FNN Recommendation

Voltage Regulating Distribution Transformer (VRDT) – Use in Grid Planning and Operation

July 2016

English translation of FNN-Recommendation: rONT – Einsatz in Netzplanung und Netzbetrieb

Note: In the event of any discrepancy between the English and the German version, the latter shall prevail.

FNN

VDE

FNN FORUM NETZTECHNIK/
NETZBETRIEB IM VDE

Legal notice

Bismarckstraße 33, 10625 Berlin
Tel.: + 49 (0) 30 3838687 0
Fax: + 49 (0) 30 3838687 7
E-mail: fnn@vde.com
Internet: http://www.vde.com/fnn

Juli 2016

FNN FORUM NETZTECHNIK/ NETZBETRIEB IM VDE

Voltage Regulating Distribution Transformer (VRDT) – Use in Grid Planning and Operation

July 2016

FNN FORUM NETZTECHNIK/ NETZBETRIEB IM VDE

Contents

List of figures

List of tables

Foreword

The increasing amount of electrical energy being fed into the grid from dispersed generation plants is presenting the operators of public, electrical energy supply systems with new challenges. The power flows increased by the additional feed-in are significantly increasing the need for grid reinforcement, especially in rural distribution grids. This is often needed to ensure voltage stability.

Voltage Regulating Distribution Transformers (VRDT) are one possible alternative to conventional grid reinforcement, which is often very costly. These transformers decouple the voltage levels of the low- and medium-voltage grids, making better capacity utilization of the voltage band possible.

This FNN-Recommendation explains how VRDTs work and presents possible applications and real-life examples. The aim of the document is to assist distribution grid operators with grid planning and operation when using a VRDT.

The FNN-Recommendation was produced by the "Voltage Regulating Distribution Transformer" project group at Forum Netztechnik/Netzbetrieb im VDE (FNN).

Introduction

Motivation

The highly volatile feed-in of electrical energy from dispersed generation plants produces much greater fluctuations in voltage, especially in the medium and low-voltage grids. This makes compliance with the limit values defined for safe and reliable grid operation increasingly difficult, especially the requirements for voltage stability defined in DIN EN 50160. There is often a need for these levels of the grid to be reinforced and such work is often very costly and time-consuming.

Over the last few years, however, numerous alternative technical solutions have been developed and their combination tested in live grids. One effective solution to overcoming voltage fluctuations in the low-voltage grid is the Voltage Regulating Distribution Transformer (VRDT). In many cases, the VRDT is an economical alternative to conventional grid reinforcement. For some grid operators, as a standard tool the VRDT has become an important component in turning grids into smart grids.

This FNN-Recommendation focuses on VRDT use. Other technical solutions for voltage stability are not considered. On this topic, please refer to the FNN study on static voltage stability [1] and the FNN-Recommendation on reactive power management [2].

Aim of the FNN-Recommendation

The aim of this FNN-Recommendation is to describe the basic function of the VRDT and to present possible applications in grid planning and operation. This document is a collection of experiences gained with the technology in a number of projects. This document is intended for grid planners and project planners, e.g. at utilities or service providers, to assist with decisions about whether VRDT use is feasible and if so in what form.

This document answers the following questions:

- What standards and terms are relevant to VRDTs? (see sections 2 and 3)
- How does the design of a VRDT differ from that of a conventional transformer? (see section 4)
- In what applications does the use of a VRDT present a technical and economical solution? How can these applications be identified? (see section 5 and the Annex)
- What aspects need to be taken into account when planning a VRDT? (see section 5)
- What aspects should be taken into account when operating a VRDT? (see section 6)

1 Scope of application

This FNN-Recommendation applies to LV and MV distribution grids up to U_m = 36 kV and only to voltage regulation based on transformers (not converter technology).

It provides recommendations and information about the technical, operational, and planning options for using a VRDT in the distribution grid.

2 References to standards

The documents cited below refer to the subject matter of this FNN-Recommendation. Because they are also referenced within the document, it may be necessary to refer to them when applying the document.

For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

VDE-AR-N 4105 Power generation systems connected to the low-voltage distribution network - Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks

DIN EN 50160 Voltage characteristics of electricity supplied by public distribution systems

DIN EN 50588-1 Medium power transformers 50 Hz, with highest voltage for equipment not exceeding 36 kV

DIN EN 60076 Power transformers

DIN EN 60214 On-load tap-changers

DIN EN 60870-5 Telecontrol equipment and systems (Parts 101 – 104)

DIN EN 61000-3-11 Electromagnetic compatibility (EMC) - Part 3-11: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems - Equipment with rated current ≤ 75 A and subject to conditional connection

DIN EN 61850 Communication networks and systems for power utility automation

3 Terms and abbreviations

3.1 Terms

3.1.1 Rated operating voltage [IEV 442-01-07]

Nominal voltage of the electricity supply grid at which use of the installation material is intended.

3.1.2 Rated power [IEV 421-04-04]

By agreement, value of the apparent power, which is the basis for configuration, manufacturer's guarantees and tests for a transformer, a compensation reactor or an earth-fault neutralizer, and which defines the level of rated current which can flow at the rated voltage present under the specified conditions.
COMMENT: Both windings in a transformer with two windings have the same rated power, which by definition is the rated power of the transformer. In transformers with several windings, the rated power may be different for each winding.

3.1.3 Rated voltage range [IEV 151-16-49]

Range of supply voltage stated by the manufacturer, expressed by its upper and lower rated voltage SOURCE: IEC 62368-1:2010, 3.3.10.5

3.1.4 Rated current (of a winding of a transformer or compensation reactor) IEV 421-04-05]

Level of current flowing through a phase conductor connection point on a winding, which can be determined by dividing the rated power of a winding by the rated voltage of the winding and an appropriate phase factor.

3.1.5 Rated current (for installation material) IEV 442-01-02]

Electrical current assigned by the manufacturer for a defined operating condition for an installation material.

3.1.6 Rated voltage ratio (of a transformer) [IEV 421-04-02]

Ratio of the rated voltage of a winding to the rated voltage of another winding with a lower or the same rated voltage.

3.1.7 Operating voltage [IEV 601-01-22]

Voltage magnitude during normal operation at a certain time at a certain point on the grid. COMMENT: This may be an anticipated, estimated or measured value.

3.1.8 Highest operating voltage of a grid [IEV 601-01-23]

Highest value of operating voltage which occurs at any time at any point on the grid during normal operation. COMMENT: These values do not take account of transient changes, e.g. caused by switching operations in the grid, or temporary random fluctuations in voltage.

3.1.9 Power section

The components which, in the same way as the active part, carry or are subject to the transformer's operating voltage and operating current regardless of where they are installed.

3.1.10 Nominal voltage of a grid [IEV 601-01-21]

Appropriate, rounded voltage magnitude for designating or identifying a grid.

3.1.11 Lowest operating voltage of a grid [IEV 601-01-24]

Lowest value of operating voltage which occurs at any time at any point on the grid during normal operation. COMMENT: These values do not take account of transient changes, e.g. caused by switching operations in the grid, or temporary random fluctuations in voltage.

3.1.12 Voltage Regulating Distribution Transformer (VRDT)

A power transformer of up to U_m = 36 kV with an automated switching device, which ensures on-load voltage regulation.

3.1.13 Regulating range

The regulating range defines the on-load adjustment range of the transformer voltage and is normally stated in the form of the basic position (nominal ratio) of the transformer and the number of steps in the direction of higher and lower voltage, e.g. 20.0/0.4 kV ±4 x 2.5 %.

3.1.14 Control losses

Power loss occurring as a result of additional components in the power section depending on primary equipment and operating status. The estimate of control losses should be agreed between the manufacturer and user. Power loss for the measurement and control technology components are not included.

3.1.15 Voltage level [IEV 601-01-25]

One of the nominal voltages used in an electricity supply system

3.1.16 Tap changer (OLTC)

Equipment for changing the tap connections of a winding which can be operated while the transformer is energized or on-load.
(Extract from DIN EN 60076-1 (VDE 0532-76-1):2012-03)

3.1.17 Step voltage

With transformers which change their transmission ratio in discrete steps, step voltage describes the quasi-stationary jump in voltage associated with switching. This is usually stated with reference to the nominal voltage and together with the number of steps defines the regulating range.

3.1.18 De-energized tap-changer (DETC)

Equipment for changing the tap connections of a winding which can only be operated while the transformer is de-energized (disconnected from the grid).
(Extract from DIN EN 60076-1 (VDE 0532-76-1):2012-03)

3.1.19 Delay time [IEV 521-05-21]

Duration of interval between a sudden change in the input signal level and the time at which the output signal level passes a defined value close to its starting value.

3.1.20 Intended operating current (of a circuit) [IEV 826-11-10]

Current that a circuit is to manage in uninterrupted operation.

3.2 Abbreviations

BNetzA	Bundesnetzagentur (Federal Network Agency)
DETC	De-Energized Tap-Changer
EEG	Erneuerbare Energien Gesetz (German Renewable Energy Law)
GP	Generation Plant
GU	Generation Unit
FNN	Forum Netztechnik/Netzbetrieb im VDE (Grid Technology/Grid Operations Forum at the Association for Electrical, Electronic & Information Technologies)
Max V	Maximum Voltage
HV	High Voltage
IEV	International Electrotechnical Vocabulary
ICT	Information and Communication Technology
MV	Medium Voltage
LV	Low Voltage
OLTC	On-Load Tap-Changer
SS	Secondary Substation
DT	Distribution Transformer
PV	Photovoltaics
Q	Reactive power VRDT Voltage Regulating Distribution Transformer
PLC	Programmable Logic Controller
TCC	Technical Connection Conditions
PS	Primary Substation
DGO	Distribution Grid Operator
WT	Wind turbine

4 The technology of VRDTs and how they work

4.1 General

With conventional distribution transformers, a transmission ratio ideal for the installation site is set using what is known as a de-energized tap-changer (high-voltage tap-changer). By selecting an appropriate transmission ratio, the voltage in the entire connected LV grid can be kept within the permissible voltage limits.

The de-energized tap-changer is set at the installation site and usually has to be adapted only rarely, in response to changed grid conditions, for example. Tap-changers which can only be actuated when de-energized (DETC) are therefore used for conventional distribution transformers.

Given the increasing rate of change in the generation and consumption structure, however, customer-oriented voltage regulation is sometimes a useful contributor to voltage stability and has resulted in the development of the Voltage Regulating Distribution Transformer (VRDT), which can be actuated automatically or manually when on-load and energized.

Regardless of the technical implementation selected and its operating principle, a VRDT generally consists of an active transformer part, a controlling element, and a control unit with regulation (Figure 1).

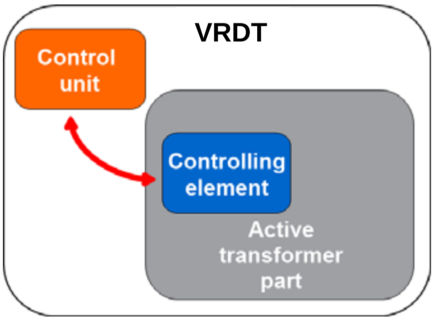


Figure 1: Schematic illustration of the components of a VRDT

Below you will find general statements on the VRDT components and a brief description of the solutions currently available on the market.

4.2 Structure of the VRDT

Depending on the VRDT's operating principle, the de-energized tap-changer (DETC) is replaced or supplemented by a controlling element which can switch on-load (OLTC). The active transformer part must have the corresponding characteristics, which generally include the number and positions of the winding taps or if needed also supplementary components, such as limitation and commutation restrictors, extra windings, etc.

The transformer and controlling element form a functional unit, where the controlling element is usually fitted in or on the transformer tank. This means that the tank geometry, oil volume, nature of the cooling ribs etc. are different from a conventional distribution transformer. It follows that a conventional distribution transformer cannot be appropriately converted for a reasonable amount of effort and money.

In most cases, the VRDT's dimensions (base area, height) can be selected such that they can be used in existing secondary substations.

Depending on the technical implementation and the VRDT's operating principle, during operation so-called additional losses may result from the controlling element and/or extra components, windings, etc. These are generally taken into consideration when configuring the function unit (comprising active transformer part and controlling element) such that the requirements of the EU Regulation [3] are met by the variants of the controlling elements listed below, which are available on the market.

The applicable standardsfor power transformers and standards typical of the industry (e.g. station dimensions, service life) are also met by the VRDT.

4.3 Technical realization of the controlling element and control unit

In terms of controlling elements, over the last few years, manufacturers have tested various technological concepts for switching taps in distribution transformers on-load. Of the controlling elements available for volume production, a distinction is made between three technological means of switching transformer windings:

- Switching with on-load tap-changer on high-voltage side
- Switching with contactors on low-voltage side
- Switching with contactors on low-voltage side together with a booster transformer

In addition to the controlling element, a control unit using voltage regulation algorithms is also needed. Basically, the control unit undertakes the following basic functions:

- Voltage measurement and evaluation
- Signal conversion and triggering of switching operations via algorithms
- Controls for commissioning and manual control of the controlling element
- Optical display elements for the tap position and status of the control unit
- Switch for switching between various control modes (e.g. Manual, Auto, and Remote)

Some manufacturers also offer the following control unit functions as options:

- Measurement of electrical or analog/digital signals of the transformer and/or from the secondary substation (e.g. temperature, etc.)
- Linking of remote sensors for specifying the desired voltage value
- Communication with the network control center

The basic function of the control unit enables independent voltage regulation to a fixed desired voltage value on the LV busbar. Regulation to a desired value (current/power) depending on power flow and regulation concepts taking account of a remote measured value sensor are also available as options.

Control units currently available on the market have dimensions in various geometries (e.g. in the order of WxHxD 40x40x20 cm or 20x80x15 cm). These are intended for local installation in or on the secondary substation. This is usually also possible in compact stations. Furthermore, they can also be used in pole stations, but static general conditions must then be taken into account.

4.4 Overview of the controlling elements and control units available on the market

This technical document presents controlling elements and VRDTs available for volume production for which there are DIN EN 60076 type tests and which are available on the market with a short lead time. Refer to the table below for their technical characteristics.

Table 1: Overview of the controlling elements and control units available on the market

Type of controlling element	Switching with on-load tap-changer on high-voltage side (example GRIDCON® iTAP®)	Switching with power contactors on low-voltage side (example FITformer® REG)	Switching with contactors on low-voltage side together with a booster transformer (example Minera SGrid)
Operating principle	On-load tap-changers driven by motors, fitted on the cover, and installed in the transformer oil in the tank, can be used to dynamically switch the tap windings of distribution transformers on-load in one direction or the other and thereby change the transmission ratio of the distribution transformer as with power transformers. In addition to the on-load tap-changer, the setup also needs a control unit, which can be used for independent voltage regulation to a fixed desired voltage value on the LV busbar.	The circuit basically comprises vacuum and air contactors, resistors and a controller. The regulation principle is based firstly on a bypass being activated by closing a contactor. The current flows through the bypass such that the mechanical contactors can even switch under nominal load without unwanted peaks or drops in voltage. Only once the target position is reached the bypass opened and therefore deactivated. The regulation unit is housed in a separate area directly on the transformer tank. Furthermore, an additional tap changer can be used for load-free switching.	To regulate the controlling element's tap positions, this VRDT uses a set of power contactors to switch the booster's windings and keep the output voltage in a defined range. The contactors are installed outside the tank in a removable control cabinet. While the power contactors are switched, a bypass is activated to ensure perfect switching and to prevent unwanted peaks in voltage. After switching, the bypass is automatically deactivated by its interconnection. The interconnection also ensures that internal switching errors cannot occur in the contactors being used.
Rated characteristics	• 160 kVA to 2,250 kVA (10 kV with delta connection on high-voltage side) • 160 kVA to 4,500 kVA (20 kV with delta connection on high-voltage side)	250 kVA to 630 kVA (up to 36 kV)	• 160 kVA to 1,000 kVA (for 7.2 kV to 36 kV with delta connection on high-voltage side) • Higher power values available on request as special solutions
Short-circuit voltage	4 %, 6 % or as requested by customer	4 %, 6 % or as requested by customer	4 %, 6 % or as requested by customer

Type of controlling element	Switching with on-load tap-changer on high-voltage side (example GRIDCON® iTAP®)	Switching with power contactors on low-voltage side (example FITformer® REG)	Switching with contactors on low-voltage side together with a booster transformer (example Minera SGrid)
Switching device	Switching takes place in vacuum cells on the high-voltage side (on-load tap-changer designed for up to 700,000 tap-change operations)	Switching is undertaken by a combination of vacuum and air contactors and resistors on the low-voltage side (depending on their size, the vacuum contactors used have a life of up to 5 or 10 million mechanical switching cycles at rated operating current)	Switching is undertaken by power contactors to switch the booster's windings (on-load tap-changer requires no maintenance for the life of the transformer with an electric switching capability of 1.45 million cycles)
Regulating range – on-load	• On-load tap-change operation: 5, 7 or 9 taps with up to 3 % (freely selectable) • Step voltage: 600V/step	Load regulating range in 3 steps Minimum tap change of 250 kVA ±2.5% 400 kVA ±3.3% 630 kVA ±4.0%	• On-load tap-change operation: 5 or 9 taps (from 1 to 2.5 % per tap) • The load-free de-energized tap-changer (DETC) is produced with 5 taps as standard.

Type of controlling element	Switching with on-load tap-changer on high-voltage side (example GRIDCON® iTAP®)	Switching with power contactors on low-voltage side (example FITformer® REG)	Switching with contactors on low-voltage side together with a booster transformer (example Minera SGrid)
Control unit	Plug & play control cabinet can be located anywhere in the transformer station with the following functions: • Regulation to a fixed desired value • Regulation to desired value dependent on power flow (current/power) • Regulation including a remote measured value sensor • Can be integrated in higher-level regulation concepts • Optional storage of Power Quality measurement data on an SD card (U, I, P, Q, S, cosphi, status, and tap position) • Automatic, remote, and manual mode • Raise / lower operation	Control cabinet can be located anywhere in the transformer station with the following functions: • Automatic, remote, and manual mode • Standard: Two-stage voltage regulation on the busbar (parameters for slow and fast switching, delay times) • Remote: Voltage regulation and monitoring via serial or TCP/IP-based communication • Manual: Manual voltage regulation using control buttons on control unit • Optional: Additional current measurement • Optional: Regulation based on dispersed measurements in the low-voltage grid (SICAM product portfolio with superordinate regulation unit) • Alternative: External signal • All set parameters are stored on a micro memory card (MMC)	Plug & play control cabinet can be located anywhere in the transformer station with the following functions: • Regulation to a fixed desired value • Regulation to desired value dependent on power flow (current/power) • Regulation including a remote measured value sensor • Can be integrated in higher-level regulation concepts and station automation • Optional storage of measurement data on an SD card, with access via laptop or 3G online access to HTML webpage • Automatic, remote, and manual mode • Parallel operation of several VRDTs as master/follower

Type of controlling element	Switching with on-load tap-changer on high-voltage side (example GRIDCON® iTAP®)	Switching with power contactors on low-voltage side (example FITformer® REG)	Switching with contactors on low-voltage side together with a booster transformer (example Minera SGrid)
Communication equipment and protocols	• PLC fieldbus terminals • Ethernet interface • Communication protocols IEC 60870-5-104 and MODBUS TCP	• Hardware ports: 2x RJ45/Ethernet 1x RS 485 • Protocols: IEC 60870-5-104 (standard) • Optional: IEC 60870-5-101 (balanced / unbalanced / dialup) IEC 60870-5-103 IEC 61850 ABB RP570/1 Siemens Sinaut-ST1 L&G Telegyr 800 MPT-S DNP3.0 Modbus RTU	• Ethernet interface • Communication protocols Modbus, IEC60870-5 (101 – 104), and Profibus • Connection of external measured value sensors via 3G, LAN, wireless or Power Line
Type tests	• Transformer type-tested to IEC 60076 • On-load tap-changer type-tested to IEC 60214	• Transformer type- and routine-tested to IEC 60076	• Evidence of routine, type, and special tests to IEC 60076 • Evidence of 26th BImSchV (German Federal Immission Control Act) for electromagnetic fields

In addition to the controlling elements listed, various new concepts based on different technological approaches are being developed and/or at prototype status.

5 Planning information

5.1 How VRDTs work

A VRDT basically works by decoupling the low and medium voltage. This produces the main benefit of using a VRDT, namely the ability to redistribute the voltage band available in accordance with DIN EN 50160.

Starting with the regulated HV/MV transformer, the voltage band is generally distributed using the cable structures of the medium voltage, the conventional distribution transformer, the cable structures in the LV, culminating in the building connection. This is shown in Figure 2 (scenario A).

Due to the decoupling of the LV from the MV, selective use of a VRDT provides a way of redistributing the voltage band downstream of the VRDT within the requirements. This is shown in Figure 2 (scenario B).

When using VRDTs in a line, decoupling the voltage of the MV line from the voltages in the LV grids in this line allows the voltage band in the MV line in question to be utilized right up to the upper and lower voltage band limit. This means, however, that the desired value on the HV/MV transformer cannot be freely selected, but rather is still determined by the distribution of the voltage band in the other MV lines. This is shown in Figure 2 (scenario C).

Due to the complete decoupling of the LV from the MV, using VRDTs in all areas provides a way of redistributing the voltage band upstream of the MS within the requirements in addition to redistributing the voltage bad downstream of the LV. This is shown in Figure 2 (scenario D).

So far there is no comprehensive scientific research whether there is a negative influence on grid stability from a high penetration of VRDTs in case of a looming voltage collapse. Results of ongoing research on this topic are expected for early 2017. Once available, this information will be published in an addendum to this document.

Annex B2 contains examples of how the voltage bands can be distributed taking into consideration the influencing factors needed.

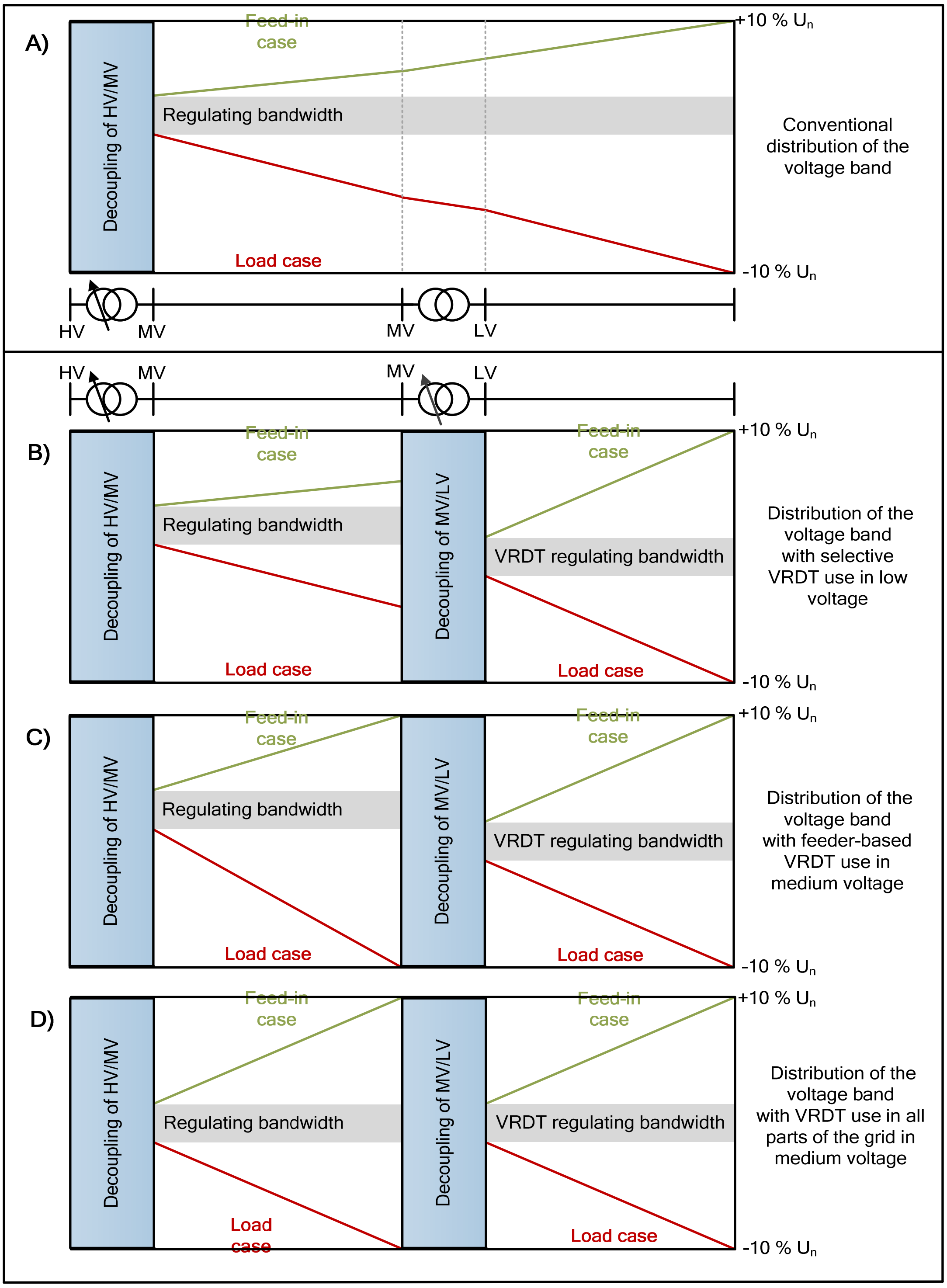


Figure 2: Distributing the voltage bands

A) With conventional distribution transformer
B) With selective use of VRDT
C) With use of VRDTs in lines
D) With use of VRDTs in all areas

5.2 Applications

A VRDT can be used to achieve better capacity utilization of the available voltage band by decoupling the voltage at the MV/LV connection point. These days, it is most commonly used to connect additional GPs. In this way, of course, additional loads can also be handled in an existing grid. Furthermore, initial attention is also being given to optimizing the grid topology itself, e.g. by merging two distribution grids to eliminate one SS, and to optimizing reactive power management. These applications are briefly explained below.

5.2.1 Rectification of voltage band problems

Infringement of voltage limit values can be easily avoided using VRDTs. Not only is this the case in LV grids, but also in the MV grid if used in all areas or with intelligent selectiveness. Several VRDT applications are presented below.

5.2.1.1 Selective use with a focus on the low-voltage grid

Selective use of a VRDT makes sense if the voltage limit values defined in your own planning principles are being infringed in the LV grid. Decoupling the MV from the LV level provides the planner with a wider voltage band. Figure 3 shows an example of isolated stations with a VRDT.

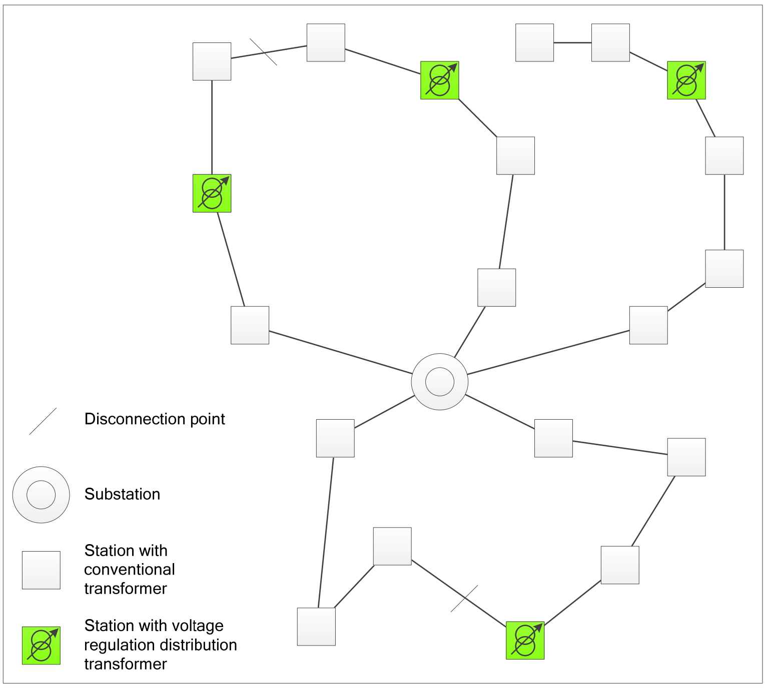


Figure 3: Selective use of the VRDT in a MV grid

Application examples include:

- Where voltage bands are being infringed at individual points at the LV level by feed-ins or consumers (e.g. heat pumps or E-mobility).
- Where voltage bands are being infringed at individual points at the MV level by hugely fluctuating feed-ins (e.g. wind turbines) or consumers (e.g. industrial plants) near the substation in question.

Advantages:

- Grid reinforcement measures in the LV grid can be avoided, minimized or delayed and can then be undertaken later in an optimized manner.
- The VRDT provides greater planning certainty than e.g. conventional grid reinforcement because there is greater potential for integrating feed-in and demand in the entire distribution network.

5.2.1.2 Line-based use with a focus on the medium-voltage grid

Line-based use of a VRDT makes sense if the voltage limit values defined in your own planning principles are being infringed in the MV grid starting at a certain distance from the primary substation. In such cases, decoupling the corresponding MV line from the LV grids below it ensures that the VRDT keeps the voltage at the LV level constant despite the voltage at the MV level being too high or too low. Figure 4 shows a MV grid where all SS exceeding a particular limit value for change in voltage are equipped with a VRDT. This permits considerably greater changes in voltage than usual in the MV grid without the grid having to be reinforced.

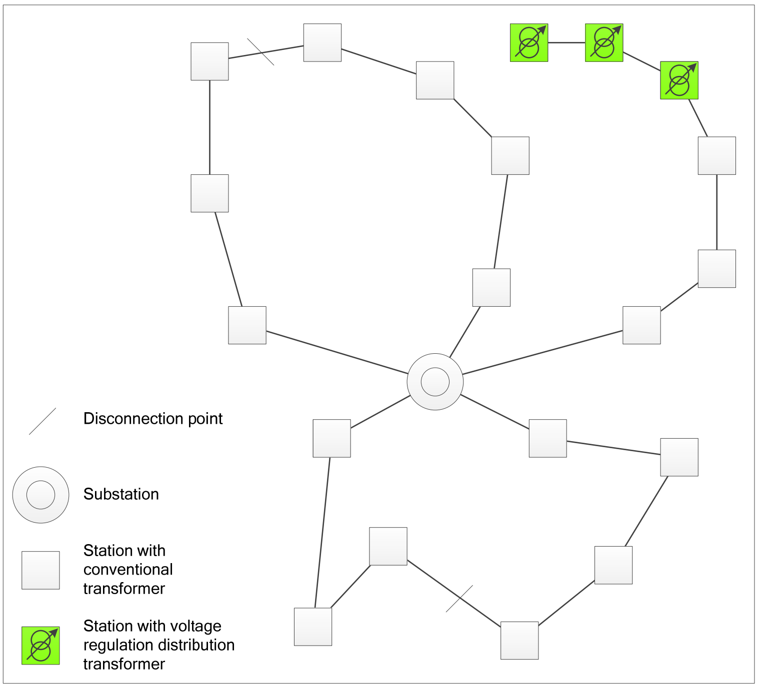


Figure 4: Line-based use of VRDT in a MV grid

Application examples include:

- Where voltage bands are being infringed in a larger interconnected area at the MV level (e.g. at the end of feeders or with openly operated ring structures), due to large fluctuating or constant feed-ins and/or consumers in the vicinity of the substation in question

Advantages:

- All the advantages from section 5.2.1.1 apply for the individual LV grids
- Grid reinforcement measures in the MV grid can be avoided, minimized or delayed and can then be undertaken later in an optimized manner.

Notes:

- Because the requirements of DIN EN 50160 are still observed at every MV grid connection, customer stations in the line can still be operated with conventional DTs.
- It may not be necessary to use a VRDT in LV grids with very small or no increases in voltage.

5.2.1.3 Use in all parts of the grid with a focus on the medium-voltage grid

Use of a VRDT in all parts of the grid makes sense if there is a risk of the voltage band being infringed in the entire MV grid. It should be noted that there is no need to use a VRDT for substations in the vicinity of the primary substation as far as MV is concerned. A sensible approach in this scenario would be to successively equip all substations affected by voltage grid infringements, starting with those furthest away from the primary substation (Figure 5). Unlike the use of VRDTs in individual lines, in this case the desired voltage value on the HV/MV transformer can be reduced and an even higher voltage rise be permitted in the MV grid, for example. This is shown in Figure 2 (scenario C).

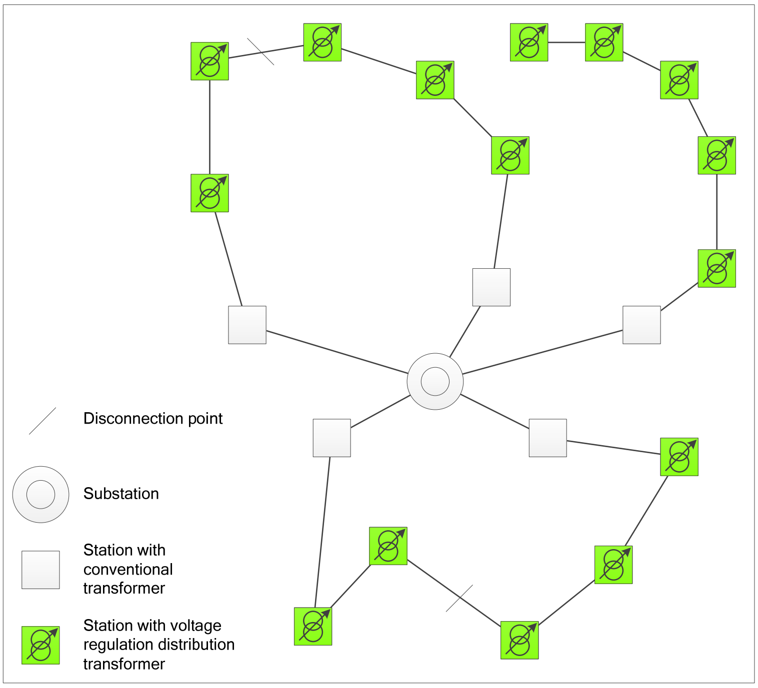


Figure 5: Use of the VRDT in all parts of the MV grid

Application examples include:

- Where voltage bands are being infringed in a larger interconnected area at the MV level as a result of excessive voltages from the HV level, which cannot be compensated for by the tap changer on the HV/MV transformer.
- Where voltage bands are being infringed in a larger interconnected area at the MV level as a result of hugely fluctuating or constant feed-in with a direct connection to the primary substation, which cannot be compensated for by the tap changer on the HV/MV transformer.
- Connection of more generation power in a grid characterized by feed-in by reducing the desired voltage value at the tap changer of the HV/MV transformer.

Advantages:

- All the advantages from section 5.2.1.1 apply for the individual LV grids
- Grid reinforcement measures in large parts of the MV grid can be avoided, minimized or delayed and can then be undertaken later in an optimized manner.
- The replacement of a HV/MV transformer with a transformer with a different transmission ratio and/or a tap changer can be avoided or delayed.

5.2.2 Optimization of the grid topology

Another objective that can be pursued using a VRDT is to take this technology into consideration for planning target grids and to optimize existing grid topologies. This is particularly interesting given that the role of the grid is changing from feed-in and demand perspectives. For example, two or more LV grids can be combined to form one larger grid area to save on one or more grid substations. The VRDT then compensates for the resultant higher levels of voltage fluctuation. The supply radii of SS with VRDT can be increased as shown in the illustration in Figure 6.

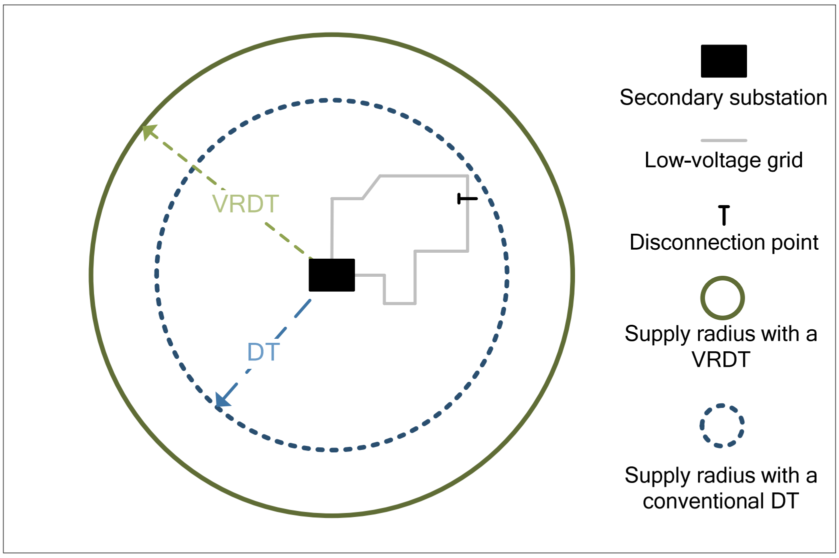


Figure 6: Example of increase in the size of the supply radius using VRDTs

Furthermore, automation and monitoring of the SS and the integration of systems on the LV grid or smart meters via the secondary substation may offer technical and economic benefits in terms of inspection costs. Such scenarios have already been implemented [4].

5.2.3 Support for reactive power management in MV/LV grids

Using a VRDT can also allow operators to tap into additional creative leeway in terms of reactive power management at the lower grid levels. The enhanced capacity utilization of the available voltage band made possible through use of VRDTs could bring about new reactive power behavior for GPs. This may be beneficial

- in terms of loading grid equipment (apparent currents),
- by compensating for one's own reactive power management (at the point on the grid connecting to the upstream grid), and
- in regard to switching abilities and/or cancellation conditions of circuit breakers (reactive currents).

For more information, please consult the documents [1,2].

5.3 Limits and special cases of VRDT use

Even though a VRDT can be used in a large number of grids to greatly increase grid connection capacity, limitations must be noted in a few special cases. Even when using a VRDT, the connected generation power cannot be increased above the thermal limits of the equipment (cables, transformer); conventional grid reinforcement or transformer replacement is needed in such cases.

5.3.1 VRDT use with very long grid offshoots

In grid offshoots with long cables and a high connected generation power, use of a VRDT should be investigated in each individual case. In any case, using a VRDT allows the voltage band to be extended by say 3 % to 8 % (see section 5.9, Figure 14). If necessary, the VRDT can be supplemented by other technical measures, such as specific grid reinforcement, separate provision of reactive power by GPs or line controllers.

5.3.2 VRDT use in inhomogeneous lines

If the lines in a LV grid are loaded very inhomogeneously, i.e. if there are mainly GPs in one feeder and if there are mainly consumers installed in another, then the voltage profiles of these feeders diverge greatly. From an electrical standpoint, this scenario is comparable with that of long grid offshoots, so the information provided under 5.3.1 applies.

5.3.3 VRDT use in parallel operation

Note the information provided in section 5.7.3.

5.4 Regulation procedures

In principle, the following variants exist for voltage regulation of the VRDT on the LV busbar. The variants are shown in order of ascending complexity:

- Regulation to a fixed desired voltage value (see 5.4.1)
- Regulation to a desired voltage value dependent on power flow (see 5.4.2)

- Regulation including a remote measured value sensor (see 5.4.3)

The first procedure is sufficient for most scenarios. In principle, the additional work involved in more complex procedures must guarantee a significant benefit in terms of grid planning. In many cases, full use cannot be made of all the voltage band reserves theoretically available because the maximum current carrying capacity of the cables in the LV grid also has to be taken into account. Depending on the procedure chosen, differing amounts of measurement and in some cases communication technology are needed. The variants are described in more detail below.

5.4.1 Regulation to a fixed desired voltage value

In this procedure, the desired voltage value on the low-voltage side of the VRDT is specified by a fixed value (e.g. 400 V) regardless of the present power flow. If the measured value is outside of the regulating bandwidth specified around this desired value for longer than the set delay time, a tap change of the regulator is triggered Figure 7 shows the possible range of the output voltage of the MV/LV transformer when regulating to a fixed desired voltage value. Like the desired value, this is independent of the level and direction of current through the transformer.

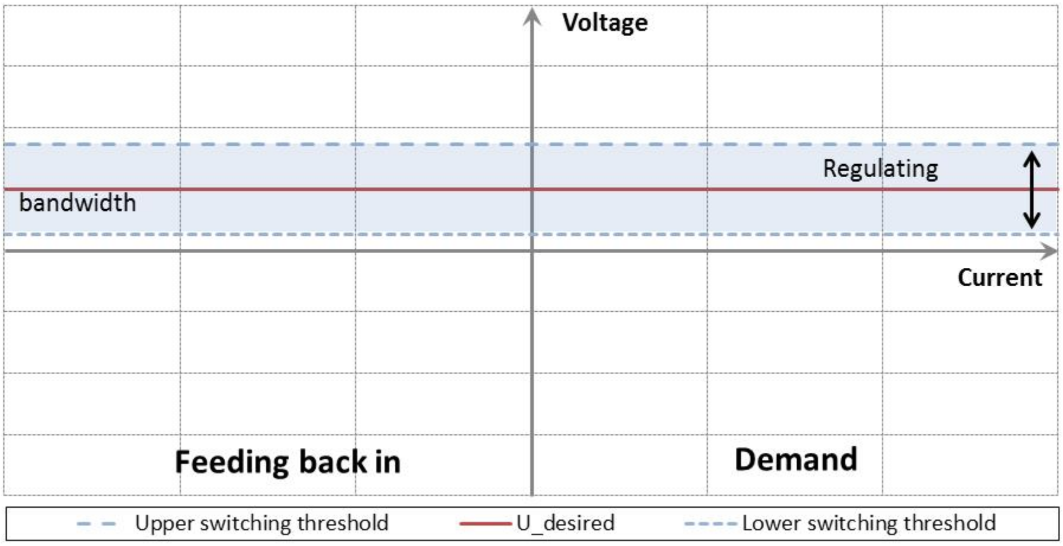


Figure 7: Illustration showing a typical regulating bandwidth with regulation to a fixed desired voltage value

The regulating bandwidth needs a minimum value because otherwise, with graduated regulators if the switching thresholds are exceeded after a tap-change process, the busbar voltage cannot be brought into the regulating bandwidth and further return control processes would be initiated. Refer to section 5.5 for the choice of different control parameters.

5.4.2 Regulation to a desired voltage value dependent on power flow

This procedure, also known as current compounding, requires not only a measurement of the LV busbar voltage but also a recording of the direction-dependent power flow through the DT. This extra information is used to adapt the desired voltage value to the present power flow situation. This technology has already proven itself in higher voltage levels.

If the LV grids are loaded sufficiently homogenously, when there is demand in the LV grid, the voltage here decreases on the way to consumers and as a consequence a higher setting is selected on the VRDT. If power is being fed back from the LV grid, a lower voltage can be selected on the VRDT because this will rise further in the LV grid due to feed-in. This allows better capacity utilization of the voltage band in the LV grid permitted by standards. Figure 8 shows an example of how the desired value progresses and the regulating bandwidth around this for current compounding.

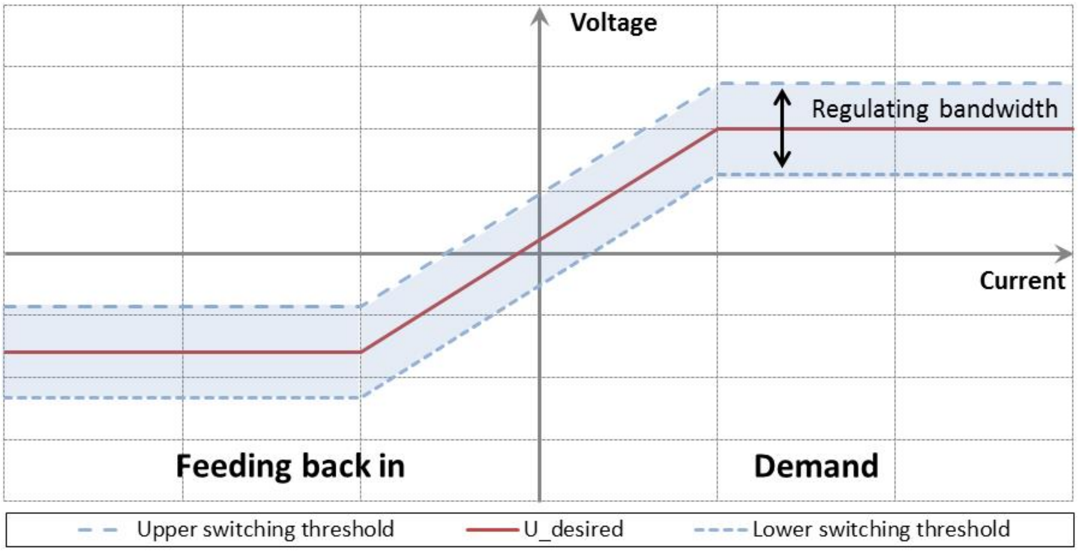


Figure 8: Illustration showing the regulating bandwidth when regulating to a desired voltage value dependent on power flow

The power value can also be used to determine the desired voltage value in place of the current.

The $U_{desired}/I_{demand}$ characteristics curve is usually determined through analysis and is often specified for all and/or one particular category of grid. Alternatively, grid calculations can be used to produce characteristic curves which are more accurate and make better use of the voltage band but can no longer be used for general purposes. One method that lies between these two extremes is described in [5].

As with regulation to a fixed desired value, the setting of a minimum regulating bandwidth and the information in section 5.5.2 should be observed for graduated regulators.

5.4.3 Voltage regulation including a remote measured value sensor

By recording at least one point in the LV grid using measurement technology, desired value regulation to this point can be set on the VRDT. This kind of regulation can offer additional potential for integration. However, it requires a grid calculation to be undertaken in advance to determine the points in the grid where the voltage is highest and lowest. Measurement technology must then be fitted on at least one of these points and linked to the control unit for communication and an alternative regulation concept must be set in case communication should fail.

5.5 Control parameters

The control response of the VRDT is determined by various configuration and setting parameters which are explained in more detail below.

5.5.1 Configuration parameters

In addition to classic configuration variables, such as rated voltage or power, other characteristics must be stated when ordering VRDTs. These are, at minimum, the regulating range, the base position, and the step voltage.

With graduated transformers which change their transmission ratio in discrete steps, step voltage describes the quasi-stationary jump in voltage associated with switching. This is usually stated with reference to the rated voltage and, together with the number of steps, defines the regulating range. The regulating range defines the adjustment range of the transformer voltage and is normally stated in the form of the base position (nominal ratio) of the transformer and the number of steps in the direction of higher and lower voltage, e.g. 20.0 kV/0.4 kV ±4 x 2.5 %. Here, 20.0 kV/0.4 kV means the rated ratio and/or ratio in the base position with four switching positions each in the direction of higher and lower voltage, where the step voltage is 2.5 %. In principle, however, the regulating range can also be arranged asymmetrically around the base position, e.g. 20.0 kV/0.4 kV +2 x 2.5 % -6 x 2.5 %.

When selecting the step voltage, remember that it also affects the flicker value in the grid (see section 5.6). The choice of regulating range determines the additionally useable voltage band, the feed-in and consumer power that can be integrated, and the supply radius which a SS can achieve.

5.5.2 Setting parameters

In this context, setting parameters are control characteristics which can be changed at any time after a VRDT has been purchased. The most important parameters include:

- Desired voltage value $U_{desired}$ in V:

  Desired value for the voltage level to be set. The value for $U_{desired}$ can be fixed or adapted variably depending on other influencing factors (see section 5.4). Because the desired voltage value cannot be maintained with absolute accuracy with graduated transformers and switching results in a jump in voltage corresponding to the step voltage, a deviation from the desired voltage value must be permitted.

- Upper and lower switching threshold as % in relation to nominal voltage:

  These two values state how far above and below the desired value the measured voltage magnitude (excluding measurement errors) may deviate before the regulator performs a tap change. It is usually a good idea to set the upper and lower switching thresholds symmetrically around the desired value. However, the area between the upper and lower switching thresholds, which is also known as the regulating bandwidth or regulation hysteresis, is ultimately relevant. The smaller the regulating bandwidth, the greater the voltage band that can also be used (see Figure 2).

  The regulating bandwidth should however always be greater than the step voltage. A value of 1.6 times the step voltage has proved highly effective in real-life situations (see Figure 9).

  A higher regulating bandwidth allows the number of switching cycles to be reduced.

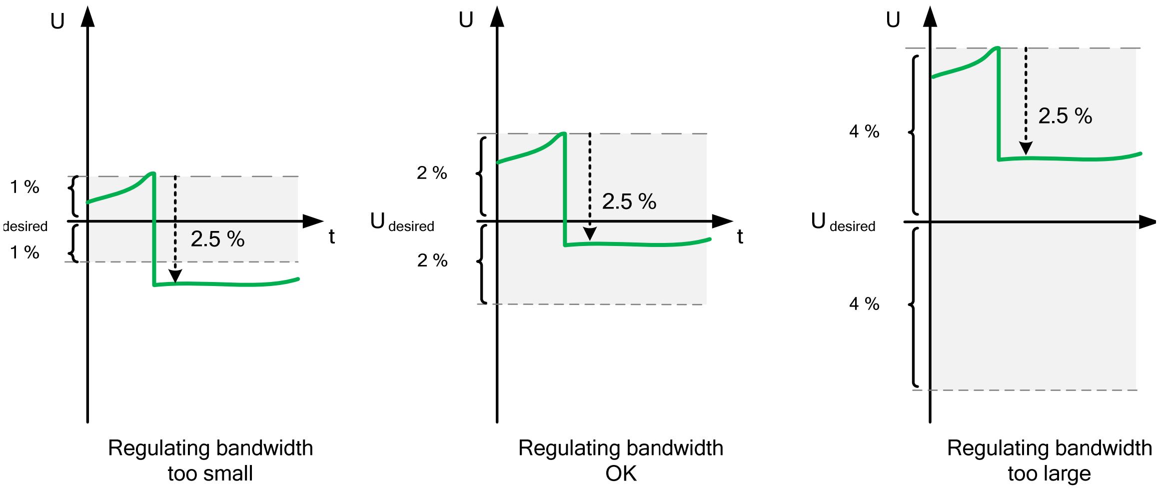


Figure 9: Different configurations of regulating bandwidth with a 2.5 % voltage level

The following set of parameters can also be defined for some VRDT types and make optimization of the control response possible:

- Delay time T_1 [s]

  This parameter defines the time by which switching is delayed once voltage has exceeded / fallen below the upper / lower switching threshold. Only if the voltage is still outside the regulating bandwidth after the delay time is a tap change initiated. This avoids unnecessary responses to brief peaks or drops in voltage, e.g. caused by a cloud passing over. 10 seconds are therefore recommended as the minimum value. In combination with a Q(U) regulation in the LV grid values greater than 10 seconds could be reasonable.

- High-speed switching

  In order to be able to respond faster in the event of larger deviations from the desired voltage value (e.g. when starting the regulator back up, it should quickly switch back into the permitted range), high-speed switching can be used.

  This is realized using the following options, for example:

  - High-speed switching threshold as % in relation to nominal voltage:

    These parameters are outside the regulating bandwidth and ensure that a tap change is initiated immediately without delay time T_1 being observed should the voltage exceed or fall below the defined high-speed switching thresholds (Figure 10).

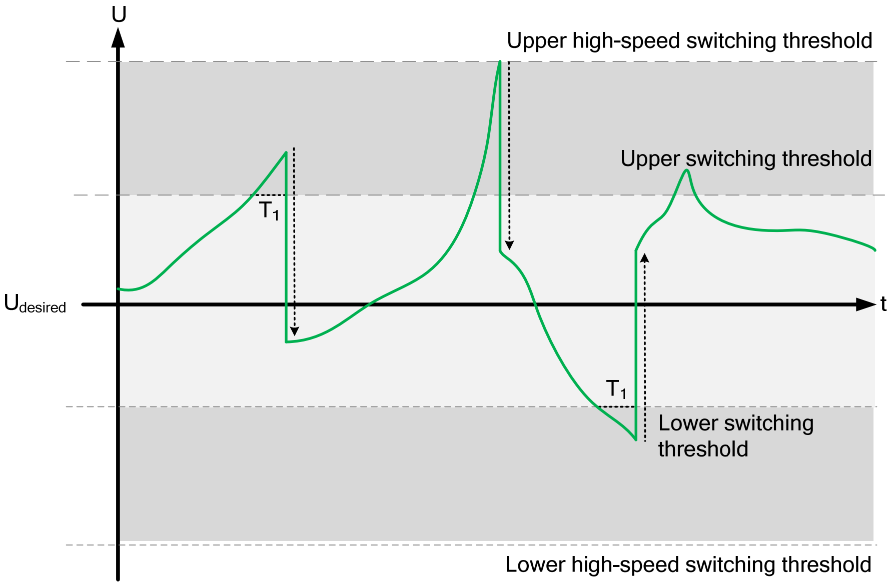


Figure 10: Use of high-speed switching thresholds

- Shortened delay time T_2 in s:

  If the measured voltage is still outside the regulating bandwidth after a tap change, another tap change is initiated after a shortened delay time T_2 ($T_2 < T_1$) (Figure 11).

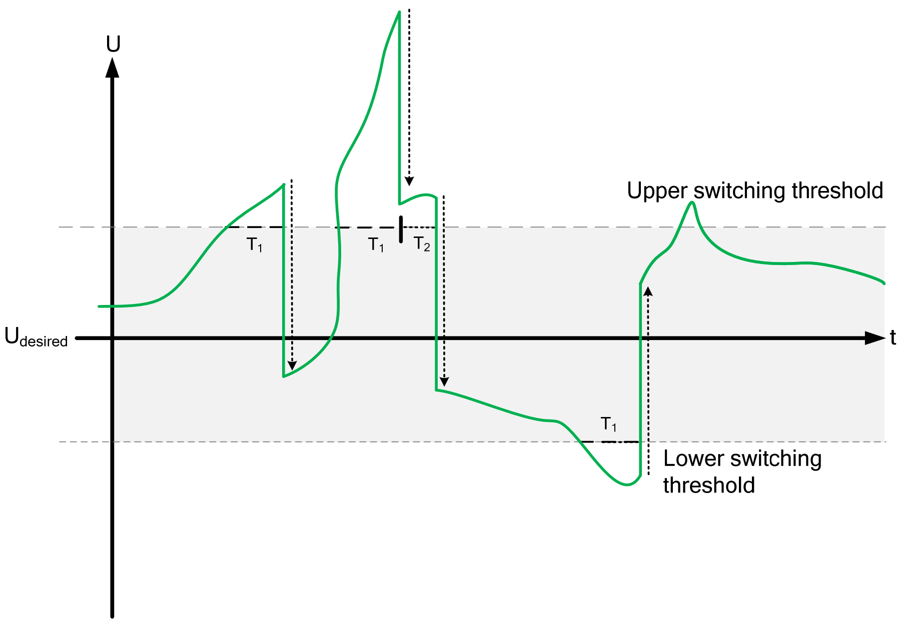


Figure 11: Use of a shortened delay time T_2

5.6 Flicker

The switching processes on the VRDT are quick changes in voltage and affect the flicker value in the supply grid. The amount of flicker produced by the VRDT depends mainly on the step voltage and frequency of switching. The latter is affected by the regulating bandwidth and set delay times. IEC 61000-3-11 can be adhered to by an appropriate choice of these parameters (see section 5.5).

5.7 Regulation in the network with other regulators

5.7.1 Interaction between VRDT and HV/MV transformer

A tap change by a HV/MV transformer affects all underlying node voltages. With a VRDT, a response to this change in voltage may also take the form of a tap change.

It should however be noted that not all tap-change operations by the HV/MV transformer result in a VRDT tap-change operation. This is heavily dependent on the value of the voltage just before the tap-change operation and on the step voltage of the HV/MV transformer. Practical experience and a theoretical study [5] have shown that the tap changes initiated on the VRDT by the tap changes of a HV/MV transformer are limited and do not therefore affect the life of the VRDT.

Even if VRDTs are used over large areas, the impact on the current and reactive power flows in the MV grid is very low. The HV/MV transformer is not therefore affected by use of a VRDT.

5.7.2 Interactions between VRDT and generation plant

If the VRDT parameters are set correctly, it has no major impact on the active power fed in by the GP. The voltage adjustments caused by a VRDT only result in minor changes to the power flows and regulation hysteresis ensures that it does not react to these. Interactions relating to active power can therefore be ignored.

If reactive power is provided by a fixed cos(phi) or a cos(phi)(P) concept (see VDE-AR-N 4105 and/or [6]), this is only dependent on the active power fed in so there are no interactions between the VRDT and GP.

When using Q(U) regulation in GPs in the LV, potential interactions with the VRDT should be noted. For example, a tap change by a VRDT and the resultant change in voltage may impact on the provision of reactive power by the GPs using a Q(U) concept. Both procedures can be used in parallel with appropriate parameterization [1]. Further optimization of parameterization is investigated in other projects [7].

5.7.3 Parallel operation of Voltage Regulating Distribution Transformers

When transformers are operated in parallel, a distinction can be made from a locational standpoint between grid parallel operation and busbar parallel operation and from a time-related standpoint between continuous parallel operation and brief parallel connection.

Continuous grid parallel operation of VRDTs is possible in theory. But, given the possible additional loading from the circulating reactive currents produced and the greater planning work involved, this is not recommended and we would refer to the information in section 6.4.

If brief grid parallel connection of VRDTs is needed for operational reasons, the information in section 6 should be observed.

It is essential that the transformers run in synch, even for short periods of parallel busbar operation. Manufacturers provide various procedures / solutions for this, e.g. master-follower (master-slave) or circulating reactive current minimization.

5.8 Aspects of the cost-benefit analysis

5.8.1 Costs

When using a VRDT, the grid operator has to take into account investments and operating costs. There are also initial costs, e.g. for producing documentation, training operating staff, etc.

Investment in a VRDT may include the following factors:

- Procurement

  The procurement costs depend on the chosen technical solution and its parameters. It should be noted that the control unit may have to be replaced during the VRDT's life.

- Assembly

  When assembling the VRDT, not only the costs of installing the power transformer itself but also the costs of assembling the sensors (e.g. current transformer) and the control electronics should be taken into consideration.

- Communication connection

  The costs for setting up optional data transfer to the control centre depend on the type of communication route and the volume of data to be transferred.
  No communication connection is generally needed when operating a VRDT with a fixed desired value or desired value dependent on power flow. If remote measurement sensors are used, additional costs for implementing the communication connection needed should be taken into account.

- Documentation

  The VRDT should be taken into account in the grid operator's documentation of technical data and GIS systems.

Compared with a DT, there are only minor differences in operating costs provided there is no communication connection. The costs for maintaining a substation with VRDT are not significantly higher. In comparison with a DT, no significant increase in electrical loss should be expected. The VRDT solutions currently available, which are listed in this document, also satisfy the relevant Ecodesign Directive from 2015 [3].

5.8.2 Benefits

Most of the benefits gained from using a VRDT relate to the aspects explained briefly below:

- Substitution for conventional grid reinforcement
- The advantage of greater flexibility and increase in grid capacity
- Reduction in complexity
- Saving in terms of SS

The main benefit of the VRDT is as a **substitution for conventional grid reinforcement** in the MV and LV grid (further benefits, see applications in section 5.2). Grid reinforcement is driven primarily by voltage stability whereby the cost of laying cables represents the largest part of the complete costs due to higher costs of underground work. Using a VRDT can often postpone or totally prevent this often costly grid reinforcement [1,5,8].

The question of whether a VRDT is an **economical alternative to conventional grid reinforcement** depends on how much grid reinforcement can be substituted. The costs of grid reinforcement are mainly dependent on factors such as the nature of the soil and the surface (grid reinforcement costs in urban areas are higher than in rural ones). Depending on the factors listed, a VRDT may be a more cost-effective alternative to conventional grid reinforcement.

Another benefit of the VRDT comes from the **advantage of greater flexibility** in implementation and the robustness of its use in the face of future uncertainties. While lengthy planning and approval procedures may be required for cable reinforcement, the short realization times associated with the VRDT (planning, procurement, implementation) enable rapid responses to the addition of generation power. The risk of so-called stranded investments – costs of grid reinforcement which have proven unnecessary when projects haven't actually gone ahead – can also be avoided because a VRDT can be easily replaced with a normal DT and used in another location.

Using a VRDT can reduce the intermeshing of grids in cases where this wasn't previously possible for reasons of voltage stability. This **reduction in complexity** simplifies grid management.

For more about savings in terms of SS, refer to section 5.2.2.

5.8.3 Regulatory aspects

From a regulatory standpoint, using VRDTs is an investment in the grid (CAPEX) and, like conventional grid reinforcement, it raises capital assets and pays interest in accordance with the German Incentive Regulation Ordinance (AregV).

Because of the "technology neutrality" of the incentive regulation, using a VRDT is neither hampered nor especially encouraged. The VRDT is therefore always a good investment when it represents the best option from a technical and economic standpoint.

5.9 VRDT as standard equipment

The aspects to be considered when using a VRDT as standard equipment are shown in Figure 12.

In cases of voltage-related reinforcement of the LV grid and/or performance-related addition of substations and/or transformer replacement, the VRDT should be investigated in terms of cost-effectiveness, technical suitability, durability (in particular generation/load forecast, potential for additions and remaining service life) as a possible alternative to conventional grid reinforcement measures.

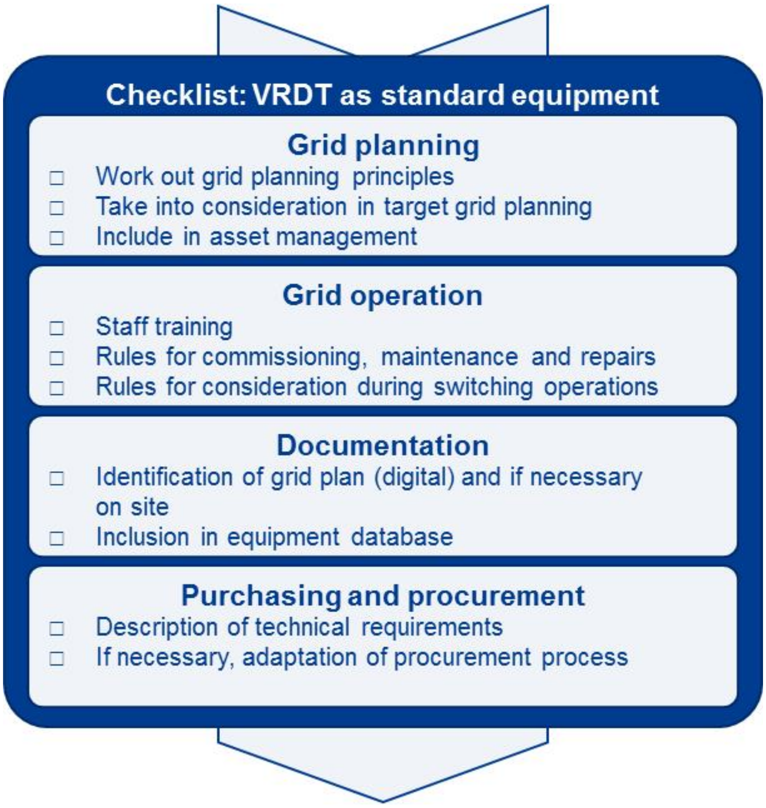


Figure 12: The aspects to be considered when using a VRDT as standard equipment

5.9.1 Avoiding reinforcement of the LV grid

The grid planning criteria listed below assume complete decoupling from the voltage band of the MV grid and a VRDT with a regulating range of ±10 %, 9 taps and a step voltage of 2.5 %. Regulation to a fixed desired voltage value is also assumed. The example below is based on a desired value of 98 % of nominal voltage. If VRDT use is driven by demand, the desired voltage value selected in Figure 13 can be increased.

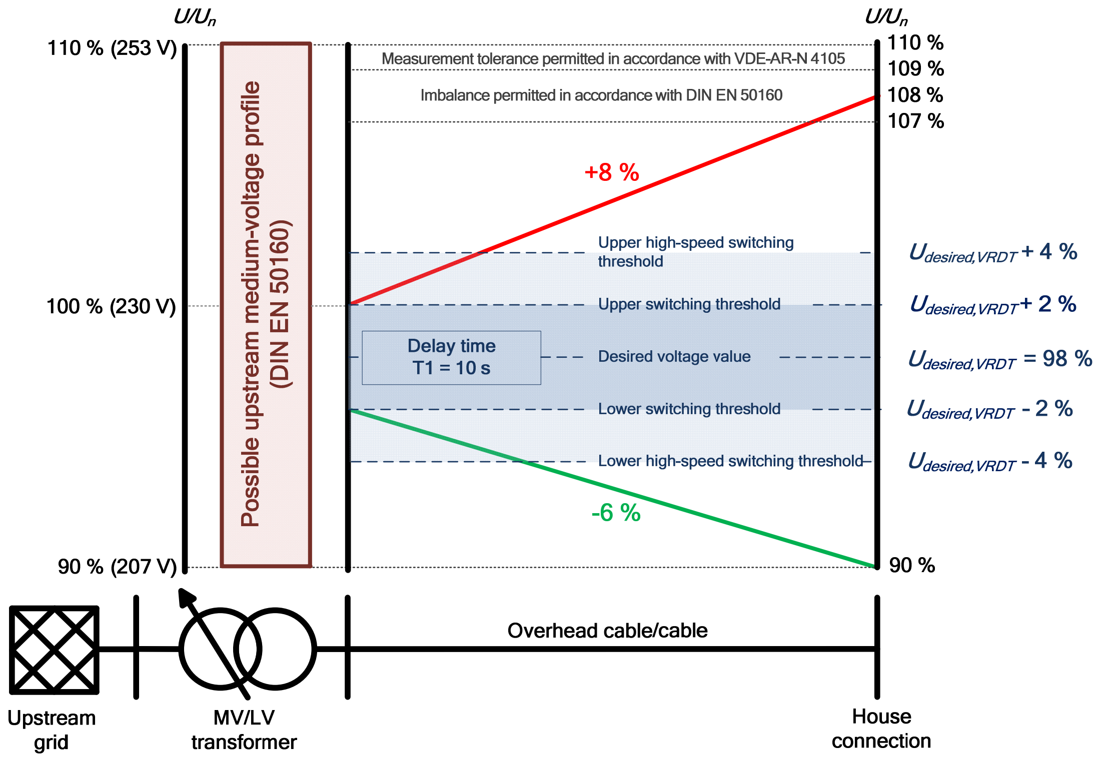


Figure 13: Example of distribution of the voltage band using VRDT at a desired voltage value of 98 % U_n(for explanations of delay time T_1, see section 5.5.2)

4 % is selected here as the regulating bandwidth (range between upper and lower switching threshold), i.e. 1.6 times the step voltage (see section 5.5.2). In accordance with DIN EN 50160, ±10 % of the nominal voltage is available to the grid operator. In consideration of the tolerance permitted in VDE-AR-N 4105 between the set value and trigger value of the ±1 % protection against voltage increases, a corresponding range of 1 % is reserved in the voltage band in Figure 13. Furthermore, voltage imbalances (negative sequence system/positive sequence system) of up to 2 % are permitted in accordance with DIN EN 50160. In our example, firstly this is considered for the feed-in case and is assumed to be 1 % of the voltage band. Secondly, it is considered for the load case (using 6 % by way of example), as has become standard in grid planning.

As shown in Figure 13, this results in a maximum permitted slow change in voltage at LV level of 8 % for GPs and a maximum drop in voltage for the load case of 6 %.

If we assume that the imbalances permitted by DIN EN 50160 are fully exhausted, the permitted slow change in voltage should be reduced by this percentage.

For grid calculations with VRDT, greater attention should be paid to the level of equipment utilization. This applies especially to utilization of the SS, existing cables, and overhead cables.

5.9.1.1 Permitted slow changes in voltage

When the grid is running smoothly as shown in Figure 13, the level of changes in voltage caused by all GPs with a grid connection in a LV grid must not exceed a value of 8 % compared with voltage without GPs at any connection point in this grid:

$$\Delta u_a \leq 8\ \%.$$

In accordance with VDE-AR-N 4105, the value of $\Delta u_a \leq 3$ % may be deviated from in justified, isolated cases based on the grid operator's requirements. VRDT usage is one such case.

5.9.1.2 Permitted rapid changes in voltage

The changes in voltage at a connection point brought about by simultaneously activating or deactivating GUs do not result in non-permitted grid perturbations if the maximum change in voltage does not exceed the value of 3 % (in relation to U_n) at the connection point:

$\Delta u_{max} \leq 3$ % (in accordance with VDE-AR-N 4105, section 5.4.2).

5.9.2 Avoiding reinforcement of the medium-voltage grid

The grid planning criteria listed below assume complete decoupling of the voltage bands and VRDTs with a regulating range of ±10 %, 9 taps and a step voltage of 2.5 %. In accordance with DIN EN 50160, ±10 % of the nominal voltage is available to the grid operator. In consideration of the tolerance permitted in VDE-AR-N 4105 between the set value and trigger value of the ±1 % protection against voltage increases, a corresponding range of 1 % is provided in the voltage band in Figure 14 as for MV. Furthermore, voltage imbalances of up to 2 % are permitted in accordance with DIN EN 50160. This 2 % is already taken into account in our example.

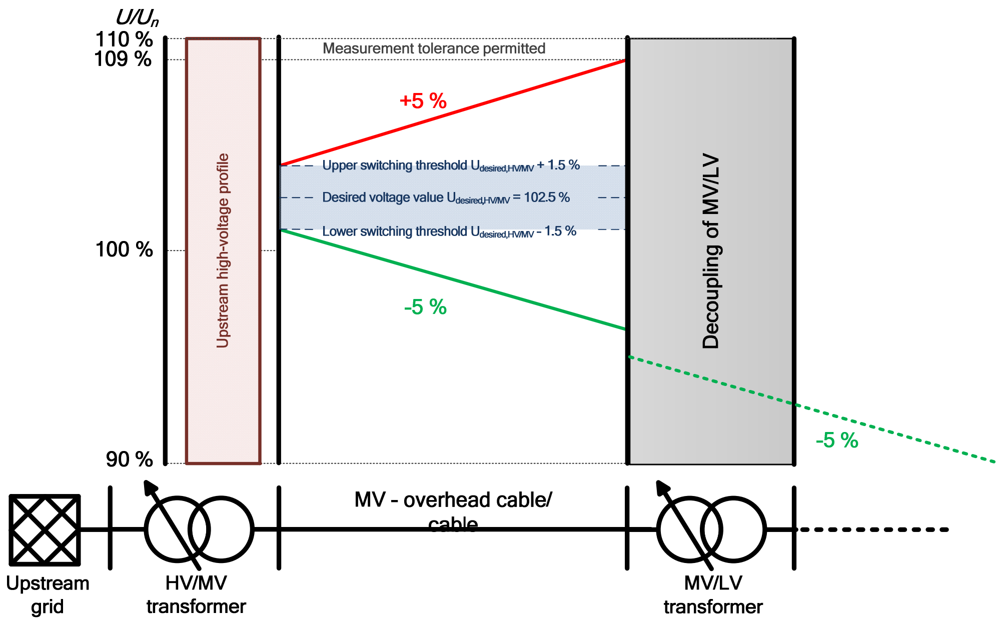


Figure 14: Example of distribution of the voltage band with medium voltage-oriented VRDT use

When distributing the voltage band, an efficient supply and the equipment load-carrying capacity should be taken into consideration in addition to the requirements laid down in DIN EN 50160. In the case of a voltage band configuration with a predominance of GPs in the MV grid, for an assessment covering all areas, all secondary substations in the supplied area of a primary substation should be assessed and substations with raised voltage values equipped with a VRDT (i.e. examine all areas and use VRDT where needed). If a permitted voltage drop at LV level of 5 % and 1 % on the MV/LV transformer and a permitted voltage drop at medium-voltage level of 5 % is considered for the remaining substations, this results in a desired voltage value of 102.5 % at a regulating bandwidth of 3 % of the HV/MV transformer. In Figure 14, this results in a maximum permitted slow change in voltage at MV level of 5 % for GPs and a maximum drop in voltage for the load case of 5 %.

If VRDTs are used in all areas, in accordance with EN 50160, the entire voltage band is available both at MV and LV level independently of one another. If necessary, the desired voltage value on the HV/MV transformer can therefore be reduced further in order to further increase the value for raising voltage.

The quasi-stationary power flow calculation is undertaken in accordance with [6]. Dynamic simulation of the VRDT is not needed. For grid calculations with VRDT, greater attention should be paid to the level of equipment utilization. This applies especially to utilization of the existing cables and overhead cables.

5.9.2.1 Permitted slow changes in voltage

When the grid is running smoothly as shown in Figure 14, the level of changes in voltage caused by all GPs with a connection in the MV grid must not exceed a value of 5 % compared with voltage without GPs at any connection point in this grid:

$$\Delta u_a \leq 5\ \%.$$

In accordance with [6], the value of $\Delta u_a \leq 2\ \%$ may be deviated from in justified isolated cases based on the grid operator's requirements. Use of VRDTs in all areas and a simultaneous small proportion of voltage increase in the medium-voltage grid caused by LV feed-in power is one such case.

5.9.2.2 Permitted rapid changes in voltage

The changes in voltage at a connection point brought about by simultaneously activating or deactivating GUs do not result in non-permitted grid disturbances if the maximum change in voltage does not exceed the value of 2 % (in relation to U_n) at the connection point:

$$\Delta u_{max} \leq 2\ \% \text{ (in accordance with [6]).}$$

6 Operating information

The operating statuses including smooth operation and possible faults on a VRDT must be visible on the control unit. The current tap position must also be displayed and manual operation guaranteed on-site. Manual operation also includes switching between manual and automatic mode and the option of manual tap changes during operation.

6.1 Initial Commissioning

The VRDT is commissioned/installed for the first time taking the manufacturer's specifications into consideration and following the procedure described below. The stipulated control parameters should be preset to enable the VRDT to be commissioned without time-consuming on-site parameterization. The control unit's voltage supply should be tapped so that a supply is ensured even if LV distribution is not energized (see Figure 15).

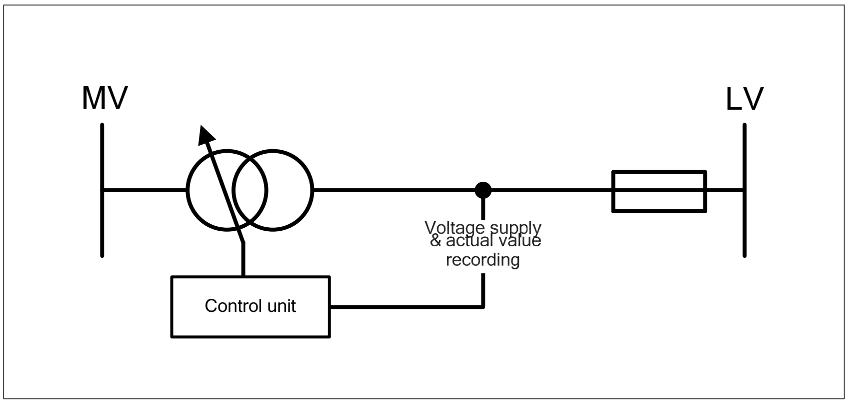


Figure 15: Tapping of voltage supply for the control unit

When a VRDT is commissioned for the first time, it is inspected thoroughly in line with the usual commissioning criteria for a DT. The extra components, such as control unit, should be checked with regard to supply voltage and wiring. The VRDT should then initially be activated to just idle with medium voltage. The control unit will then also be energized. The voltage regulator should be set to "Manual". A accurate voltage measurement, (i.e. with the use of a multi meter) should be used to check the output voltage of the VRDT in all positions. The automatic voltage regulation should then be tested. It should be switched to the end position by hand. Once this has been done, the voltage regulator should be set to "Auto". The internal algorithm should ensure that the VRDT automatically approaches its operating range as specified by the set parameters. This should be checked again using a multimeter. The voltage must be within the regulating bandwidth.

If everything is working properly, the VRDT should be set to "Manual" and adapted to the downstream LV grid. It can then be activated. Once the normal switching status has been set up, the voltage regulator must be reset to "Auto". The voltage should be checked again.

6.2 Troubleshooting

The manufacturer's specifications should be adhered to when troubleshooting. Firstly, the control unit should always be restarted/reset. If the error still persists, further measures stated in section

6.1 should be taken to identify the source of error. Manufacturer-specific ways of diagnosing errors can also be used (i.e. diagnosis interface, error display, software diagnosis). Troubleshooting can also be assisted on-site by replacing modular components.

6.3 Using an emergency power supply

When using an emergency power supply, the VRDT can generally remain in auto mode.

Alternatively, the VRDT can be made to behave like a DT by deactivating the automatic control unit. To do this, set the VRDT to "Manual" before activating the emergency power supply. As soon as the emergency power supply has taken the load, the VRDT can be disconnected. When reactivating, the VRDT should first be switched on with medium voltage. Before activating low voltage, the secondary voltage should be aligned to the grid voltage using the "Raise" / "Lower" buttons. The emergency power supply should be disconnected from the grid. Once the normal switching status has been established, the control equipment should again be set to "Auto".

Both procedures are commonly used.

6.4 Interconnecting low-voltage grids

When interconnecting low-voltage grids, the phasing and difference in voltage should be checked. If the phasing is different, phase balance must be established. If the difference in voltage is too great, the VRDT can be tapped by switching to "Manual" and by undertaking one manual tap-change after another using the "Raise" / "Lower" buttons so that the difference in voltage is reduced and/or the transmission ratio is balanced and interconnecting is possible. When normal switching status is restored, the control unit should be switched back to "Auto".

6.5 Maintenance

A VRDT requires no additional maintenance compared with that of a DT.

During the course of substation maintenance, we recommend examining the VRDT and proceeding in the same manner as at initial commissioning. Adoption of manufacturer-specific condition or status values can also be considered (e.g. number of taps, operating period, etc.).

6.6 Optional ICT connection

The benefits of a VRDT start with self-sufficient control. There is therefore no need for a remote connection to the grid control center to report measurement and status data.

The VRDT systems currently available do, however, provide the option of an ICT connection and can be integrated in higher-level control concepts if necessary. The ICT connection may range from a simple fault indication contact to integration in a control and measurement infrastructure or a connection to the grid control center using protocols common in the energy supply sector.

7 Summary

The main statements made in this FNN-Recommendation can be summarized as follows:

- A VRDT is a DT with additional controlling element and control unit. The main characteristic of the VRDT is the ability to change the voltage conditions on-load.
- A VRDT is a product ready for mass production, which can be integrated in existing SS (including compact substations).
- The VRDT is easy to use and has many advantages over a DT. It can be used for many purposes, including
  - Rectification of voltage band problems (in LV and MV grids)
  - Optimization of the grid topology
  - Optimization of reactive power management

  (The VRDT cannot resolve overload problems.)
- In grids with very long line taps and/or inhomogeneous feeders, case-by-case considerations are needed to check whether use is appropriate.
- Even the simplest control process of "voltage to a fixed desired value" is sufficient for most applications.
- An ICT connection is not usually needed.
- If the parameters are set appropriately, there are no negative interactions with other voltage-regulating equipment.
- The VRDT is therefore another component for grid planning with easily to understand technology and is often a more cost-effective alternative to conventional grid reinforcement.

List of references

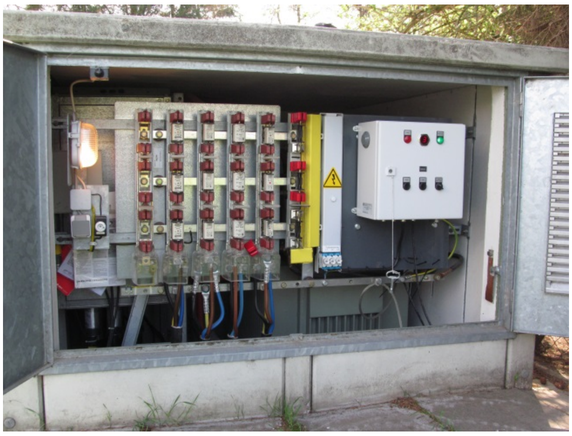
[1]	FNN	"Statische Spannungshaltung" (Static voltage stability) study, November 2015
[2]	FNN	Blindleistungsmanagement in Verteilungsnetzen (Reactive power management in distribution grids), November 2014
[3]	EU	DIRECTIVE (EU) no. 548/2014 (ECODESIGN DIRECTIVE)
[4]	Ew	special III -2015
[5]	VRDT compendium	http://rONT.info
[6]	BDEW	Technische Richtlinie – Erzeugungsanlagen am Mittelspannungsnetz (Technical guideline – generation plants on the medium-voltage grid) Richtlinie für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Mittelspannungsnetz, Ausgabe Juni 2008 (samt Ergänzungen) (Guideline for connection and parallel operation of generation plants on the medium-voltage grid, issued June 2008 (and supplements))
[7]	BMWi	Project 03ET7518D U-Control - Technische Wirksamkeit, Robustheit und Wirtschaftlich-keit neuer Verfahren zur Sicherung der statischen Spannungshaltung in Verteilnetzen mit starker dezentraler Einspeisung (U-Control - technical efficiency, robustness, and cost-effectiveness of new procedures to ensure static voltage stability in distribution grids with highly dispersed feed-in)
[8]	IAEW, E-Bridge, OFFIS	"Moderne Verteilernetze für Deutschland" ("Modern distributor grids for Germany"), study for the BMWi, 2014

Annex A: Examples of installation

The following should be noted when installing a VRDT in a control cabinet:

The operating elements must be in front of the barrier. If the VRDT's control cabinet is fitted such that operators may get impermissibly close to the transformer connections during operation, these connections should be safe to touch. A barrier is then no longer needed and the equipment can be operated.

Compact substations

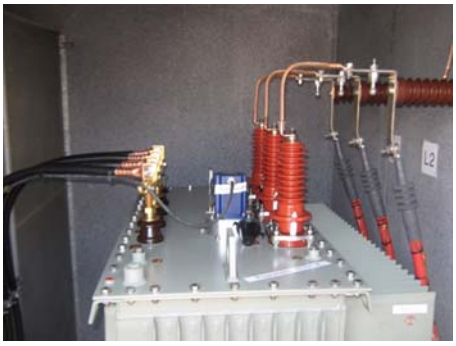



Vorsicht!
Rück-
spannung!

Control cabinet in separate ICT area
of the compact station shown on the left

With the type of installation shown here,
the transformer connections
are safe to touch.

Walk-in substations



The medium voltage is connected
using plug-in adapters

Tower substations

Control cabinet on the right inner wall of the
tower substation shown on the left
(control cable laid in underground distribution chamber)

Control cabinets

With the type of installation shown here, the transformer connections are safe to touch.

Annex B: Application examples

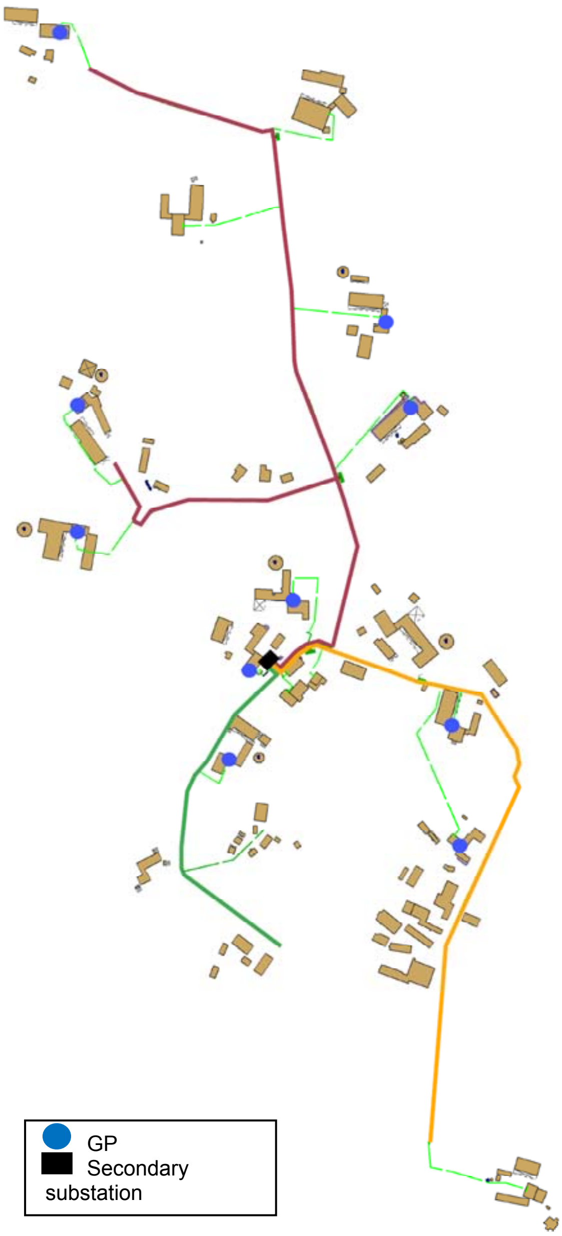
B1 LV-driven VRDT use

B1.1 Motivation for the project

The selective use of VRDTs resulted from the addition of dispersed GPs and the resultant infringement of the $\Delta u \leq 3$ % criterion of VDE AR-N 4105.

B1.2 Grid section

The grid shown is a very rural low-voltage grid. The buildings are mainly farms and single-family homes. Photovoltaic systems were successively added over short intervals. There is still potential for further systems to be added on the remaining roof areas.



Characteristics – low-voltage grid
North – south grid elongation
approx. 1250 m
East – west grid elongation
approx. 600 m
Total generation power
230 kWp (1 x >30 kW; 11 x < 30 kW)
Total load
175 kW
Total line length
4,300 m
Degree of cabling
100 %
Substation building
Existing compact substation from 2006
Conventional transformer, old
20/0.4 kV – 250 kVA – de-energized tap-changer, tap 2
Voltage regulation transformer, new
20/0,4 kV – 400 kVA – ±4 steps of 2.5 %
Form of grid
Supply via the three main lines marked in color as feeders

Figure 16: Grid section and description of a low-voltage grid in accordance with the example in B1

B1.3 Comparison of variants

The final solution results from a comparison of variants of different grid reinforcement measures. Potential roof area available at Avacon AG for further additions is also taken into consideration.

- Variant 1: Conventional grid reinforcement
  - Increase cross-section to 240 mm² in the feeders affected
  - Replace transformer with a 400 kVA variant in the existing compact substation

- Variant 2: Use of a VRDT
  - Replace transformer with a 400 kVA VRDT in the existing compact substation. The voltage regulator can also be installed inside the compact substation.
- Variant 3: Use of low-voltage linear regulators
  - Was not investigated because the 3% criterion was found to have been infringed in several feeders

B1.4 Solution selected

Variant 2 was selected. The conventional 250 kVA DT was replaced with a 400 kVA VRDT. The VRDT was installed in the existing compact structure without any special adaptations. Variant 2 saves almost 28 % of the costs of a conventional grid reinforcement (variant 1). The features of this solution are:

- Switching with on-load tap-changer on high-voltage side
- ±4 steps of 2.5 %
- Regulation to a fixed desired voltage value
- No ICT connection
- Installation of voltage regulator within the existing compact substation next to the low-voltage distribution
- Voltage band distribution and set parameters can be seen in Figure 17.

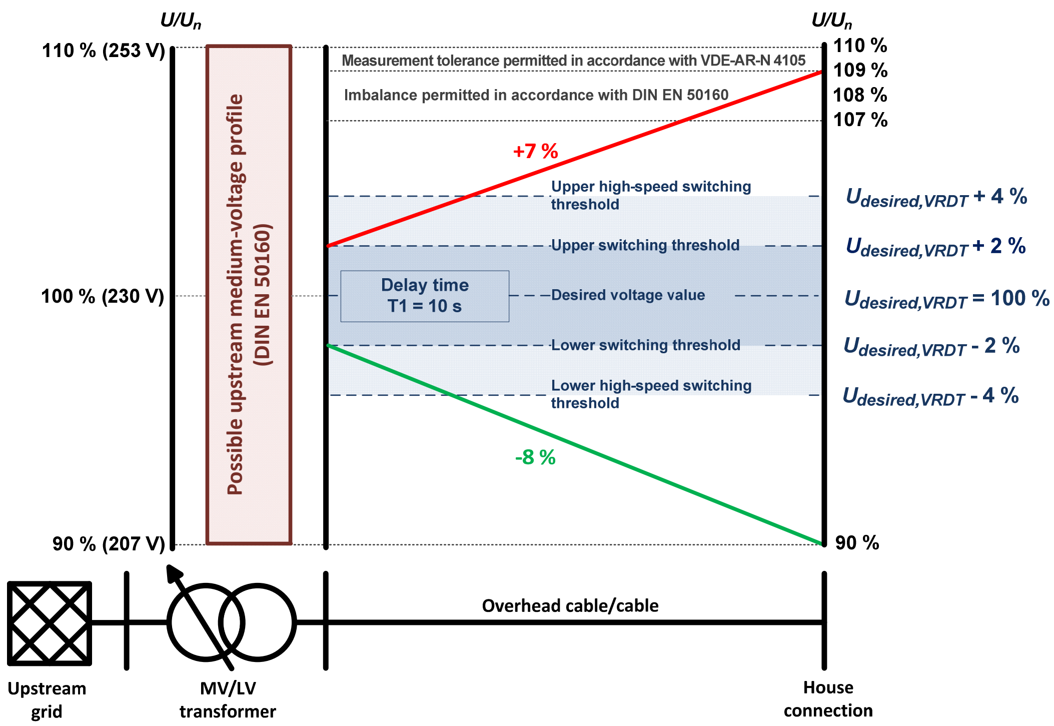


Figure 17: Voltage band distribution with VRDT at a desired voltage value of 100 % · U_n

B1.5 Planning and operating experience

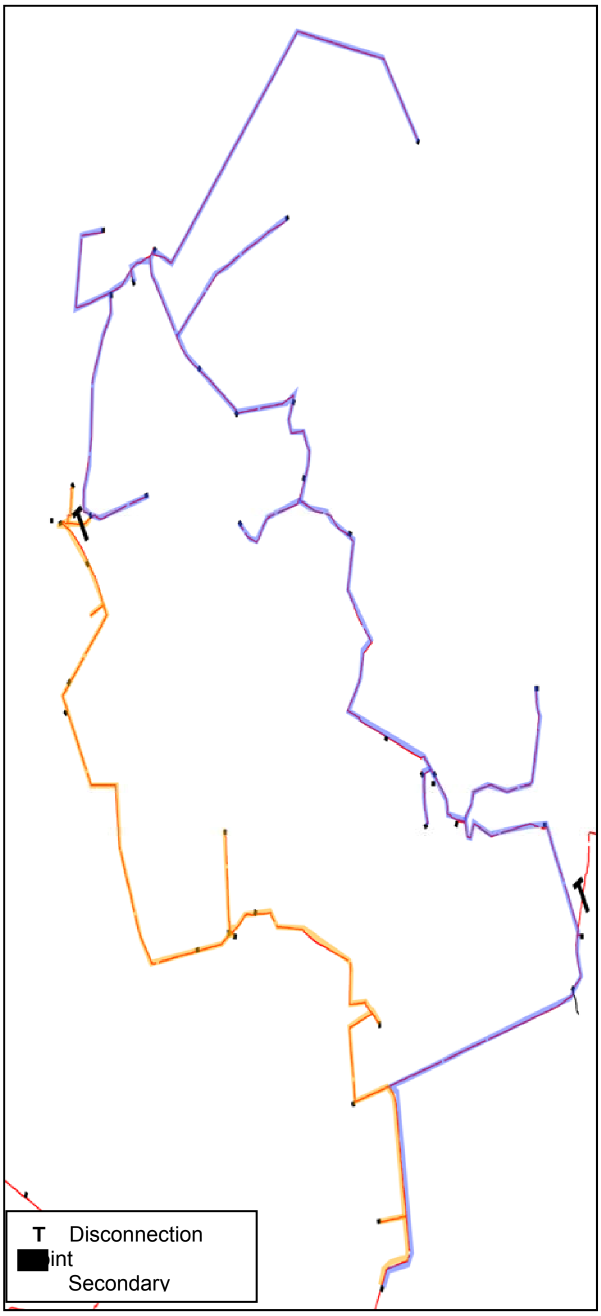
- Voltage measurements show a clear reduction in the spread of the voltage band
- Average tap-change operations per day: 5

B2 MV-driven VRDT use

B2.1 Motivation for the project

The project was implemented for reasons of voltage stability. The HV/MV transformer in the primary substation is already operated with the lowest desired voltage value possible from a supply standpoint. The existing equipment is at nowhere near its utilization limit values so a voltage-regulating measure is certainly possible.

B2.2 Grid section



Characteristics – superimposed medium-voltage ring

North – south grid elongation
approx. 9.5 km
East – west grid elongation
approx. 7 km
Total generation power
5.5 MW
Total load
1,350 kW
Total MV line length
36 km
Degree of cabling
87 %
Substation building
Mainly compact substations, no transformers with poles
Conventional transformers, old **160/250/400/630 kVA**
9/16/5/2
Voltage regulation transformers, new **160/250/400/630 kVA**
0/14/14/4 Each with ±4 taps of 2.5 %
Form of grid
Openly used, superimposed ring on a switching substation, around 7 km away from the primary substation

Figure 18: Grid section and description of a superimposed medium-voltage ring in accordance with the example in B2

B2.3 Comparison of variants

The final solution results from a comparison of variants of different grid reinforcement measures.

- Variant 1: Conventional grid reinforcement
  - Starting from the primary substation, the laying of new cables of a larger cross-section (300 mm²) on the existing line.
- Variant 2: Use of VRDTs
  - Replacement of all conventional DTs in the grid section in question with VRDTs.
- Variant 3: Establishment of a support point grid (800 mm² cable with one distribution grid core unit)
  - Laying a new 800 mm² cable starting from the adjacent primary substation to a new distribution grid core unit and integration of the existing medium-voltage grid structure

B2.4 Solution selected

Variant 2 was the chosen solution. The VRDTs were mainly installed in the existing compact structure without any special adaptations. The features of this solution are:

- Switching with on-load tap-changer on high-voltage side
- ±4 steps of 2.5 %
- Regulation to a fixed desired voltage value
- No ICT connection

Voltage band distribution and set parameters for the MV feeders with VRDT can be seen in Figure 19.

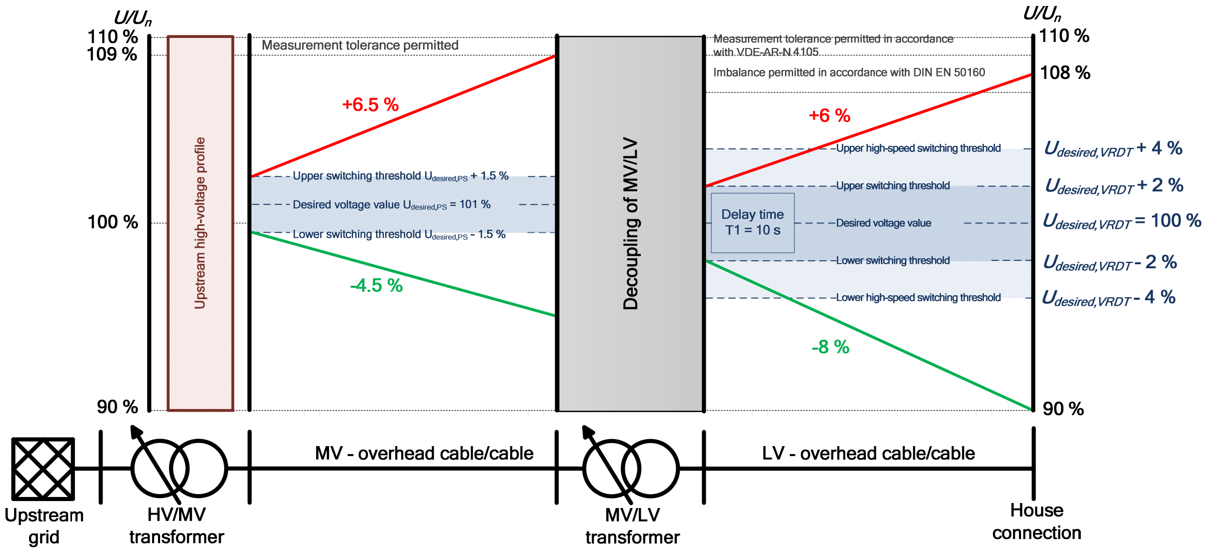


Figure 19: Voltage band distribution for the example of medium-voltage-driven VRDT use

B2.5 Planning and operating experience

This was the first project in which two-dimensional decoupling of the low and medium voltage was achieved.

B3 Selective VRDT use

B3.1 Motivation for the project

Selective use was made of the Voltage Regulating Distribution Transformer for reasons of voltage stability. The addition of dispersed generation plants and the high demands which occur at times place very different requirements on the grid configuration, especially assurance of the voltage band in accordance with EN 50160.

B3.2 Grid section

The substation grid in question experiences very different load scenarios. With the low demand for power usually experienced, the installed PV power of 560 kWp produces a distinct feed-in scenario. During the hops harvest, a distinct demand scenario of almost 600 kW of power occurs temporarily. The grid is to be configured for both the excess voltage situations which result from feed-in from renewable energy plants (low-load) and for the drops in voltage which result when demand is high but little renewable energy is being fed in (high-load).

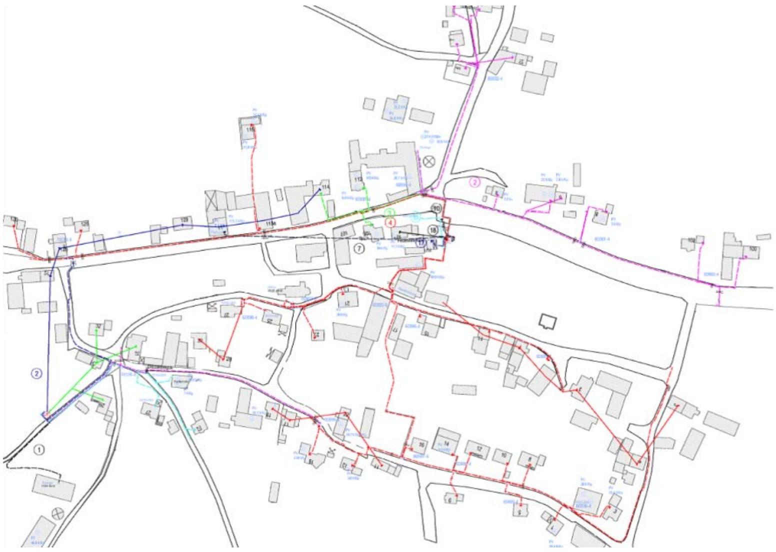


Figure 20: Grid section in accordance with example B3

The distribution grid under consideration in Figure 20 is a village low-voltage grid with high feed-in power and usually with little demand. It comprises both overhead and underground cables, has a LV cable length of around 4.3 km, and supplies around 60 domestic connections. The maximum feeder length is approx. 550 m. The large amounts of feed-in in the low-voltage grid produce an increased voltage rise in several circuits.

B3.3 Comparison of variants

The final solution results from a comparison of variants of different grid reinforcement measures.

- Variant 1: Conventional grid reinforcement
  - Distribution of the loaded substation area by installing a new secondary substation with a cable-based connection for MV and LV

- Variant 2: Use of a VRDT
  - Replacement of the existing conventional DT with a voltage regulation DT in the existing substation

Economic assessment of the two variants:

Variant 1: Example calculation for construction of new substation

20 kV cable	
25 m	Average value surface
60 m	3 cables NA2XS(FL)2Y 1x150 (including sockets and end closures)
1	20 kV cable connection to substation
New build (without serviceability)	
1	Type 2817 (compact substation)
1	Basic electrical equipment
1	SF6 switchgear (3 fields (2 cables / 1 transformer)
1	Install transformer + cable bridge with connector (3 x 8 m)
1	1,000 A busbar system for 9 switch disconnector fuses
9	Switch disconnector fuses
Distribution grid transformer (without installation)	
1	630 kVA DT
0.4 kV cable	
125 m	Average value surface
140 m	Cable NAY2Y 4x150 (cable delivery and laying, including sockets)

Maintenance	
2	Cost of maintenance for entire usage period of a transformer substation

Variant 2: Example calculation for retrofitting a VRDT

New build (without serviceability)	
1	Transformer replacement
Distribution transformer (without installation)	
1	630 kVA VRDT
1	Refitting of 630 kVA DT (rebate)
Maintenance	
1	Cost of maintenance for entire usage period of a transformer substation
1	Secondary cost of replacement for entire usage period of a transformer substation

In order to remedy voltage problems in the distribution grid shown, compared with building a new secondary substation and the cabling work involved to integrate it into the existing MV and LV grid, the use of a VRDT is the more cost-effective solution with a cost ratio of around 1:4.

B3.4 Solution selected

The VRDT allows the voltage bands to be adhered to during both feed-in and demand scenarios. The conversion work can be undertaken promptly and is limited to changing the transformer since the VRDT can be retrofitted in the existing substation. The VRDT characteristics for this solution are:

- Nominal power 630 kVA
- Ratio 21/0.42 kV
- Switching with on-load tap-changer on high-voltage side
- 9 steps with –3/+5 steps of 2.5 %
- Self-sufficient local regulation to a fixed desired voltage value of 98 % in relation to U_n on the LV busbar
- Regulating bandwidth of 4 % (±2 %) in relation to U_n

The voltage band distribution with VRDT can be seen in Figure 21.

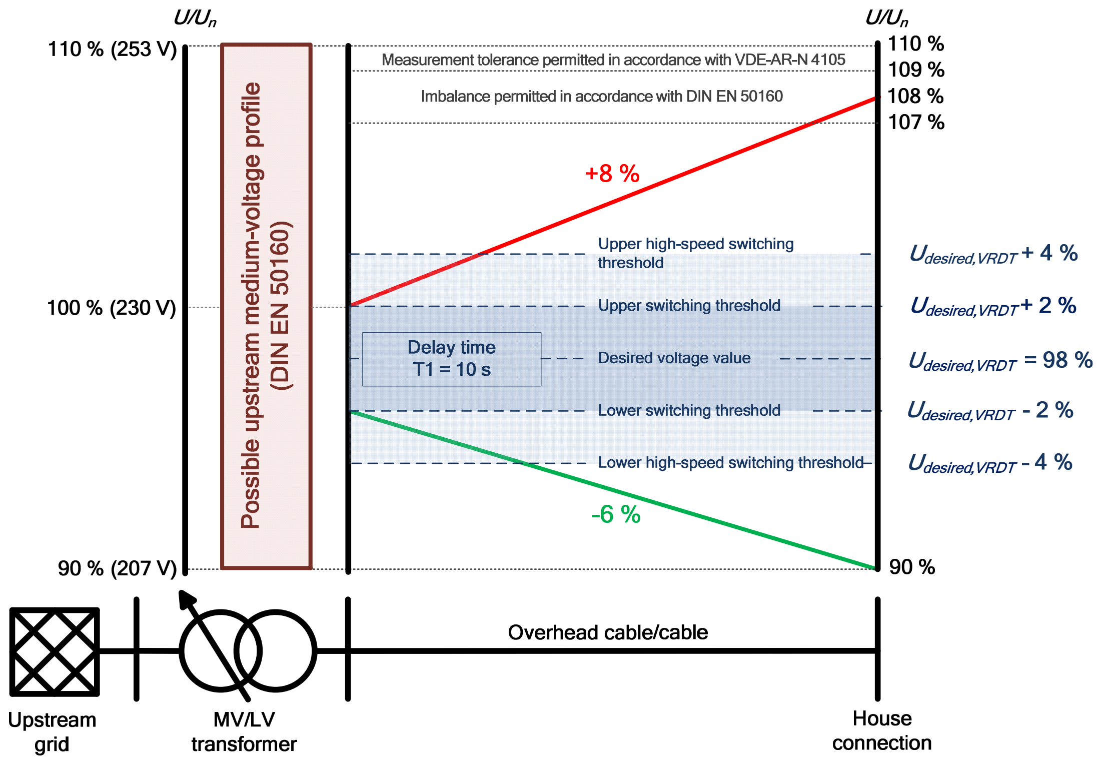


Figure 21: Example of voltage band distribution with VRDT at a desired voltage value of 98 % Un

B4 Selective VRDT use

B4.1 Motivation for the project

Selective use was made of the VRDT for reasons of voltage stability. The addition of dispersed generation plants and the high demands which occur at times place very different requirements on the grid configuration, including assurance of the voltage band in accordance with EN 50160. The VRDT's ability to regulate voltage creates design freedom in the grid configuration, for example with regard to the feeder length and supplied substation areas. If a VRDT is considered, the substation areas can occasionally be re-distributed and the total number of substations used can be reduced.

B4.2 Grid section

The distribution grid in question is a village and has five SS with approx. 250 domestic connections and a total feed-in power from photovoltaics of approx. 1.5 MWp. One of these SS is a pole substation, which needs replacing. Like the adjoining substation area, the substation supplies approx. 30 domestic connections and absorbs a feed-in power of around 140 kWp (adjoining substation area: approx. 440 kWp).

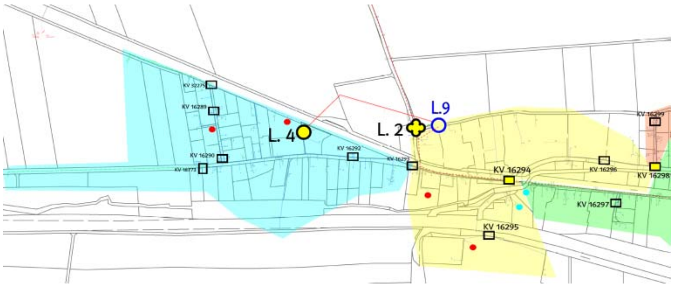



Figure 22: Grid section in accordance with example B4 -pole station and the two substation grids under consideration

B4.3 Comparison of variants

The final solution results from a comparison of variants of different grid reinforcement measures.

- Variant 1: Conventional grid reinforcement
  - Replacement of pole substation with compact substation.
  - Distribution of the loaded substation area by installing a new SS with a cable-based connection for MV and LV
- Variant 2: Use of a VRDT
  - Re-distribution of the substation areas through replacement of the existing conventional DT with a voltage regulation DT in the adjoining substation and adaptation of the low-voltage connection.

Technical assessment:

Since there are already a large number of GPs, the remaining potential for additions in the substation areas under consideration is low. Merging the two substation areas increases the total feed-in power to around 575 kWp, the total number of domestic connections supplied increases to 60, and the max. feeder length only changes slightly, rising from 510 m to 570 m. Equipment utilization and voltage band adherence must be ensured in both demand and feed-in cases. Given its ability to regulate voltage, the VRDT can assist with voltage band adherence.

Economic assessment of the two variants:

Variant 1: Example calculation for replacement of the substation

20 kV cable	
250 m	Average value surface
300 m	3 cables NA2XS(FL)2Y 1x150 (including sockets and end closures)
1	20 kV cable connection to substation
New building (without serviceability)	
1	Type 2817 (compact substation)
1	Basic electrical equipment
1	SF6 switchgear (3 fields (2 cables / 1 transformer)
1	Install transformer + cable bridge with connector (3 x 8 m)
1	1,000 A busbar system for 9 switch disconnector fuses
9	Switch disconnector fuses
Distribution transformer (without installation)	
1	160 kVA DT
Maintenance	
2	Cost of maintenance for entire usage period of a transformer substation

Variant 2: Example calculation for substation merger

New building (without	

serviceability)	
1	Cable distributor
0.4 kV cable	
250 m	Low-value surface
550 m	NAY2Y-J 4x250/50
Maintenance	
1	Cost of maintenance for entire usage period of a transformer substation
1	Secondary cost of replacement for entire usage period of a transformer substation

By merging the substation areas, replacement of the pole substation can be delayed or avoided entirely. In order to remedy voltage problems in the re-distributed distribution grid, compared with building a new SS and the cabling work involved to integrate it into the existing MV and LV grid, use of a VRDT is the more cost-effective solution with a cost ratio of around 1:2.5.

B4.4 Solution selected

The grid reinforcement variant with VRDTs allows the voltage bands to be adhered to during both feed-in and demand scenarios for the re-distributed substation area. The conversion work can be undertaken promptly and since the VRDT can be retrofitted in the existing substation is limited to changing the transformer and reinforcing the low-voltage connection between the two previously separate substation areas. The pole station is not needed and can be demolished. The VRDT characteristics for this solution are:

- Nominal power 630 kVA
- Ratio 21/0.42 kV
- Switching with on-load tap-changer on high-voltage side
- 9 steps with –3/+5 steps of 2.5 %
- Self-sufficient local regulation to a fixed desired voltage value of 98 % in relation to U_n on the LV busbar
- Regulating bandwidth of 4 % (±2 %) in relation to U_n

The voltage band distribution with VRDT can be seen in Figure 23.

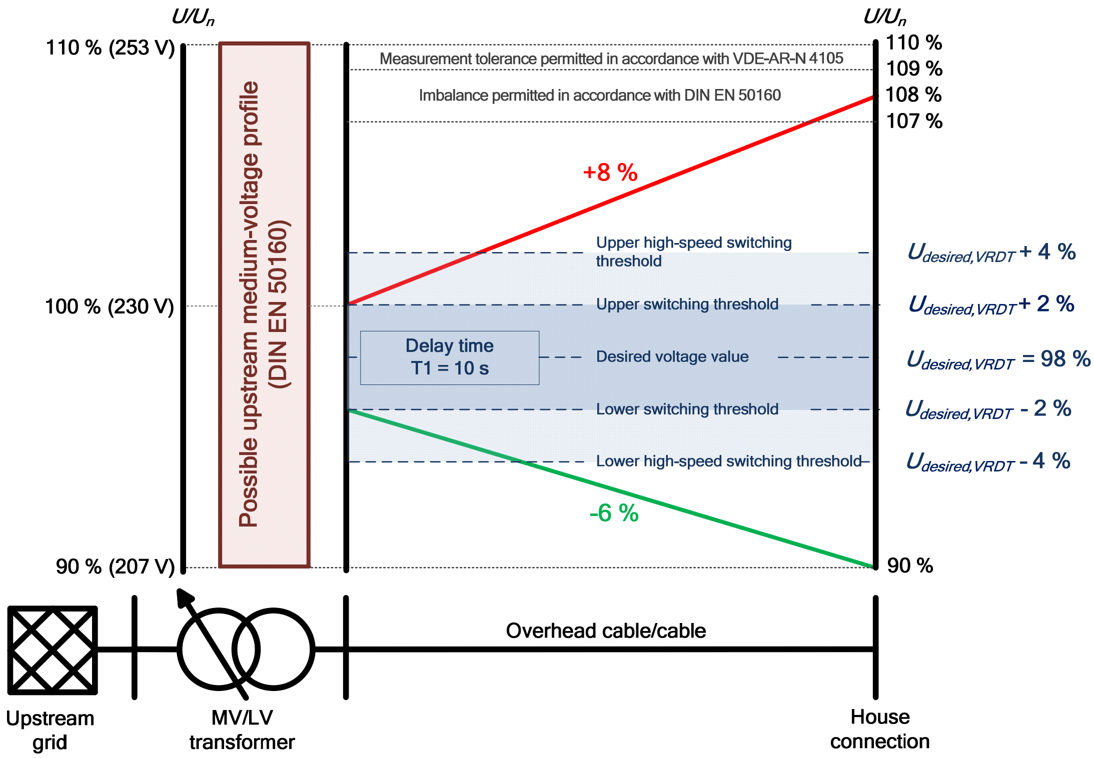


Figure 23: Example of voltage band distribution with VRDT at a desired voltage value of 98 % U_n

B5 Regulation to a desired voltage value dependent on power flow

B5.1 Motivation for the project

The addition of generation plants in the low-voltage grid and the growing grid structures have resulted in the maximum difference in voltage of $\Delta u_a \leq 3$ % permitted in VDE-AR-N 4105 being exceeded. To date, this has mainly been remedied by reinforcing the grid, which is very expensive, especially in built-up areas.

B5.2 Grid section

It is a rural one-street village with a number of former agricultural properties in the center of the village. The village therefore has some large roof areas, often facing south. These offer potential for or have already been used as locations for photovoltaic systems. The electrical energy supply occurs largely by means of low-voltage overhead cables.

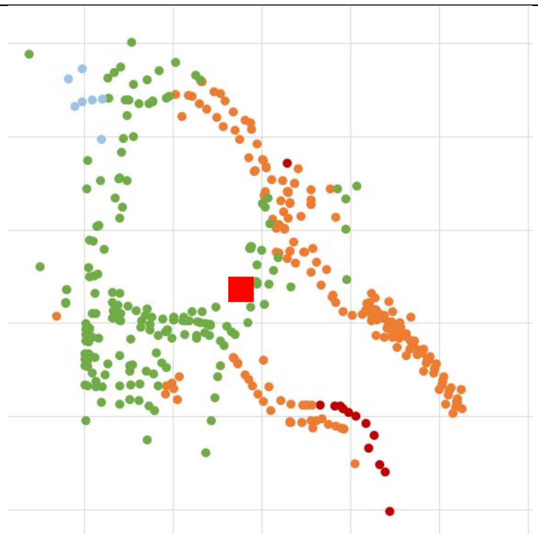
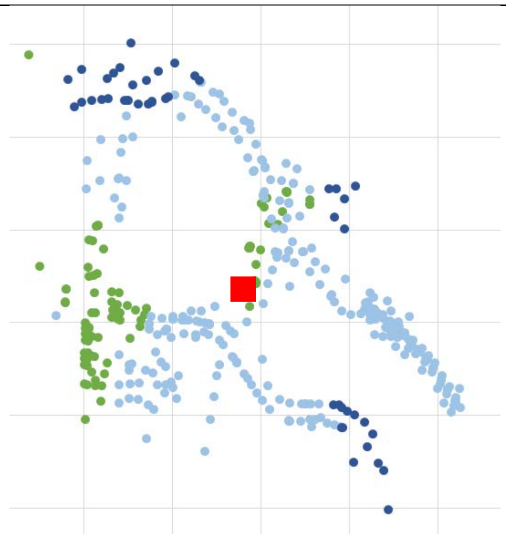
Summer	Winter
	
Maximum voltage U_{max} ≈ 250 V	Minimum voltage U_{min} ≈ 219 V

Figure 24: Node voltages in summer and winter before using a VRDT in accordance with the example in B5

Figure 24 shows the node voltages in summer and winter before using a VRDT. The maximum voltage in the summer is around 250 V and the minimum voltage in the winter is around 219 V. On the busbar of the transformer station itself, only a slight fluctuation in medium voltage of around 2 % can be seen between summer and winter. A VRDT regulating to a fixed desired voltage value would therefore have virtually no impact on the voltage magnitudes in the grid.

B5.3 Comparison of variants

- Variant 1: Conventional grid reinforcement
  - Since, for technical reasons, it would not make sense to convert the low-voltage overhead cable, low-voltage cabling would be needed here.
- Variant 2: Conventional grid reinforcement
  - Alternatively another transformer station could be built and integrated into the existing overhead-cable grid.
- Variant 3: Use of a VRDT
  - VRDT with desired voltage value dependent on power flow

B5.4 Solution selected

The costs for variants 1 and 2 are 6-7 times higher than for buying and installing a VRDT in the existing SS.

A VRDT with desired voltage value dependent on power flow is used. Figure 25 shows the set standard characteristics curve of the VRDT. If the feed-in power is high, the voltage on the busbar is reduced below the nominal voltage U_N and if demand is high, it is raised above the nominal voltage U_N. The difference between the maximum and minimum voltage on the busbar therefore increases, but the fluctuations in voltage in the grid can be restricted considerably.

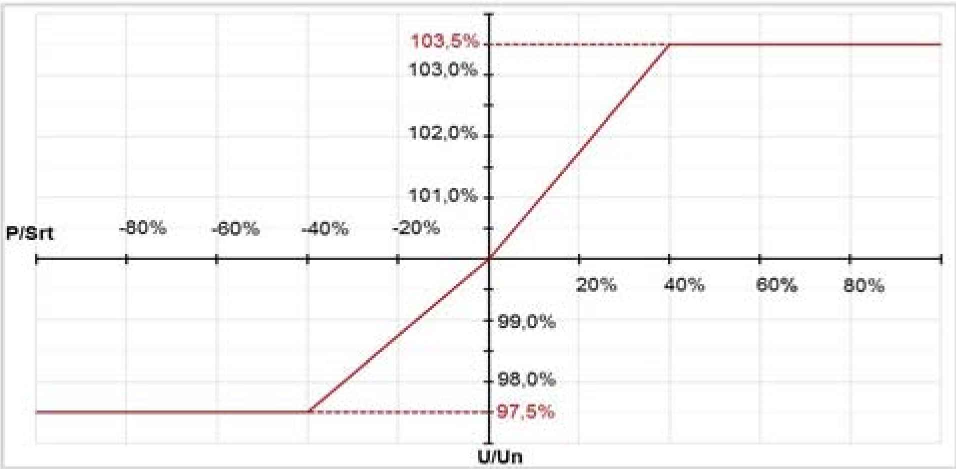


Figure 25: Set characteristics curve on the VRDT in accordance with the example in B5

B5.5 Planning and operating experience

Figure 26 shows the node voltages in summer and winter when using a VRDT. The effect is particularly pronounced in the summer when the maximum voltage is reduced from 250 V to 236 V. The maximum voltage rise of $\Delta u_a \leq 3$ % in accordance with VDE-AR-N 4105 is therefore once again met throughout the grid.

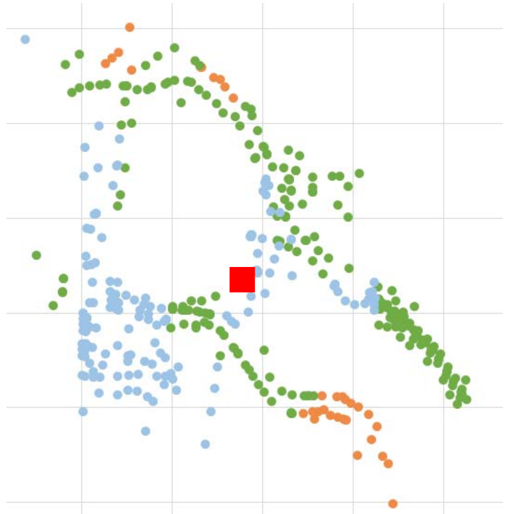
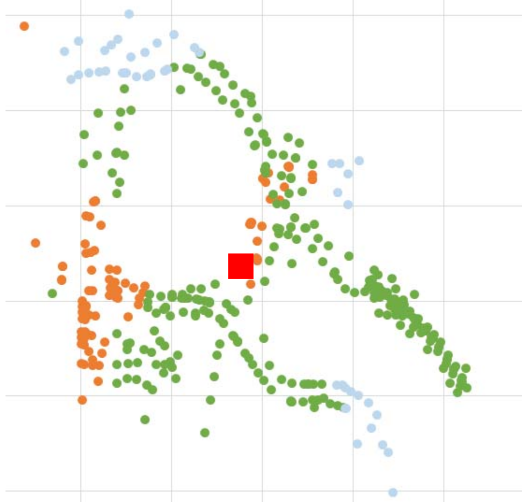
Summer	Winter
	
Maximum voltage U_{max} ≈ 236 V	Minimum voltage U_{min} ≈ 221 V

Figure 26: Node voltages in summer and winter when using a VRDT in accordance with the example in B5

