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OPTIMISATION OF THE LOAD FLOW CALCULATION METHOD IN ORDER TO PERFORM TECHNO-ECONOMIC ASSESSMENTS OF LOW-VOLTAGE DISTRIBUTION GRIDS

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ABSTRACT: Decentralised power generation may lead to an inverse power flow compared to a centralised power supply system. Thus, voltage rises have to be limited at customer level with minimum extra costs during high PV power injection. Therefore, active and reactive power control of PV inverter will become more and more important because the additional grid operator's and end customers' investments could be nearly neglected. The decentralised control has to be triggered directly by the line voltage at the PV inverter ensuring an efficient use based on static characteristics, which are defined by the grid operator without the need of additional investment in IT infrastructure. The voltage dependent control of decentralised power generators is not implemented in the open source load flow calculation software Matpower. An elegant solution was found by integrating the dynamic change in active and reactive power directly into the load flow equations. This provides the basis for the techno-economic assessments which will be performed for different low-voltage distribution grid classes in Switzerland, Germany and Austria.
Keywords: Low-voltage distribution grid, photovoltaic, active power control, reactive power control, load flow calculation

1 INTRODUCTION

High injection rates of PV electricity in the distribution grid may increase the line voltage at the feed-in point of the inverter close to the limits defined by the grid code. Distribution system operators are responsible to comply with these voltage standards by planning regulations or retrofit the hardware in the grid.

In spring 2016, the three-year project "Cost effective smart grid solutions for the integration of renewable power sources into the low-voltage networks" (CEVSol) was started at the ZHAW in Switzerland. The Swiss electric utilities of the Canton of Zurich (EKZ) and Schaffhausen (EKS) are involved as industrial partners providing low-voltage distribution grid (LVDG) data, measurements and practical inputs. Further on, the ZAE Bayern and the Vorarlberger Kraftwerke (VKW) are associated partners for discussing and comparing the experience and best practice of LVDG analysis in Germany and Austria, respectively. Additionally, the VKW have already performed field tests regarding decentralised voltage dependent regulation of PV inverters [1].

The goal of this project is to classify the LVDG in different grid classes and to determine the most cost-effective solution for voltage stability within each class. There are various studies that classified their distribution grids using socio-techno-economic data. Therefore, model regions were extracted with the objective of extrapolating the needs of grid infrastructure of greater supply areas e.g. throughout Germany [2]–[5]. The different approaches can be taken into account partially as starting point for the CEVSol project. The methodology to be developed should provide the most cost-effective solution or a combination of solutions for the individual typical grid class. The goal is to maintain voltage stability by considering the corresponding strategy approach of the individual distribution system operator (DSO). The results should serve as a guideline for DSOs within their planning phase in order to assess the cost of the expected critical grid classes due to increasing PV capacity.

Classical grid reinforcement, active and reactive power control (APC and RPC), line voltage regulator, on-load tap changer, battery storage and load management are going to be analysed technically using load flow simulations. After that, the economic analyses will be performed resulting in a techno-economic assessment for each grid class. Possible grid classes are small/medium industries, city limits, urban settlements, village centres/peripheries and hamlets.

Two LVDGs representing a village with periphery and a hamlet are the first identified classes of LVDGs. During the technical analysis, it became clear that voltage dependent APC and RPC are powerful measures for maintaining voltage stability. Solar inverters will have a big influence in future LVDGs in terms of stabilising the voltage. Today, such products available on the market offer the possibility to control the reactive and active power directly by measuring the local line voltage. Thus, no external hardware will be needed.

The load flow simulations have been performed using Matpower, an open source toolbox for Matlab [6]. But this software could not handle voltage dependent control of decentralised power generators in a time-efficient manner. Therefore, an appropriate solution had to be developed.

2 APPROACH

An economic highly attractive solution would be to utilise the PV inverter as the control unit to stabilise the line voltage with a minimum use of additional IT infrastructure. This requires the implementation of some static characteristics for the APC and RPC as a function of the local line voltage during the installation of the inverter. Thus, each PV inverter needs static characteristic curves that describes its behaviour of P(V) and Q(V) described in Figure 3. According to these profiles, the inverter adjusts its active and reactive power injections depending on the measured line voltage without real time information from the grid operator. After the power adjustment, the line voltage will have changed, which will lead to another adjustment of power injections according to the defined characteristic curves. The APC and RPC will end as soon as the steady state voltage is reached. It is highly important to assess this effect of line voltage control within the grid code limits for different PV penetration levels on sunny days during the planning stage of the DSO. The standard load flow calculations cannot reflect this behaviour because the active and reactive power are constant input parameters of that simulation.

The most intuitive solution would be achieved by building an iterative process around the standard load flow calculation procedure shown in Figure 1. First of all, the load and generation profiles have to be initiated or updated. Then, it is proposed to solve the load flow calculation by the Newton-Raphson method. Once the calculation is converged, all node voltages are compared to the node voltages of the previous iteration. If the changes are greater than the allowed error value, the corresponding parameter for active and reactive power injection will be adapted and a further load flow calculation will be performed. This iteration is executed until steady state voltages levels are reached at each node. After that, the whole process has to be repeated for each time step.

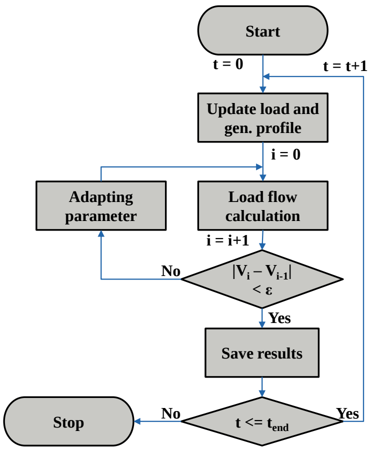

Figure 1: The iterative process adapts the parameter for APC and RPC and performs load flow calculation until the steady state voltages are reached at each node.

This procedure results in a too lengthy total calculating time. The more decentralised generators are controlled, the more complex it gets to define the loop that adapts the parameters for the APC and RPC and the longer it takes to converge to a stable solution. Therefore, the origin of the problems was identified and eliminated directly within the load flow calculation resulting in a slightly different mathematical formulation (see chapter 3) of the load flow equations. With that solution, only one load flow calculation has to be performed and the outputs are directly the steady state voltages.

The developed solution is applied in the analysis of the LVDG in Dettighofen, Germany. This village with periphery has a PV production share of 46% regarding the total electricity consumption. In 2014, the distribution grid was analysed and the effect of constant APC and RPC was investigated [7]. Therefore, the same grid data, PV production data and load data can be used to verify the implementation of the adapted load flow equations regarding the use of Q(V) as RPC and P(V) as APC.

3 ADAPTED LOAD FLOW EQUATIONS

The load flow equations of the active power g_h^p and the reactive power g_h^q balancing are written regarding the node h. The net active power injection p_h and reactive power injection q_h are the differences of generated power p_G and q_G and load power p_L and q_L, respectively [8].

$$g_h^p: \quad p_h = v_h \cdot \sum_{k=1}^{N} v_k (g_{hk} \cdot \cos\theta_{hk} + b_{hk} \cdot \sin\theta_{hk})$$
$$= p_G - p_L$$

$$g_h^q: \quad q_h = v_h \cdot \sum_{k=1}^{N} v_k (g_{hk} \cdot \sin\theta_{hk} - b_{hk} \cdot \cos\theta_{hk})$$
$$= q_G - q_L$$

The quantities g_{hk} and b_{hk} correspond to the conductance and susceptance of the line between the nodes h and k. The phase angle difference between those nodes is written as θ_{hk}. At each node, the power of a generator or a load is assumed to be constant during one time step within the load flow calculations. This assumption is no longer valid for the active and reactive power control or for voltage dependent demand side management.

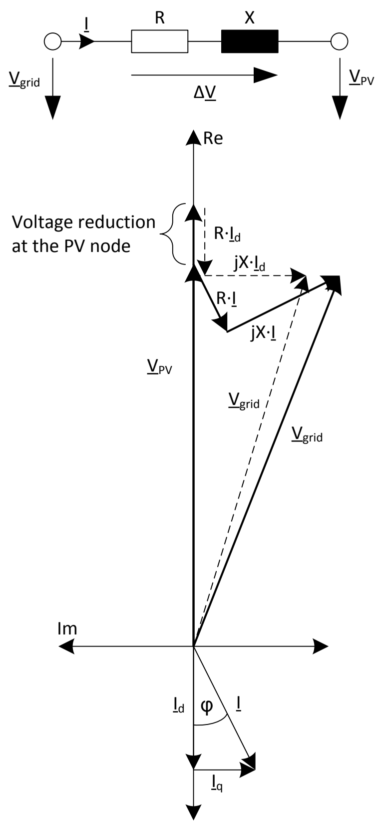

Figure 2: The phasor diagram of the line voltage (passive sign convention) shows the effect of under-excited reactive power injection at the PQ node. The grid voltage

V_{grid} is held constant at the end of a line and hence, the voltage V_{PV} is decreased compared to the case where only active power is injected.

Figure 2 shows the effect of under-excited reactive power injection at the end of the distribution line with the power input of the PV inverter at the line voltage label V_{PV} and without an additional load. The injection of reactive power reduces the line voltage V_{PV} as the basic principle of RPC during constant active power injection of the PV inverter. The supplied reactive power of the generator at a PQ node is an input value of the load flow equations and the reduced node voltage corresponds to their output value. The RPC will change the input value depending on the output value and the given characteristic curve Q(V). That means the angle φ is changed until the voltage V_{PV} is stable. This dynamic will be implemented in the load flow equations.

Therefore, the powers at the generator and load have to be considered as voltage dependent variables. Additionally, all nodes are treated as PQ nodes.

$$g_h^p = \underbrace{v_h \cdot \sum_{k=1}^{N} v_k (g_{hk} \cdot \cos\theta_{hk} + b_{hk} \cdot \sin\theta_{hk})}_{p_{bus}(\theta, v)}$$
$$- p_G(v_h) + p_L(v_h) = 0$$

$$g_h^q = \underbrace{v_h \cdot \sum_{k=1}^{N} v_k (g_{hk} \cdot \sin\theta_{hk} - b_{hk} \cdot \cos\theta_{hk})}_{q_{bus}(\theta, v)}$$
$$- q_G(v_h) + q_L(v_h) = 0$$

The Newton-Raphson method is often used to solve the non-linear load flow equations because it converges fast and efficient except for ill-conditioned cases [8]. The method is described using vector notation (bold variables) as follows:

$$\begin{bmatrix} \Delta\boldsymbol{\theta} \\ \Delta\boldsymbol{v} \end{bmatrix} = -J^{-1} \cdot \begin{bmatrix} \boldsymbol{g}^p \\ \boldsymbol{g}^q \end{bmatrix}$$

$$\begin{bmatrix} \boldsymbol{\theta}^{i+1} \\ \boldsymbol{v}^{i+1} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\theta}^{i} \\ \boldsymbol{v}^{i} \end{bmatrix} + \begin{bmatrix} \Delta\boldsymbol{\theta} \\ \Delta\boldsymbol{v} \end{bmatrix}$$

The Jacobian matrix J contains the partial derivative of all load flow equations regarding all node voltages and phase angles. The red marked partial derivatives are added to the original matrix (black) due to the voltage dependency of the generators and loads.

$$J = \begin{bmatrix} \frac{\partial \boldsymbol{g}^p}{\partial \boldsymbol{\theta}} & \frac{\partial \boldsymbol{g}^p}{\partial \boldsymbol{v}} \\ \frac{\partial \boldsymbol{g}^q}{\partial \boldsymbol{\theta}} & \frac{\partial \boldsymbol{g}^q}{\partial \boldsymbol{v}} \end{bmatrix} = \begin{bmatrix} \frac{\partial \boldsymbol{p}_{bus}}{\partial \boldsymbol{\theta}} & \frac{\partial \boldsymbol{p}_{bus}}{\partial \boldsymbol{v}} + \frac{\partial \boldsymbol{p}_L}{\partial \boldsymbol{v}} - \frac{\partial \boldsymbol{p}_G}{\partial \boldsymbol{v}} \\ \frac{\partial \boldsymbol{q}_{bus}}{\partial \boldsymbol{\theta}} & \frac{\partial \boldsymbol{q}_{bus}}{\partial \boldsymbol{v}} + \frac{\partial \boldsymbol{q}_L}{\partial \boldsymbol{v}} - \frac{\partial \boldsymbol{q}_G}{\partial \boldsymbol{v}} \end{bmatrix}$$

The derivatives correspond to the slopes in the inverter profiles describing the behaviour of active and reactive power as shown in Figure 3.

Before the start of the simulation, each inverter profile has to be adjusted individually. The derivatives of the two solid lines are not continuous at the two edges (Figure 3). This may lead to a convergence problem of the Newton-Raphson method. In such cases, the profile can be approximated by an smooth logistic function (dashed lines) [9]. The behaviour of the reactive power is chosen in the following example so that half of the control range is exhausted at a voltage 1.03 pu. For the active power control curve, it has to be considered how the inverter is rated compared to the PV power plant. Here, it is assumed that the nominal power of the inverter corresponds to nominal power of the PV power plant. On a clear sky day in spring time, the nominal power of a PV module is never achieved due to the negative temperature coefficient resulting in a power decrease at higher module temperatures. This case is shown in the right lower part of Figure 6 and Figure 7, respectively. For this reason and for the purpose of verifying the APC, the active power control starts at the same voltage level as the reactive power control. Generally, the APC should start at higher voltage levels because it is economically preferable. The P(V) and Q(V) characteristics can be individually defined and the electric utilities should provide this information with their grid codes for installing and connecting a PV inverter to the distribution grid.

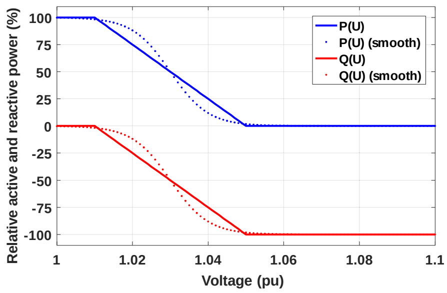

Figure 3: The profiles for active and reactive power control can be chosen individually for each decentralised generator within the load flow calculation. The negative percentages for the reactive power control represent the under-excited operation mode. The dashed lines are the alternative inverter profiles if the numerical method does not converge because the derivative of the solid curves is not continuous at the two edges.

4 LOW-VOLTAGE DISTRIBUTION GRID DATA USED FOR VERIFICATION

The implementation of the adapted load flow equations is verified by analysing the voltage dependent APC and RPC applied to the LVDG in Dettighofen, which is located in Baden-Württemberg, Germany. The same grid data, PV production data and load data is used as required for the case study in 2014 where the critical western part of that LVDG was analysed regarding different measures for voltage maintenance. This grid sector has a 400 kVA transformer and an installed PV capacity of 535.5 kWp [7]. Additionally, the distribution grid consists of 218 nodes, 228 lines and 33 PV power plants distributed over 25 different nodes. Figure 4 shows the single-pole schematic of the distribution grid with two long stubs connected to the distribution box VK6 in the south west with a total PV installation of 99.3 kWp. In this part of the grid sector, there are no major non-residential loads except some farmer houses with electric appliances.

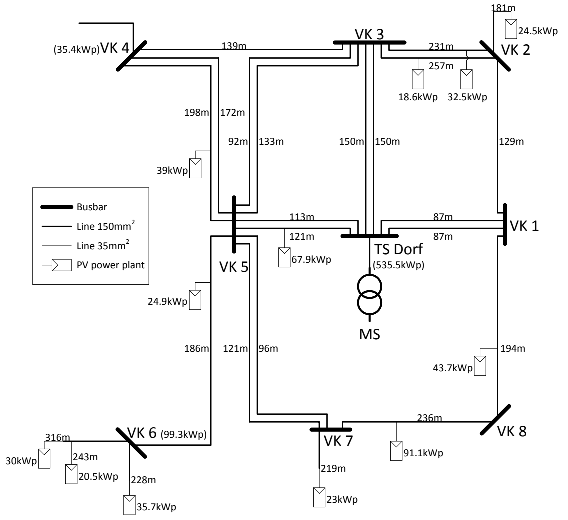

Figure 4: The single-pole schematic represents the critical western part of LVDG in Dettighofen, whereby only the largest PV plants are indicated. Two long stubs are connected to the distribution box VK6 carrying PV power with a nominal capacity of 99.3 kWp. In total, there are 33 PV power plant distributed over 25 nodes with an overall installed PV power of 535.5 kWp.

The simulations are performed for a clear sky day on Sunday 18th May assuming that all PV power plants are tilted by 30° and facing south. The generation profiles are modelled based on solar irradiance measurements [7]. The load profiles at each house connection are represented by the VDEW standard load profile H0 from E.ON Westfalen Weser (North Rhine-Westphalia) [10]. These profiles are scaled assuming a constant cosφ of 0.93 and an annual electricity consumption of 4500 kWh. The resolution of the used production and load data are 10 min intervals [7]. The identical APC and RPC profiles are assigned to each decentralised power generator according to Figure 3. As soon as the corresponding node voltage is higher than 1.01 pu, the active and reactive power will be decreased and increased according to Figure 5. The APC and RPC end when the node voltage reaches 1.05 pu.

5 RESULTS

First, the standard simulation is performed without any voltage control measures. The resulting node voltages are shown in Figure 6 as a snapshot of the situation at the time 14:00. The first numbers and the colour in the graphic indicate the relative voltage at the corresponding grid node. There are voltage rises of 5.0% and 5.6% relative to the nominal grid voltage at the ends of the two long stubs in the south western part of the LVDG, which is caused by decentralised feeding-in of the PV power plants with an overall nominal power of 99.3 kWp.

The second load flow simulation includes the voltage dependent APC and RPC together with the adapted load flow calculation. The voltages rises are limited to 2.9% and 3.1% according to results in Figure 7. The results of a previous study are equalised at the most critical nodes but there, the static comprehensive use of ACP and RPC were investigated [7]. In Figure 7, the first numbers represent again the relative voltages at the corresponding node. If there are PV power plants connected to that node, the percentage of active power curtailment (2nd number) is added followed by the percentage of utilisation of the reactive power control. It is evident that only the required quantity of active and reactive power is controlled. If only RPC is active, the voltage rises will be limited to 3.9% and 4.3%, respectively.

Figure 5 shows the simulated relative active and reactive power for the voltage dependent APC and RPC compared to the inverter profiles at the weakest node during the analysed day. The reactive power follows the given Q(V) profile. The active power has to be considered differently because the controlled active power is related to the nominal power of the PV power plant. The injected power does not reach the nominal PV power due to the power reduction at high module temperatures and in the morning and in the afternoon, where no perfect orientation to the sun is achieved. As a consequence, the simulated active power is lower or equal than the P(V) profile.

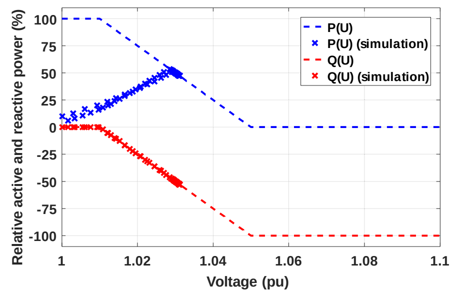

Figure 5: The simulated active and reactive power injection is compared to the given P(V) and Q(V) inverter characteristics during the course of the simulated day.

The more complex load flow calculation lead to losses of simulation speed performance over the analysed day as soon as the inverter control is activated. The detailed evaluation of the computation performances are shown in Table I. The computation time increases by a factor of 5 to 7 depending on the used inverter profile types. The reason is that there are higher amount of iterations per load flow calculation at the time at which the APC or RPC is used. The smooth inverter curve shows a better performance than the inverter profile with the edges according to Figure 3.

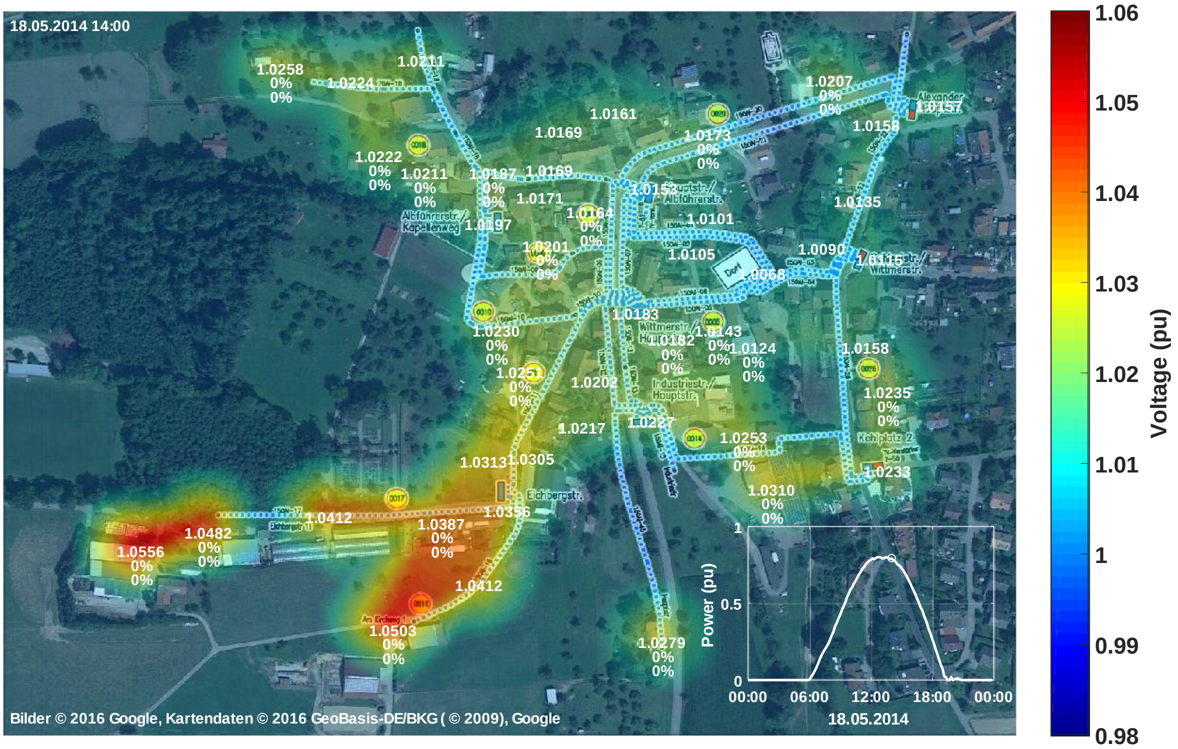

Figure 6: The mapping of the line voltage is given relative to the nominal voltage value at the south western part of the low-voltage distribution grid in Dettighofen, Germany, at 14:00 on a clear sky day in May. The number and colour in the graphic stand for the relative voltage at the corresponding grid node. Active and reactive power control are inactive. There are two long stubs with a total PV capacity of 99.3kWp, where the voltage rises reach their maximum of 5.0% and 5.6%, respectively, at 14:00 [11].

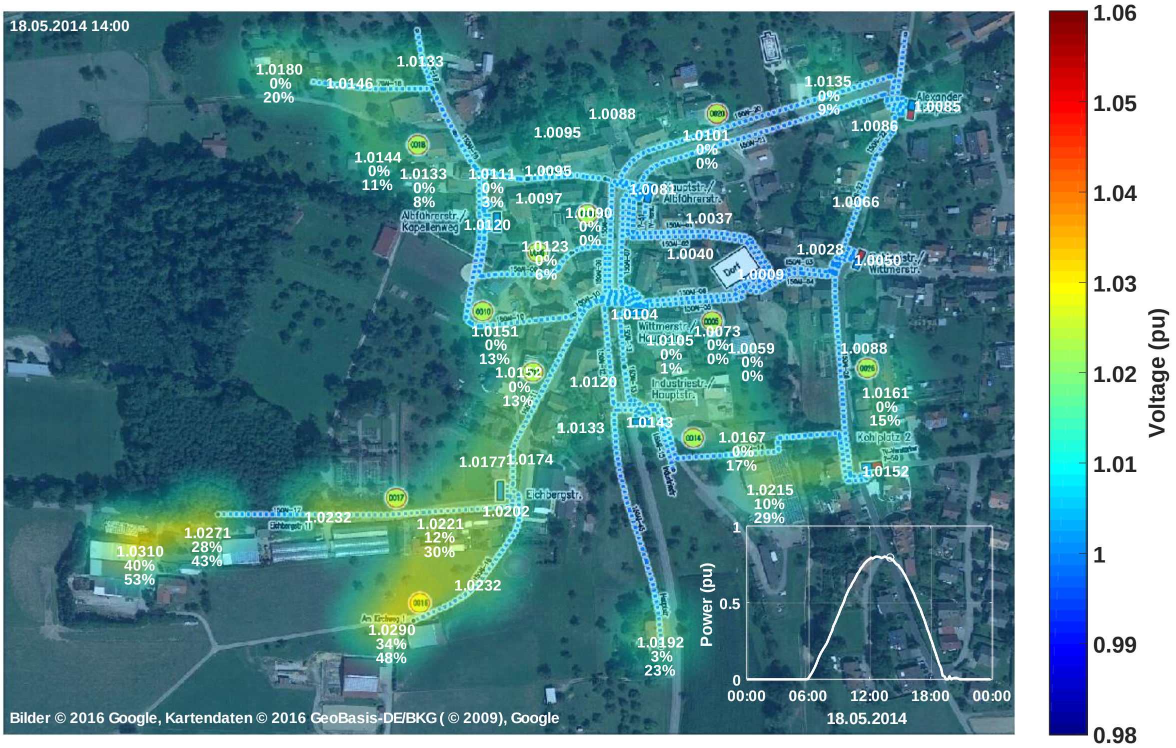

Figure 7: The voltage rise at the end of both stubs can be limited to 2.9% and 3.1%, respectively, as soon as the voltage dependent active and reactive power control is activated. The decentralised generators are only regulated where it is necessary according to the applied power flow calculation algorithm (Eq. in chapter 3) together with the inverter profiles in Figure 5. The results of a previous study can be achieved but there, the static comprehensive use of ACP and RPC were investigated [7]. The first number represents the voltage relative to the nominal voltage at that connection point. If there are PV power plants connected to that node, the percentage of active power curtailment (2nd number) is added followed by the degree of utilisation of the reactive power control [11].

Table I: The computation times and the number of iterations of the Newton-Raphson method are specified for the simulations (18.05.2014) without control and with APC/RPC according to the P(V) and Q(V) inverter characteristics described in Figure 3. The load flow calculations were performed by a Dell ultrabook with 16GB RAM and an Intel® Core™ i7-5600U CPU (2.6GHz).

Simulations	Standard w/o control	PQ control	PQ control (smooth)	Units
No of iterations of the Newton-Raphson method	2 to 3	2 to 14	2 to 17	#
Time per load flow calculation	4 to 30	14 to 81	9 to 63	ms
Total simulation time (incl. overhead)	0.78 (1.18)	5.16 (5.63)	3.60 (4.00)	s

6 CONCLUSION

The voltage dependent inverter control of active and reactive power according to the P(V) and Q(V) characteristics was successfully integrated into the open source load flow calculation software Matpower [6]. The developed and adapted solution can be applied to any other software tool. In the basic load flow equations, the power of a generator or a load is assumed to be constant during one time step. This is no longer valid for the voltage dependent APC and RPC or demand side management. This fact led to a modification of the load flow equation as well as the Jacobi matrix used in the Newton-Raphson method, which solves the non-linear load flow equations. Consequently, the simulation output is immediately the regulated voltages for each node of the distribution grid and time step. The user does not need to build complicated iterative processes around the complete load flow calculation. Different measures for voltage stability can be easily combined within the simulation allowing for a better techno-economical assessment.

In 2014, the LVDG with a PV share of 46% in Dettighofen, Germany, was analysed. Simulation results showed that the voltage rise could be limited to 3% by static centralised overall APC and RPC [7]. With the presented adaptation of the simulation method, roughly the same results could be achieved with targeted use of inverter control. Now, the two measures (APC and RPC) can be analysed more realistically with regards to technical as well as economical aspects.

The benefit of the local application of the APC and RPC is that each inverter feeds in reactive power individually if it is needed. This reduces the reactive power in the distribution grid and the amount of reactive power that is transferred to the next voltage level compared to the constant power factor approach. For example, the distribution system operator VKW in Vorarlberg, Austria, is already successfully applying the local P(V) and Q(V) control on approximately 2500 PV inverters [12].

The described simulation method allows different PQ strategies for each decentralised generator. Further on, the DSO can investigate where and which PQ-inverter profile should be used by the customers PV inverter. Thus, APC and RPC can be planned and deployed purposefully by the grid operator without further investments into information and communication technologies or hardware.

ACKNOWLEDGMENT

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