \cdot \left[Z_P \cdot \left(\frac{U_{node}}{U_n}\right)^2 + I_P \cdot \frac{U_{node}}{U_n} + P_P\right] \quad (1)$$

where:

P_{init} – initial value of the active power consumption of the whole LVG,

$U_n = 0.4kV$ – nominal voltage of LVG,
Z_P, I_P, P_P – ZIP coefficients.
The ZIP coefficients for the P_{LVG}^{Load}, are set to $Z_P = I_P = 0.3;\ P_P = 0.4$, while for the P_{LVG}^{PV} thay are set to $Z_P = I_P = 0;\ P_P = P_Q = 1$, which means the power output of the PVs is independent of the node voltage.
Figure 6 shows the assignment of LVG type and Q_{LVG} characteristic to each DTR.

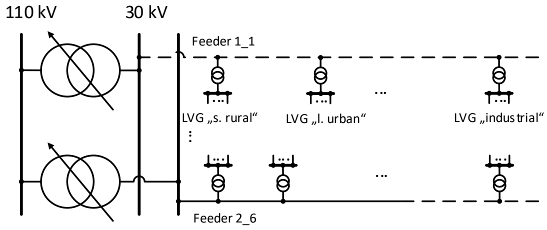

Figure 6: The assignment of LVG type and Q_{LVG} characteristic to each DTR.

Model Approach 2

In the LVG Model Approach 2, the LVG is modelled through a lumped load and a lumped injection. They are modelled using the ZIP model (1). The ZIP coefficients for the LVG lumped load are set to $Z_P = I_P = 0.3;\ P_P = 0.4$ The lumped injection, which represent the rooftop PVs production is modelled using the constant power load factor, where the ZIP coefficients are set to $Z_P = I_P = Z_Q = I_Q = 0;\ P_P = P_Q = 1$, which means the power output of the PVs is independent of the node voltage. The *Q(U)* controller of the PVs is not considered in this modelling approach.

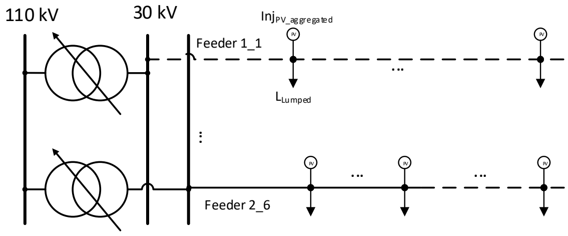

Figure 7: Characteristic of the LVG Model approach 2, 3 and 4

Model Approach 3

In the LVG Model Approach 3, the LVG Model Approach 2 is used with a change. The reactive power of the lumped injection is defined by the local *Q(U)* controller described in **Figure 3**.

Model Approach 4

In the LVG Model Approach 4, the LVG lumped loads and the LVG lumped PVs are modelled using the constant *P*, *Q* load model with the ZIP coefficients $Z_P = I_P = 0;\ P_P = 1$. The *Q(U)* controller of the PVs is not considered in this modelling approach.

EVALUATION OF GRID CALCULATION MODELS

Simulations are performed using the power flow tool PSS SINCAL 15.0.
Figure 8 shows the most relevant voltage profiles of the MVG, for the winter scenario and a PV feed-in of approximately 2 MW. The LVG have been modelled using the Model Approach 1. It can be seen that for almost all feeders, the voltage is within a narrow range of 97.5 % and 102 % of nominal voltage. Only Feeder 2_1 has a significantly large voltage drop of 12%. The voltage at the beginning of the 10 kV grid is increased using the OLTC of the 30kV / 10kV transformer.

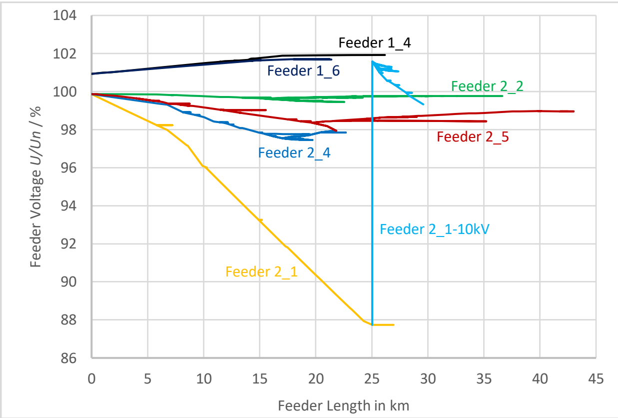

Figure 8: MVG voltage profile; winter scenario and the actual PV injection

Figure 9 shows the voltage profile in the MVG in presence of high PV share: tenfold PV feed-in compared to the currently nominal PV production. It can be seen that in feeders with high PV penetration, the voltage rises sharply, see Feeder 2_5. In this scenario, the PV systems consume about 4Mvar reactive power due to the *Q(U)* control.

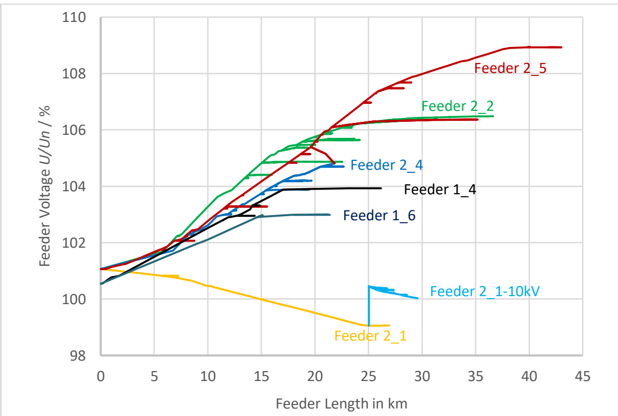

Figure 9: MVG voltage profile; spring scenario and high PV injection

Comparison of different LVG model approaches:

Figure 10 shows the voltage profile of one MVG Feeder, Feeder 2_2. It is calculated for the spring scenario and high PV injection by using different LVG modelling approaches. Voltage profiles calculated by using LVG traditional modelling, Model Approach 2 and 4, have a similar voltage running. They distinctly differ from the voltage profiles calculated by using LVG Model Approach 1 and 3. In the last cases, the additional reactive power provoked by PV systems is taken into account. This reactive power have a global effect on the subordinate grid [8] that is expressed by the voltage shift of about 1% on the bus bars 1 and 2, Figure 1. There are also differences between the calculations using the LVG Modelling Approach 1 and 3.

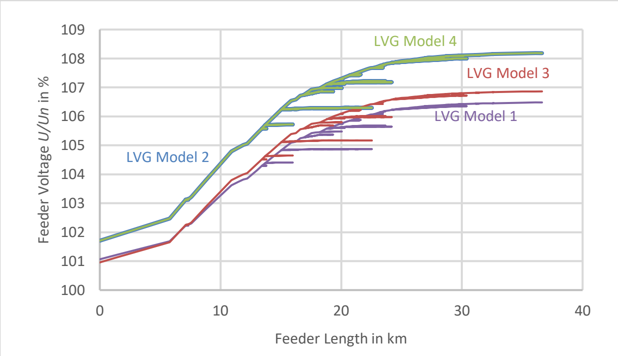

Figure 10: Voltage profile of Feeder 2_2 calculated by using different LVG modelling approaches for the spring scenario and high PV injection.

The discrepancies in voltage profile calculations are caused by various parameters. Figure 11 shows the reactive power sources available in Feeder 2_2 calculated by using different LVG modelling approaches for the spring scenario and high PV injection. The reactive power sources are: PVs, Q^{PV}, which impacts the reactive power behaviour of the LVG. Q^{LVG}; means the LV reactive power losses on overhead lines and cables as well as the Q demand of the LVG lumped loads. ΔQ^{OL} and ΔQ^{Cables}, means the reactive power losses of the MVG overhead lines and cables. Q^{shunt} means the reactive power output of installed capacities in the MVG. Q^{total} is the sum of reactive power of the Feeder 2_2. The traditional modelling methods do not longer capture the behaviour of the *Q(U)* control in the LVG PVs correctly and thus the reactive power behaviour of the entire MVG is changing. Between the LVG Model Approach 1 and 3, the discrepancy on Q^{PV} calculation is about 688%. This impacts the Q^{LVG} and the Q^{total} behaviour. Compared to the other LVG Model Approaches, using the LVG Model Approach 1 changes the behaviour of the Feeder 2_2. It shows an inductive behaviour due to the increased *Q* consumption of the PV systems. This behaviour affects MVG voltage levels, Figure 10. The increased *Q* demand in LVG Model 1 provokes a lower voltage increase along the MVG feeder.

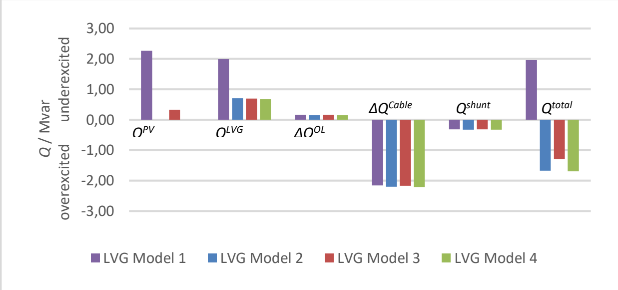

Figure 11: Reactive power sources in Feeder 2_2 calculated by using different LVG modelling approaches for the spring scenario and high PV injection.

CONCLUSION

The large scale integration of rooftop PV systems requires the use of local *Q*(*U*) controls to alleviate the violation of upper voltage limit. These local controls modifies the reactive power behaviour of the whole power system. The traditional models used for power flow calculations does not take into account these additional reactive power flow. The discrepancy between the voltage calculations in MVG using the traditional and the adequate LVG modeling discussed in this document reaches a maximum of 1.78%. It is shown that in the case of high PV penetration, the traditional LVG modeling methods are unsatisfactory.

REFERENCES

[1] Lund, P., 2007, "The Danish cell project – Part 1: Background and general approach", IEEE, Power Engineering Society General Meeting, Tampa, USA,

[2] Martensen, N., Kley, H., Cherian, S., Pacific, O. and Per Lund, 2009, "The Cell Controller Pilot Project: Testing a Smart Distribution Grid in Denmark. Grid Interop" The Road to an Interoperable Grid, Proceedings, 216-222, Denver, USA.

[3] Hidayatullah, N. A., Paracha, Z. J. and Kalam, 2011, "Impact of Distributed Generation on Smart Grid Transient Stability", Smart Grid and Renewable Energy Journal, 2, 99-109.

[4] D. Kosterev, A. Meklin, J. Undrill, B. Lesieutre, W. Price, D. Chassin, R. Bravo, and S. Yang, 2008, "Load Modeling in Power System Studies: WECC Progress Update," in Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, IEEE, July

[5] A. Bokhari, A. Alkan, R. Dogan, 2014, „Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial and Industrial Loads", IEEE Transactions on the Power Delivery, VOL. 29, No. 3

[6] M. Sadeghi, G. Abdollahi sarvi, 2009, "Determination of ZIP Parameters with Least Sqaures Optimization Method", IEEE Electrical Power & Energy Conference

[7] Ilo, A., Gawlik, W., Schaffer, W. and Eichler R., 2015, "Uncontrolled reactive power flow due to local control of distributed generators", CIRED, Lyon, France

[8] Ilo, A., 2016, "Effects of the Reactive Power Injection on the Grid – The Rise of the Volt/var Interaction chain", Scientific Research Publishing

[9] Zhang F. et al., "The reactive power voltage control strategy of PV systems in low-voltage string lines," 2017 IEEE Manchester PowerTech, Manchester, 2017, pp. 1-6.

Acknowledgments

This work is done as part of DeCas-Project, which has received funding in the framework of the joint programming initiative ERA-Net Smart Grids Plus, with support from the European Union's Horizon 2020 research and innovation program.