CONTROL ALGORITHMS FOR VOLTAGE REGULATED DISTRIBUTION TRANSFORMERS – MAXIMUM GRID-INTEGRATION OF PV AND MINIMAL WEAR

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ABSTRACT

The German "Energiewende" has led to a massive installation of small and medium scale photo voltaic generation systems in low voltage distribution grids throughout the last years. This article describes latest research results regarding optimal use of voltage regulated distribution transformers (VRDT) for mitigation of expensive grid reinforcement measures. A suitable methodology for assessment of VRDT control algorithms is presented. It is applied to five different grids in Aachen (Germany), where a field trial is to be carried out to analyze the use of different VRDT algorithms in practice. Results show that VRDT with busbar voltage control is sufficient in most cases and selection of suitable algorithms for special grid situations is not trivial.

INTRODUCTION

Voltage regulated distribution transformers (VRDT) have been shown to be effective to reduce conventional grid reinforcement in low voltage grids with strong PV penetration [1]. Different types of control algorithms have been proposed [2-4]. However, no comparison of such algorithms has been carried out so far and no guidelines for their selection and parameterization have been given.

Therefore, a systematic comparison of different control algorithms is required both in theory and practice. This paper aims at describing a suitable methodology as well as exemplary results. As part of the "Smart Area Aachen" project five different rural and suburban grids are analyzed and suitable VRDT control algorithms as well as their parameter settings are determined. Furthermore, general guidelines to maximize PV hosting capacity are derived.

FIELD TRIAL "SMART AREA AACHEN"

The joint project "Smart Area Aachen – Voltage Quality for Future Distribution Grids" is carried out by the Institute for High Voltage Technology of RWTH Aachen University, INFRAWEST GmbH (local DSO for Aachen) as well as Maschinenfabrik Reinhausen GmbH. The project receives governmental funding in order to improve the design and control of VRDT, gain practical experience in different types of grids and analyze general guidelines as well as benefits and drawbacks of VRDT under the manifold conditions in German distribution grids. Different types of VRDT featuring different types of control algorithms will be first tested in five distribution grids (seven in a later stage of the project). Two remote voltage measurements are available in each grid for VRDT control.

Grids under Study

Five different low voltage distribution grids have been chosen by INFRAWEST GmbH representing the variety of German distribution grids that can be considered candidates for VRDT use (i.e. industrial networks as well as urban and city grids are excluded). The grids that have been selected can briefly be described as follows:

Table 1: Grids for field trial - overview

Name	**Number of Customers**	**Total PV installed**	**Structure**
A	21	250 kWp	Rural, farms and multifamily homes, 2 radial feeders, PV directly connected (direct connection to substation)
B	56	142 kWp	Rural, single family homes and farms, ring structure and 3 radial feeders, 100 kWp directly connected
C	98	209 kWp	Small village, private households and farms, 7 radial feeders, 200 kWp directly connected
D	9	144 kWp	Rural, private households and farms, 2 radial feeders
E	152	192 kWp	Small village, mostly households, 8 radial feeders

Control Algorithms for Voltage Regulated Distribution Transformers

All field trials are carried out using extended versions of Maschinenfabrik Reinhausen's Gridcon® Transformer featuring nine tap positions and a tap voltage of 2.5% of nominal voltage, i.e. allowing a total voltage variation of +/-10%.

As compared to the commercially available product, new control algorithms have been implemented and connection of remote voltage and current sensors is possible, i.e. more information about the actual voltages is available for the purpose of optimal voltage control. Algorithms under study are as follows.

Busbar voltage control (BVC)

The controller of the VRDT measures the voltage on the low voltage side busbar of the transformer. The voltage is kept within a given tolerance +/- U_B around a set-point voltage U_0. Typically, the tolerance is U_B=2% and the set-point is at nominal voltage U_N, i.e.

$$U_N\text{-}U_B \leq U \leq U_N + U_B$$

More details are given in [5].

Power-dependent set-point adjustment (PSA)

PSA strictly is an extension of BVC. Voltages are kept within a given tolerance (also +/-2 % for this analysis), but a power-dependent offset is added to the set-point voltage, i.e. the actual set-point voltage is raised in times of high load (in order to compensate voltage drops) and lowered in times of high feed-in, which is determined by measuring the load flow across the transformer.

$$U_N + dU(P)\text{-}U_B \leq U \leq U_N + dU(P) + U_B$$

PSA is similar to line drop compensation, which has been available for primary substation transformers for long time and is described in many publications such as [6]. However, rules for PSA configuration are not available and are therefore part of this study.

Remote sensor control (RSC)

RSC also is an extension of BVC. In addition to BVC, voltages are measured at different points in the low voltage grid and transmitted online to the VRDT controller. All voltages are kept within a given tolerance around a set-point voltage, which typically is set to nominal voltage. In addition to BVC a second tolerance band U_{B2} is introduced, which is applicable to all remote voltages and which is typically much larger than +/-2% (up to +/-10%). As long as voltage rise or voltage drop along the different feeders are moderate, the VRDT works in BVC mode.

$$U_N\text{-}U_{B1} \leq U_{busbar} \leq U_N + U_{B1}$$

Only as voltage rises / drops become very large and voltages at remote sensors exceed the applicable tolerance band, the busbar voltage may leave its tolerance band U_{B1} and all voltages are kept within the tolerance of U_{B2}.

$$U_N\text{-}U_{B2} \leq U_{all} \leq U_N + U_{B2}$$

Multi-sensor control (MSC)

Like RSC, MSC makes use of remote voltage measurements. The tap position T is controlled such that voltages in the underlying distribution grid take on the optimal values. The optimum is determined such that the summed absolute deviation D of all voltages at all sensors depending on the tap position $U_S(T)$ from a given set-point (typically nominal voltage) is minimized. The deviation of the busbar voltage can be given a weight g, where g can be 0, 1 or n (i.e. it is disregarded, equally weighted as every remote sensor or given the same importance as all remote sensors together).

$$\min_T \rightarrow D(T)$$

$$D(T) = \sum_S |U_S(T)\text{-}U_N| + g \cdot |U_{busbar}(T)\text{-}U_N|$$

METHODOLOGY FOR EVALUATION

The assessment of different control algorithms is carried out in three steps as depicted in **Figure 1**.

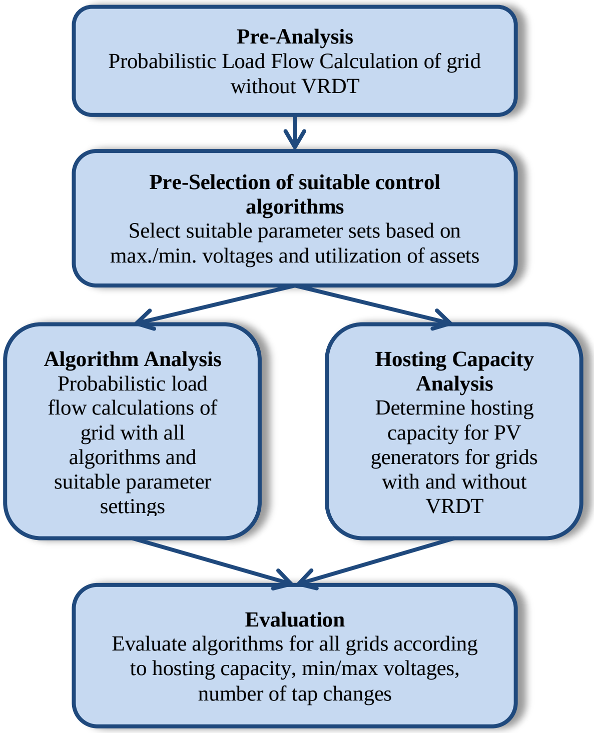

Figure 1: Four steps to select algorithm

Probabilistic Load Flow Calculation

In order to properly determine expected voltages and load flows in low voltage distribution grids regardless of the high uncertainty of intermittent loads and feed-in, probabilistic load flow calculation is used for all simulations presented here. Calculation results are to be interpreted as probability for certain states of the distribution grids, e.g. 95 % percent probability that voltages due not exceed certain limits[1]. The existing simulation environment (see [7] for details) has been extended by all VRDT control algorithms presented above. It is important to note that the algorithms are realistically implemented as part of the simulation environment. They do not merely work on the evaluated results (i.e. the voltages and load flows expected with given probability), but results of the extend algorithm can also be interpreted as probability of states of the distribution grid with VRDT and can therefore directly be compared to results without VRDT.

Assessment Criteria

The evaluation of suitable control algorithms for all grids under study is conducted according to different criteria, which will be presented in the following.

Maximum voltages

In general, the aim of using VRDT is to mitigate violations of the allowable voltage band of +/-10% according to DIN EN 50160. Therefore, the reduction of maximum voltages using VRDT and the increase of minimum voltages are the main criteria for assessment. For certain control algorithms the decrease of maximum voltages can lead to a decrease of minimum voltages. Therefore, special attention is also paid to the difference between minimum and maximum voltage. Maximum and minimum voltages are determined for all grids, algorithms and parameter settings.

Hosting Capacity for Photo Voltaic Generation

The hosting capacity for photo voltaic generation, i.e. the installed power of PV generators that can be installed without violating voltage limits according to DIN EN 50160 and VDE-AR N 4105 and without causing any overload of lines and transformer, is taken as a measure for how effectively the VRDT can help to integrate more PV into given distribution grids. It is determined for every grid with and without VRDT as well as with and without remote measurements.

Number of Tap Changes

The number of tap changes per year is an indicator for the expected wear of the on-load tap changer. It is expected to be largely influenced by the algorithm and parameter setting and it is therefore calculated for all of these.

Selection of Algorithms for Field Trial

The grids that have been selected for the field trial have been in operation without VRDT for long time. Some of them have been reinforced few years ago to be able to host all PV generators that are currently installed. As a consequence, the main purpose of installing VRDT in these grids is not mitigation of voltage problems, but gaining experience with different types of algorithms. Thus, algorithms and their parameter settings have to be selected in such a way that VRDT operation can be expected. E.g. the boundaries of the tolerance band for RSC have to be much “narrower” than would be advisable in grids with large voltage rise or voltage drops having a real need for voltage control or reinforcement.

[1] In the following, the expression maximum/minimum voltage and maximum load are used for the voltages and load flows that can be expected not to be exceeded with 95 % probability, unless otherwise stated.

MAIN RESULTS

Pre-Selection of Suitable Parameter Sets

In order to pre-select suitable parameter sets for detailed algorithm analysis, calculations have been performed to determine minimum and maximum voltages as well as maximum asset utilization in case without VRDT. Results are shown in **Table 2**. Three out of five grids show moderate voltage rise and moderate voltage drops. Only grid C stands out with 5.8 % voltage rise and grid E stands out with 9.7% voltage drop. The maximum spread between minimum and maximum voltage is 12 % and also occurs in grid E. Minimum voltages at available sensor position $U_{min,S}$ (cable distribution cabinets) differ from minimum voltages at all other nodes U_{min} of the grid by only 0.0 % to 0.7 %. For grids C to E the same is true for maximum voltages. Grids A and B do not offer the possibility to measure voltages in cable distribution cabinets close to the directly connected PV generators. Resulting differences between maximum voltage U_{max} and maximum voltage at sensor positions $U_{max,S}$ are 1.8 % to 3.9 %.

Table 2: Results of Pre-Analysis

Name	A	B	C	D	E
U_{max}	1,025	1,044	1,058	1,040	1,023
U_{min}	0,960	0,955	0,977	0,980	0,903
$U_{max,S}$	1,007	1,005	1,051	1,040	1,019
$U_{min,S}$	0,960	0,957	0,984	0,980	0,903
L_{max}	0,567	0,631	0,901	0,889	1,092
$L_{max,T}$	0,513	0,494	0,726	0,511	0,573
$L_{T,Umax}$	0,513	0,428	0,726	0,511	0,154
$L_{T,Umin}$	0,304	0,439	0,086	0,189	0,544

(maximum and minimum voltage (U_{max}, U_{min}), max and min voltage at available sensor positions ($U_{max,S}$, $U_{min,S}$), max load (L_{max}), max. transformer load of all times ($L_{max,T}$) and transformer load during max. and min. voltage ($L_{T,Umax}$, $L_{T,Umin}$))

Detailed Analysis of Different Algorithms

All Algorithms Generally Suitable

Voltage measurements in all field trial grids are fairly exact with few exceptions. Where deviations are large (U_{max} in grids A and B), only directly connected PV generators are affected and maximum voltage rise across these connection lines can easily be estimated. Furthermore, all grids show a significant utilization of the transformer at times of maximum voltage ($L_{T,Umax}$, grids A – D) or at times of minimum voltage ($L_{T,Umin}$, grid E).

Therefore, from the pre-analysis it can be concluded that generally all algorithms can be used for testing in all field trial grids. Possible parameter sets can be derived from the pre-analysis.

Selection of Possible Parameter Sets

All calculations are performed with several different parameter sets for each algorithm. These parameter sets have been derived as follows.

- **PSA:** grids A-D: reduce set-point voltage during feed-in situations in order to reduce max. voltage (raise of min. voltage for grid E). Parameter sets are chosen such that the voltage reduction is 25 %, 50 %, 75 % or 100 %, of max. voltage rise, respectively, when feed-in is 80 % of its maximum value. E.g.
$$\mathrm{dU}(0) = 0$$
and
$$\mathrm{dU}(P = 0.8 \cdot L_{T,Umax}) = -0.25 \cdot (1{,}044-1)$$
for grid B. In-between these two points dU(P) is linear.
- **RSC:** U_{B1} = +/-2 % for all grids. U_{B2} are chosen such that max. voltage from pre-analysis will significantly be reduced (for A-D, min. voltage raised for E).
- **MSC:** $U_0 = U_N$, g = 0, 1, n (with n the number of remote sensors). No adjustment according to pre-analysis required.

Exemplary Results

Power dependent set point adjustment (PSA) proves to be suitable also in detailed analysis especially for grids B and D. Maximum voltages can be reduced by 1.5 % and 2.1 %, respectively. Minimum voltages are only reduced by 0.1 % and 0.7 %, respectively, at the same time. For both grids these achievements can be made with the 75 % configuration only. 50 % configuration reduces the maximum voltages much less and 100 % configuration reduces maximum voltages only little more, while reducing the minimum voltages much more. See **Table 3** for details.

Table 3: PSA for grids B and D

Parameter setting	Reduction of U_{max}	Reduction of U_{min}	Tap changes
Grid B			
25 %	0,000	-0,003	0
50 %	-0,007	-0,003	82
75 %	**-0,015**	**-0,001**	**164**
100 %	-0,018	-0,019	256
Grid D			
25 %	0,000	-0,001	0
50 %	-0,013	-0,004	112
75 %	**-0,021**	**-0,007**	**212**
100 %	-0,025	-0,027	316

Remote Sensor Control (RSC) is most suitable for grids C and E, as voltage rise and drop are highest out of all grids and minimum as well as maximum values can be measured with high accuracy. Differences between minimum and maximum voltage at sensor positions can be as large as 6.7 % ($U_{max,S} - U_{min,S} \leq 6.7$ %, grid C) and 11.6 % (grid E), respectively, but may be much less, as $U_{max,S}$ and $U_{min,S}$ do not necessarily occur simultaneously. A total width of the allowable voltage band of 8 % (i.e. U_{B2} = +/- 4 %) is sufficient to keep the voltage within in grid C at all times. Setting U_{B2} = +/- 6 % is adequate for grid E. Setting U_{B2} = +/- 7% is adequate, too, and yields a strongly limit number of tap changes at the cost of a little less rise of minimum voltage. See **Table 4** for details. A strong dependence of the number of tap changes from the actual load and feed-in situation can be concluded from the large spread between a maximum of 467 and a minimum of 136 tap changes per year between the different repetitions of the probabilistic assessment.

Table 4: RSC for grid C and E

Parameter setting	Reduction of U_{max}	Reduction of U_{min}	Max. tap changes	Min. tap changes
Grid C				
U_{B2} = +/- 4 %	-0,012	-0,011	54	50
Grid E				
U_{B2} = +/- 6 %	0,011	0,027	467	136
U_{B2} = +/- 7 %	0,011	0,018	88	26

Multi Sensor Control (MSC) turns out to be the most efficient algorithm to use in grid A, although no significant differences can be found between its different parameter settings. A rise of minimum voltages of 1.4 % and a rise of the maximum voltage of 0.9 % can be expected. The number of tap changes is moderate with a maximum of 380 to be expected. Again, a strong dependence of the tap changer operation on the actual load and feed-in situation can be observed.

Hosting Capacity for Photovoltaic Generation

Hosting capacity has been determined for all grids and for VRDT without remote voltage measurements. Only for grid E, where in some cases the voltage band is limiting the hosting capacity while using VRDT without remote measurements, calculations have been repeated for VRDT with remote measurements. If asset utilization is limiting the hosting capacity, no further increase of hosting capacity can be expected from using remote measurements. Results are shown in **Figure 2** and **Figure 3**, respectively.

Three cases have been looked at for determining hosting capacity of grids A – D: no VRDT, grids with VRDT and limited hosting capacity per house (30 kWp) or unlimited hosting capacity per house. Existing PV generators are not included in any of the calculations. The possible gain of hosting capacity in grids A – D varies largely from almost none (C) to roughly 200 % gain (A). In all cases transformer or line ratings are limiting. Therefore, no further gain of hosting capacity could be achieved with more complex algorithms or remote measurements.

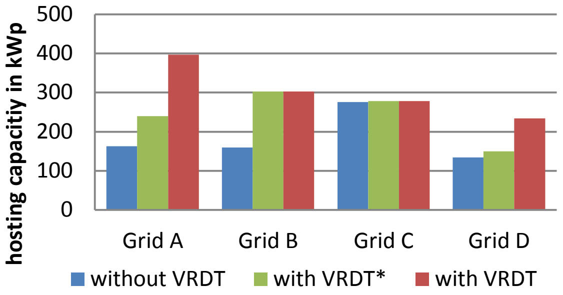

Figure 2: hosting capacity grid A – D (with VRDT*: Hosting capacity limit to 30 kWp per house by definition
Parameter: BVC, $U_0 = U_N$, U_B = +/- 2.5 %)

Hosting capacity of grid E cannot be determined with the same parameter setting as for grids A – D. This is because of the strong voltage drops which would exceed the threshold of 90 % of nominal voltage with the above configuration. To take this into account, the tolerance band of the VRDT with BVC is moved up in two steps (parameters P1 and P2) and RSC is used for comparison (parameter P3). Hosting capacity can be increased by 41 % (P1) to 48 % (P3). Although the difference between hosting capacity with VRDT for parameters P2 and P3 is negligible, RSC is advantageous in this situation. Both transformer utilization as well as voltages are relevant limits in this case. Although total hosting capacity is similar, siting and sizing of the PV generators is different. Much more flexibility for PV generator positioning is available with parameter P3 as compared to P2. Voltage restrictions are much more restricting for positioning PV in long feeders and these are much weaker with RSC.

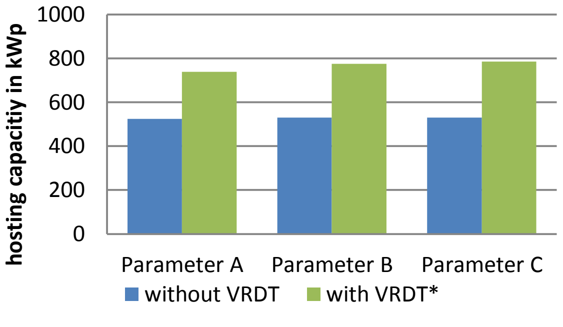

Figure 3: hosting capacity grid E
Parameter P1: BVC, $U_0 = 1.035 * U_N$, U_B = +/- 2.5 %
Parameter P2: BVC, $U_0 = 1.025 * U_N$, U_B = +/- 2.5 %
Parameter P3: RSC, $U_0 = U_N$, $U_{B1} = U_{B2}$ = +/-8%

CONCLUSIONS AND OUTLOOK

Different VRDT control algorithms have been analyzed for five exemplary distribution grids in Aachen, Germany. Results show that bus bar voltage control is sufficient in most grids, while remote sensors can offer more flexibility for PV generator positioning. PV hosting capacity can be increased by as much as 200 % and is always limited by transformer utilization. Larger gains can be expected in grids with longer feeders.
Results of the analysis will be used for field trial configuration and will be compared against field trial results. Further analysis will be conducted regarding algorithm selection and parameter setting for scenarios with more PV generators installed.

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