TECHNO-ECONOMIC ASSESSMENT OF PLANNING PRINCIPLES FOR LOW VOLTAGE GRIDS IN THE PRESENCE OF MASSIVE DISTRIBUTED PV GENERATION

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ABSTRACT

The present planning principles for new low voltage grids from the German DSO Pfalzwerke Netz AG are not sufficient for the predicted PV feed-in power of 2030. The newly developed principles make use of controlled MV/LV distribution transformers with line drop compensation (L-CDT). Their voltage-improving effect allows to deploy inexpensive single-sided radial cable grids. Furthermore, the use of L-CDT calls for the replacement of the today's German process for PV connection requests defined in VDE AR-N 4105. A new calculation approach with a voltage limit of 108 % U_n instead of 103 % U_n is recommended to take full advantage of the L-CDT's capability of increasing the maximum installable PV power. Depending on the grid structure and extent, a factor of 1.3 to 3.5 in installed PV power is admissible compared to the use of traditional distribution transformers and today's VDE AR-N 4105.

INTRODUCTION

Need for new planning principles

Planning principles for low voltage (LV) grids are catalogues with technical specifications grid operators can apply for new grids or re-construction of existing LV grids. They include standardized equipment e.g. for cables and standard grid topologies. As principles, they cover most supply tasks, only for special situations variations may be necessary. Therefore, planning principles are an essential tool for grid planning. Pfalzwerke Netz AG is a German DSO operating a large number of rural LV grids. The most recent LV planning principles are from year 2007 and not sufficient for the expected PV feed-in of 2030. Also affordable and supportive Smart Grid technologies have not yet been available in 2007. Hence, TU Kaiserslautern and Pfalzwerke Netz AG have developed new planning principles, in particular considering controlled distribution transformers.

Controlled Distribution Transformers (CDT)

The controlled MV/LV distribution transformer (CDT) is a distribution transformer (DT) with an on-load tap changer for controlling voltage magnitudes. Main goal is to keep the voltages at all house connections within the valid band of ± 10 % defined by EN 50160. Commercially available in Germany since 2013 (e.g. Siemens FITformer REG, MR GRIDCON), some grid operators gathered experiences in pilot projects, mainly as replacement for traditional DTs in LV grids with high amounts of installed PV power and high voltage magnitudes during PV feed-in. A distinctive characteristic of CDTs is the control scheme:

- **F-CDT** with fixed voltage set point, i.e. 100 % U_n. Only a local inexpensive voltage metering is needed.
- **L-CDT** with line drop compensation. The set point changes with the active power flow, Figure 1 shows the proposed control characteristic. A local power flow metering is needed in addition.
- **A-CDT** with additional remote voltage metering. The voltage at the LV bus bar is set in a way that the voltages at all points of measurement are shifted to valid values if possible. Extra components and communications between the points of measurement and the CDT are needed.

Various studies show that CDTs can often replace classical grid extension (additional lines etc.) at much lower costs in cases where the maximum extent of DG power is limited by high voltage magnitudes [1 to 5]. These studies also show generally higher potential for L- than for F-CDTs. Pfalzwerke Netz AG intend to apply simple and robust solutions without additional components or communication. For this reason, only F- and L-CDTs were taken into account.

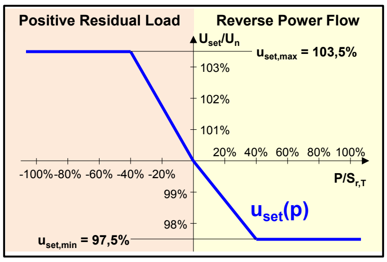

Figure 1: Exemplarily Characteristic for L-CDT

Connection Request Process for new DG systems

The installation process for new DG systems in German LV grids includes power flow calculations to ensure voltages below 110 % U_n. Instead of comprehensive calculations with differing values for MV magnitudes, loads and DG feed-in, a simplified method descripted in the standard-like technical guideline VDE AR-N 4105 [6] is used since August 2008. The power flow calculations are done with a LV grid model where the loads are set to 0 W, the DG systems to their rated feed-in powers, and the MV magnitude at DT bus bar to 100 % $U_{n,MV}$. If the magnitudes at all house connections are not exceeding U_{max} = 103 % U_n and the loading of lines and transformer are in the range defined by the grid operator, the installation is usually permitted. In case of higher values the guideline gives no recommendation. The value 103 % bases on assumptions made on the voltage rise over MV lines, MV/LV DTs, and LV lines, see upper grey curve in Figure 2. The HV/MV transformer is assumed as controlled, therefore the MV magnitude at its bus bar is fixed to 104 % $U_{n,MV}$. The maximum voltage rise across MV lines is 2 % according to the corresponding technical guideline for MV grids [7]. With a combined voltage rise of 3 % across DT and LV lines, a reserve of 1 % to the limit of 110 % U_n (upper red line) is granted. By using CDTs, assumptions about MV magnitudes and the voltage rise over DTs are no longer necessary. Instead, assumptions about the voltage magnitude at the CDT's LV bus bar must be made: The leftmost part of the green curve in Figure 2 shows the voltage magnitudes for the F-CDT. As main result, the voltage rise over LV lines can be much higher than for traditional DTs (109 % - 101 % = 8 % in the example of Figure 2), permitting higher DG powers without violating the voltage limit. For the L-CDT with its lower LV magnitude at the bus bar in case of back feeding, the voltage rise over LV lines can be even higher (in this example: 109 % - 97 % = 12 %). It is clear that in the case of CDTs, the application of VDE AR-N 4105 results in too restrictive DG powers and is therefore inappropriate.

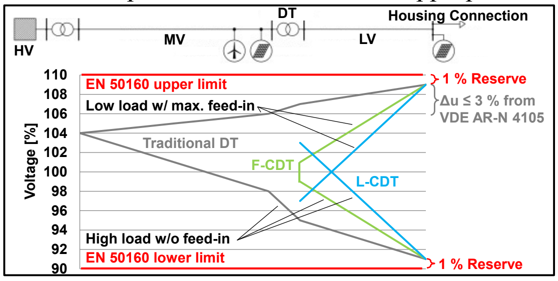

Figure 2: Exemplarily Voltage Drop Segmentation

STUDY 1: NEW PLANNING PRINCIPLES

Approach

For each LV grid of Pfalzwerke Netz AG (~ 3,000) the installed PV powers of 2030 have been forecasted. With a cluster analysis, all grids were analyzed to identify LV supply tasks which represent many grids [5]. The most supply tasks are very similar and well represented by the supply task "ST1" (104 house connections, predicted total installed PV power of 320 kW). Figure 3 shows a grid model with a radial network (DT in the upper right part).

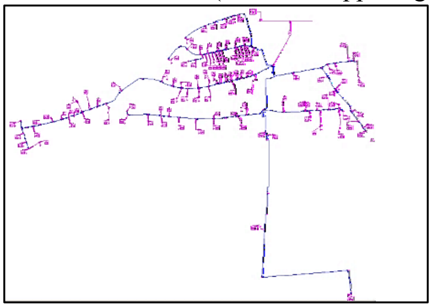

Figure 3: Grid Model of "ST1"

For "ST1" 144 grid variations with properties given below were created. For each variation, a time series power flow calculation for one year in 15 min time steps was performed. The resulting maximum and minimum voltages and maximum loadings were analyzed. With the resulting cost of losses, investment and operational costs (based on cost rates from Pfalzwerke Netz AG), the total cost of each grid variation for a 20 year period was summed up as net present value. Two variations were selected, checked with another supply task "ST2", and combined to the new LV planning principles.

Technical Grid Properties

Network Station

The MV magnitude at DT bus bar was set to fix 20 kV. The DT was modeled in 6 variations as combination of control scheme (traditional DT **K**, **F**-CDT, **L**-CDT) and rated power (**250** kVA, **400** kVA). For F-CDT, $U_{set,fix}$ = 100 % U_n was chosen. For L-CDT, the characteristic from Figure 1 was applied, which was experimentally identified with the goal to enable the least performant grid variations to meet the technical requirements descripted below. All CDTs were designed with ± 4 steps at 2 % U_n step width.

Grid Lines

NAY2Y cables with the conductor cross-sections of 4 x **095** mm², 4 x **150** mm² and 4 x **240** mm² were chosen to model 8 different topologies, which are the combination of 4 basic topologies **S**, **P**, **M**, **V** (see Figure 4) and the cable laying types "single-sided" **1** and "both-sided" **2**. While for classical radial grids (S) and classical meshed grids with radial branches (M) every cable trench includes one cable, the types P and V also include trenches with two cables. The idea is to achieve better voltages at small extra cost as cable installation costs are dominated by trench costs. The shorter cable in P is connected to every neighboring household, while the longer cable is only connected to the remaining households close to the end of the line. No interconnection between these cables is foreseen. The length ratio between the two cables was chosen to 2:3 according to [1]. The extra lines in V have no connection to households but only to the network station and central cable distributors. For house connections, NAY2Y 4 x 35 mm² cables were used.

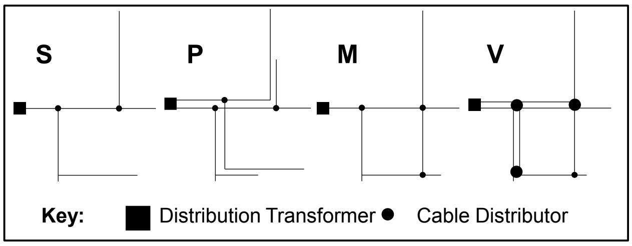

Figure 4: Schemes of the 4 Basic Topologies

House Connection

Every household consists of a load and a PV system. All loads show identical 15 min time series for one year, taken from measured values from a Smart Meter project [8]. The PV feed-in of all households follows a 15 min time series taken from the same project, but the real rooftop orientation of the houses were included, resulting in individual time series for each house and a PV feed-in simultaneity of 86 %. In the base scenario, each PV system has P_{inst} = 3.1 kW and cos φ = 0.95 inductive (PF according to [6]), called **31-095**. 3 more scenarios were studies: **31-100** (P_{inst} = 3.1 kW, cos φ = 1), **37-095** (P_{inst} = 3.7 kW, cos φ = 0.95 ind.) and **37-100** (P_{inst} = 3.7 kW, cos φ = 1).

Investigated Combinations

The 144 grid variations are the combination of

- the 4 basic topologies (S, P, M, V),
- the 2 cable laying types (1, 2),
- the 3 DT control schemes (K, F, L),
- the 2 values for S_{rT} (250, 400) and
- the 3 conductor cross-sections (095, 150, 240).

The naming scheme is "S1-K250-095" etc.

Power Flow Calculation Results

For each one-year-simulation, the maximum voltage $u_{b,max}$ and the minimum voltage $u_{b,min}$ at all households, the highest line loading $i_{b,max}$ of all lines and the highest DT loading $s_{b,DT,max}$ were identified (all values related to nominal voltage, rated current or rated power, resp.). The grid variations had to meet the following requirements:

$$\mathbf{u_{b,max}} \le \mathbf{104\ \%} \qquad \mathbf{u_{b,min}} \ge \mathbf{95\ \%}$$
$$\mathbf{i_{b,max}} \le \mathbf{80\ \%} \qquad \mathbf{s_{b,DT,max}} \le \mathbf{90\ \%}$$

All variations with S_{rT} = 250 kVA failed at the criteria for $\mathbf{s_{b,DT,max}}$ and were not considered further. However, all variations showed values for $\mathbf{i_{b,max}}$ of 75 % or (much) less. PV scenario 37-100 generally shows the highest (worst) maximum voltages $\mathbf{u_{b,max}}$, scenario 31-095 the lowest. The results for 37-095 are in general better than for 31-100, meaning that the voltage-reducing effect of the PV systems' reactive power consumption is stronger than the voltage-raising effect of 20 % higher active power. Bigger cable cross-sections result in better voltages and lower losses. The cheapest topology S1 shows the highest, the most costly topology V2 the lowest voltages. Independent from other aspects the order is

S1→M1→P1→V1→S2→P2→M2→V2.

The DT control scheme significantly affects $u_{b,max}$: For traditional DT and F-CDT, the values are almost the same, caused by the fixed MV magnitude and the small voltage increase at the LV bus bar due to PV feed-in: It is almost always too low to trigger a tap change. In contrast, the **L-CDT** shows massive voltage reduction: In many grid variations, the highest voltage does not occur at a line terminal during high PV feed-in, but at the DT's LV bus bar during high load! This high load voltage magnitude of 103.5 % is the result of the chosen characteristic, see Figure 1; so for the mentioned grid variations, the maximum voltages at the line terminals are equal or below 103.5 %. Nevertheless, in all of these cases the voltages are valid with $u_{b,max} \le$ 104 %.

The results for the minimum voltage $\mathbf{u_{b,min}}$ are comparable: While F-CDTs only gain little advantage over traditional DTs, L-CDTs dramatically improve the minimum voltage. Analog as for maximum voltages, minimum voltages are most often caused not by high loads, but high PV feed-ins, with minimum voltages at the L-CDTs' LV bus bars.

Financial Analysis

As an exemplary result, Figure 5 shows the diagraph of $u_{b,max}$ for scenario 37-100 over costs. Each dot represents a grid variation with traditional DT, each triangle a grid variation with L-CDT. F-CDTs show worse effects at almost the same costs and were ignored. The color represents the cable cross-section. The costs are normalized to the costs of the least expensive variation. The diagraph only includes those variations which fulfill all four technical requirements. For clarity reasons, only the grid topologies with blue triangles (400 kVA L-CDT, 150 mm²) are marked with text. Additionally, the grid variation of the 2007 LV planning principles is marked with "S2-K400-150".

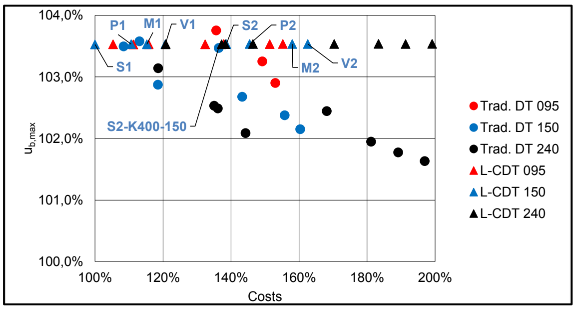

Figure 5: $u_{b,max}$ over Costs for PV Scenario 37-100

Voltages generally reduce with higher costs, with a cost factor of 2 between the cheapest and the priciest variation. There are only few grid variations with 95 mm² conductor cross-section, most of these variations fail due to too high voltages. The equal voltages for L-CDTs variations at 103.5 % U_n are descripted in the previous section. To make things clear Figure 6 shows the maximum voltages during reverse power flow only ("$u_{b,max,+}$"). The L-CDT variations show much lower values. The blue triangles S1 and P1 produce good results at low cost, especially with lower voltages and costs compared to "S2-K400-150" from the year 2007 planning principles.

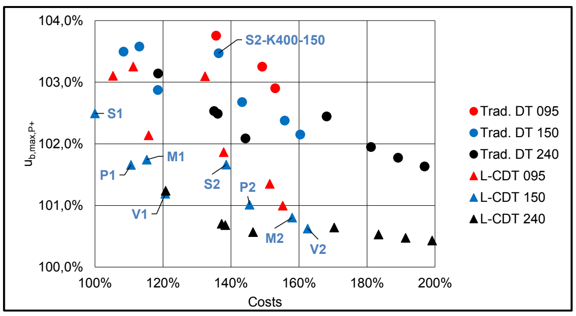

Figure 6: $u_{b,max,+}$ over Costs for PV Scenario 37-100

Selection of New Planning Principles

The variations S1 and P1 with 400 kVA L-CDT and 150 mm² conductor cross-section were chosen for the new planning principles. For validation they were tested with the rural supply task "ST2" because its long lines cause high voltage magnitudes in the today's grid with traditional DT. While S1 can handle the voltages, for all PV scenarios the maximum line loading $i_{b,max}$ is higher than 80 %. P1 generally shows fair voltages, but in spite of the parallel lines slight line overloading occurs. Therewith, the L-CDT eliminates voltage problems to an extent that the maximum installable PV power is only limited by the thermal capacity of the lines! S1 and P1 were accepted as basis for the new planning principles. Both use radial topologies and the same DT type, so that they can freely be combined within a LV grid for different feeders.

As an aid to grid planners, planning diagraphs were developed helping to decide whether S1 or P1 should be used for a certain feeder, or whether a manual planning is appropriate. The development of these diagraphs is presented in [5], here only a snapshot of the results is given. Figure 7 shows one of six planning diagraphs. In the first step, the grid planner identifies the needed line length and the maximum loading for a certain feeder. If the resulting point is located below the blue curve, S1 can be used for this feeder. If it is between the blue and the red curve, P1 is recommended. If it is above both curves, special considerations are needed. The small black segments under the red curve indicate the cost-optimal length ratio between the short and the long line for topology P1.

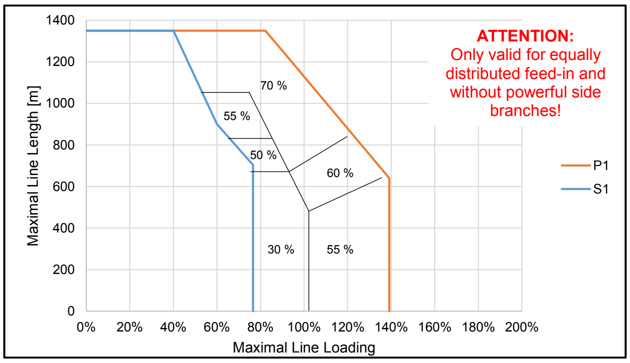

Figure 7: Exemplarily Planning Diagraph

STUDY 2: NEW CONNECTION REQUEST CRITERIA FOR GRIDS WITH CDT

Considered Approaches

The today's 103 % criterion is not suited to capitalize the full potential of CDTs. In particular L-CDTs can solve voltage problems for many grids. With these considerations, three approaches were investigated:

- **A1**: VDE AR-N 4105 as standard and reference.
- **A2**: Max. voltage U_{max} = 109 % U_n, max. line loading.
- **A3**: Only max. line loading. It is assumed that voltage problems are solved. Calculations are done by just adding the PV powers with losses been neglected.

The resulting maximum installed PV power for A3 is the absolute maximum, while for A1 it is the lowest. Central questions to answer are:

- How much **more PV power** can be installed by applying A2 or A3 compared to A1?
- For which **grid characteristics** A3 can be applied without violating the voltage band?

Modeling

The basic method is to increase the installed power of each PV system from 0 to 10 kW in 0.1 kW steps and check up to which power the criteria A1 to A3 are just met.

In contrast to the first study, also existing LV grids with CDT upgrade were considered. Their grid structures generally differ from the new planning principles. In total 78 artificial grid models from [9] were investigated, which cover a large range of supply tasks and network topologies. Some of these models have extreme characteristic with potential voltages problems. 30 grid models were built for topology S1, 30 for P1 and 18 for M1. For rural grids 4x 70 mm² Al overhead-lines and 4x 150 mm² NAY2Y cables were used, while for the 18 suburban grids cables are considered only. Traditional DTs, F-CDTs and L-CDTs were considered. The CDTs' parameters are taken from the first study. S_{rT} was chosen to serve the maximum loadings. The loads were set to 0 W or 250 W; the latter value was taken from the Smart Meter project as the minimum load during PV operation times including some reserve. The PV power was distributed homogenously ("H") and in-homogenously with variations in width ("B"), depth ("T"), and diagonally ("D") as shown in Figure 8. For this purpose, neighboring PV systems were joined to 9 local groups. The total power is equal for all distributions. In addition to the 78 artificial grid models, the real supply tasks "ST1" and "ST2" were studied accordingly.

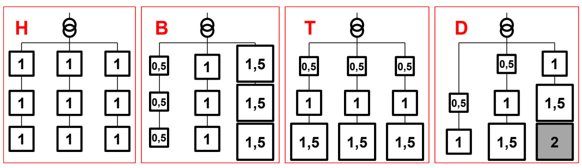

Figure 8: PV power distributions (each block represents one local group of PV systems, power in p.u.)

Selected Results

Table 1 shows the maximum installed PV power $P_{PV,max}$ with supply tasks in rows and grid topologies in columns for approaches A2 and A3. Values are given related to the reference approach A1. For better comparability, only the values for 800 kVA L-CDT, no loads, and the worst distribution D are included. For the artificial grids, the values are the mean of the maxima of the considered grids. The absolute values are between 0.9 kW (ST2, S, A1) and 9.4 kW (Dispersed Cable, P, A2/A3). The colors for A3 indicate whether single (yellow), some (orange) or most (red) calculated voltages are above 109 %. These overvoltages primarily occur for dispersed settlements (especially for overhead lines), but also for villages and suburbs. In all other cases and for both real supply tasks $P_{PV,max}$ is limited by the maximum line loading. Unfortunately, no simple criteria based on line lengths etc. could be found to distinguish both cases.

In most cases A2 provides (almost) the same powers as A3 and significantly higher powers than A1.

Table 1: $P_{PV,max}$ related to $P_{PV,max}$ of A1, for 800 kVA L-CDT, no loads, PV power distribution D

Maximal PV power in p.u. of A1	Topology S			P			M		
	A1	A2	A3	A1	A2	A3	A1	A2	A3
Dispersed OHL	1	2.8	4.6	1	2.9	4.7			
Dispersed Cable	1	2.1	2.3	1	2.1	2.1			
Village OHL	1	1.5	1.5	1	1.2	1.2	1	1.5	1.6
Village Cable	1	1.04	1.04	1	1	1	1	1.02	1.02
Suburb	1	1.7	1.8	1	1.7	1.9	1	1.4	1.4
ST1	1	1.2	1.2	1	1.6	1.6	1	1.03	1.03
ST2	1	2.4	2.4	1	1.3	1.3	1	1.1	1.1

In a sensitivity analysis for A2 also U_{max} values 107 % U_n and 108 % U_n were examined which offer higher voltage reserves. For dispersed settlements $P_{PV,max}$ shrinks by 14 % (107 %) and 7 % (108 %), resp. For villages and suburbs, the average power decrease is lower than 2 % due to the often limiting maximum line loading.

The impact of the PV power distribution varies with the number of feeders and the DT position. For all grids, $P_{PV,max}$ for D is the lowest or close to. For topology S, the average $P_{PV,max}$ for D is about 25 % lower than the respective best performing distribution, for topology P 21 %, for topology M only 3 % (with A2; values widely independent of other aspects).

A load of 250 W increases $P_{PV,max}$ by this value.

Result Comparison with New Planning Principles

Topology S shows the lowest performance at lowest cost. $P_{PV,max}$ for P (calculated with A2) is on average 45 % higher than for S and relatively independent from the DT control scheme. M shows the least differences in voltages and maximum PV power for the PV distributions due to power flows across the feeders for inhomogeneous cases. The average advantage of M compared to S is 9 %, but highly dependent on grid extent and shape and cannot be generalized. While these results were expected, P unexpectedly shows the almost always lowest voltages, outperforming M even for inhomogeneous distributions! The L-CDT again proves its superior capability to increase $P_{PV,max}$ compared to traditional DTs by on average 60 % (calculated with A1).

Suggestions for New Planning Criteria

A2 and A3 allow significantly higher maximum PV powers than A1. As A3 cannot be applied on many grids, **A2** is suggested: For a new PV installation request in a grid with CDT, the grid operator shall perform a power flow calculation similar to that of VDE AR-N 4105 but with different limits for voltages and line loadings. The proposed scheme is as follows:

- PV systems are set to their rated power. Loads are neglected as their minimum powers are small compared to the PV powers and further assumptions can be avoided.
- The MV magnitude is set to nominal voltage, the CDT to the designated characteristic. For the maximum CDT loading, no rules are defined here.
- **108 % U_n** is recommended as **voltage limit.** This allows for high installed PV powers and offers a reserve of 2 % to the limit set by EN 50160.
- A limit for the **maximum line loadings** is mandatory as line loadings will be the limiting factor in many grids. Exceeding thermal ratings may trigger interruptions of supply, therefore a limit of **90 %** is proposed. This limit can be checked by simple summing up of PV installed powers in case of radial structures.

SUMMARY AND OUTLOOK

The L-CDT in combination with radial grids offers high performance at comparatively low costs and was chosen as basis for the new LV planning principles. Consequently, a revised connection request process with a voltage limit of 108 % U_n is recommended resulting in a by the factor 1.3 to 3.5 higher installed PV power depending on the supply task and the grid structure.

Further investigations will expand the new LV planning principles to a wider range of supply tasks including urban grids. New loads like electric cars and heat pumps must be considered as well as further optimized control schemes for L-CDTs.

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