Meeting Grid Code Requirements of Decentralized Power Generators and Plants by Using Voltage Regulating Distribution Transformers as Cost-efficient Component

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***Abstract*— Due to power infeed of mostly volatile energy sources connected to distribution grids, measures are needed to ensure voltage stability in regional grid sections. Thus, grid operators require sophisticated ancillary services to counteract fast changing grid conditions while generation units are obliged to withstand voltage fluctuations in a considerable range for providing such services. So, from a manufacturer point of view technical modifications need to be taken into consideration in order to comply with the requirements from newest grid codes. In this regard a simple and applicable solution can be found in Voltage Regulating Distribution Transformers (VRDT). Initially designed to be used within the systems as a control device to provide flexibility and adjustments between medium and low voltage grids, they can also be applied as generating unit transformers in e.g. wind power plants. Their fast autonomous or integrated controllability offer huge flexibility and increases the unit's capacity. Since the connection of power generating units have to be assessed in terms of their electrical characteristics, the correct operation and reliability of such devices is crucial. Thus, in cooperation with the manufacturer Maschinenfabrik Reinhausen it was the certification office of FGH, who implemented verification and corresponding testing guidelines. As the newly certified VRDT is now equipped in first pilot generating units the worldwide firstly designed and applied verification method is introduced and gained experiences are addressed.**

Keywords - Voltage Regulating Distribution Transformers; VRDT; Grid Codes; Voltage Control, Unit Components, Reactive Power Capability

I. INTRODUCTION

Nowadays grid codes are constantly being revised in order to tackle the challenges a result of a new generation pattern with massive power infeed in low and medium voltage levels. In this context voltage operation bands in existing grid codes have led to massive discussions between grid operators and manufacturers in the last years. New and forward looking codes include operating voltage ranges that exceed the conventional capacity of currently most generating units. In the latest draft of the ENTSO-E Network Code for example, it is required to maintain an operation of the power plant at even wider voltage bands compared to the status quo, temporarily even down to 85% and up to 115% of nominal voltage, respectively (see Figure 1). However this refers to generators of type D with connection equals or above 110kV. From a manufacturer point of view this is challenging since full reactive power supply must be possible within the entire voltage band, too.

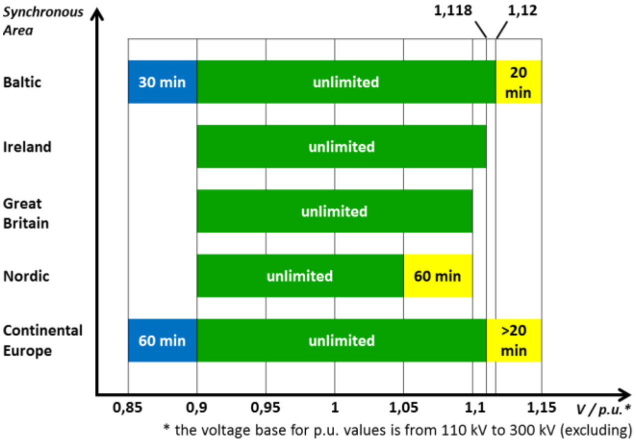

Figure 1: Voltage ranges according to ENTSO-E NC RfG [1]

Therefore many manufacturers and plant operators will have to modify and improve their technologies to be able to meet these requirements. Potentially a solution can be seen in oversizing power converters but increases the costs of each generating unit significantly. Another solution can be found in the usage of supplementary equipment which ensures an operation of the plant at stable voltage conditions even if the grid voltage changes considerably. Such device can be found in Voltage Regulating Distribution

Transformers (VRDT). Equipped with intelligent controllers the internal logic executes a switching operation within a few seconds if the voltage deviates from an individually defined set-point. This fast controllable step-up transformer can be used in configuration with single generating units e.g. wind turbine, but also in application as central farm transformer. Based on its intended utilization the communication device of the VRDT can act either together with the generation unit's control or autonomously in the plant. In both cases the generation units benefit from a harmonized operation voltage since grid fluctuations are balanced and stabilized because of an adapted transmission ratio. As the transformer can vary the secondary low-voltage within a range of +/-10% of nominal voltage, the generating units can be operated easily in larger ranges without changing the layout. Therefore, VRDT can easily decouple the generating unit's operating voltage from the grid voltage conditions within a predefined range.

II. VOLTAGE REGULATING DISTRIBUTION TRANSFORMERS (VRDT)

To aim at a successful sustainable energy supply a secured grid integration of generating systems based on renewable energies sources is necessary. Two important key factors are crucial for maintaining the security of supply and grid stability when it has to be dealt with an increasing number of dispersed generators like solar and wind energy converters. On the one hand power generating units and plants should participate in system services in order to contribute to a flexible management and operation. On the other hand an essential key factor can be seen in advanced technologies for the systems that improve the flexibility of the grid in case of regionally fluctuating power flows from generating plants to ensure further integration in accessible grid areas without exceeding the thresholds of capacity. These measures of handling strong dynamic operations must take place in the entire system, more precisely every voltage level. In this regard the VRDT has a very high potential to improve capabilities in both parts – system and power generating plants.

A. *Technology*

With the usage of VRDT the output voltage of the transformer can be controlled dynamically. The VRDT consists of some key components like a conventional distribution transformer, on load tap changer (OLTC), voltage regulator, controller and sensors. The latter ones can be installed at the VRDT or somewhere remote in the feeder which allows external control opportunities and autonomous control of a voltage set-point.

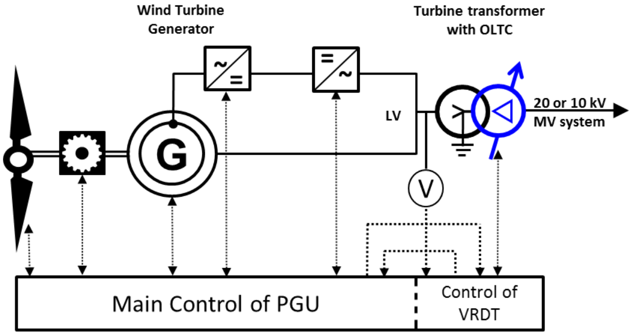

Figure 2: Configuration of a wind turbine with integrated VRDT

By integrating the tap changer at medium voltage side the transmission ratio can be changed stepwise whenever the voltage controller detects a secondary low voltage that deviates from a pre-defined set-point. Normally, a VRDT can control the voltage within a range of +/-10% of the nominal voltage (V_{nom}). This range will be divided into a fixed number of steps of the OLTC. Typically there are 9 steps which enables change the voltage by 2.5% V_{nom} with each step (V_{step}). In general, there are two levels when a switching trigger signal can be given. First, if the low voltage exceeds a determined threshold value (+/-$V_{L1,slow}$) for a specific period of time ($T_{d,slow}$) a switching command will be triggered. Second, another voltage threshold can be parameterized for fast switching (+/-$V_{L2,fast}$). If the voltage changes by a higher value than the first level and reaches a defined boundary value before the time delay ($T_{d,slow}$) is reached, a switching operation is triggered as well. In any case the initialization of these delays ($T_{d,slow}$ and $T_{d,fast}$) cannot fall below a minimum value ($T_{d,min}$) in order to avoid unintended permanent switching at fast voltage fluctuations or voltage dips otherwise a stable and passive operation at grid disturbances could be threatened. The figure below illustrates the algorithm of the controller and its switching operations (see Figure 3).

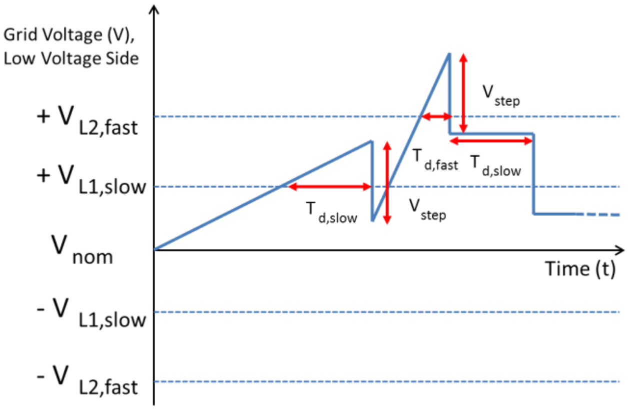

Figure 3: Control scheme of the VRDT

B. *Application*

VRDT were initially designed to regulate the voltage in distribution grids in order to aim at more flexibility in the conventionally quite static medium and low voltage grids. As a result their first purpose is to make a further penetration and integration of decentralized power generators feasible. Their application is in particular attractive when due to voltage restrictions in a specific low voltage feeder a connection of additional generating plants is not possible anymore. In these cases investments in rather new technologies like the VRDT are more efficient than in expensive grid expansion measures by erecting new comprehensive connection lines. This issue has been discussed in recent publications several times, e.g. [2].

A new concept evolves when VRDT are integrated in power generating units and plants. In such application it is beneficial for the manufacturer of the PGU to use a simple component with integrated control function which improves operating ranges of the entire PGU and thus stringent grid code requirements can be fulfilled. The control mode of the VRDT when e.g. used as a machine transformer of a wind energy converter can either interact with the main control system of the PGU or act autonomously when the setting of the VRDT control is initialized according to the requirement of the grid code and harmonized with the parameter of the controls of PGU and plant controller (see Figure 2). A basic requirement in this context can be seen in all control functions in terms of voltage control and reactive power supply. Due to the ability of keeping the low voltage on an almost constant level the provision of reactive power does not necessarily lead to restriction in capability anymore. As an example a QV-Profile of a hypothetical wind energy converter is shown (see Figure 4). In particular in terms of underexcited operation (lagging) the capability shrinks significantly with voltages close to the thresholds of 90% and 110% of nominal voltage. Therefore, an operating voltage close to nominal voltage is desired when technical modifications with respect to oversizing of components like power converters shall be avoided. For instance, the transformer account for approximately 3 to 4% of the total costs of a wind turbine whereas the share of the power converter accounts for ca. 6 to 7% [3]. Since the cost for the adapted transformer are only slightly higher compared to conventional transformers it is worth investing in the modification of the transformer instead of more expensive power electronics.

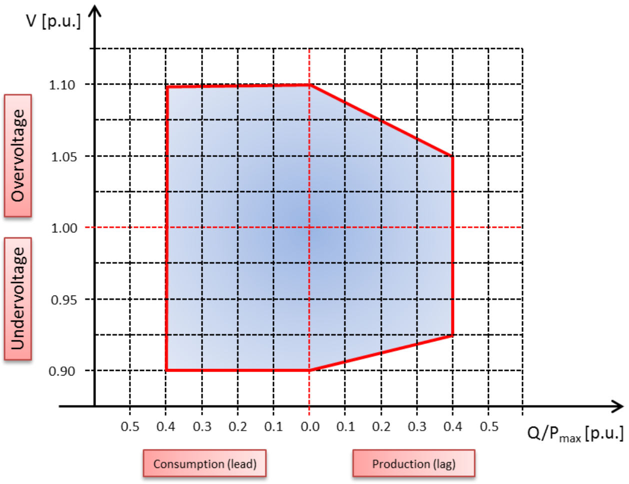

Figure 4: Example of a QV-Profile for PGU

Additionally, in the past it happened that because of this decreased reactive power potential some expensive reactive power compensation had to be installed in the plants in order to meet the requirements of the code. In this context the VRDT can be a very cost-efficient alternative, too. As a matter of fact MV/HV power transformers of the entire plant (in case of HV connection) have the ability to change their tapping as well, however this function performs normally too slow since every iterative switching step needs about 30 seconds. This time is not sufficient if the voltage changes in a shorter period and the wind power plant has to provide a specific amount of reactive power based on the systems operator’s request. The set-points of reactive power according to the Q(V) or cosφ(P) characteristic of the BDEW medium voltage directive must be reached within 10 seconds [4]. A VRDT however can change the tapping within 3 seconds if desired. Lacking capability because of abnormal operation voltages can be balanced then, and the full capability of the PGU in terms of reactive power provision can be used.

Apart from this important advantage of decoupling the reactive power capability from grid voltage it also essential that all other requirements of common grid codes are fulfilled and not invalidly influenced by the usage of the component. At least they are subjected to remain untouched or maybe even improved. While certification for generating units and plants is mandatory in Germany the transformer has been tested and certified successfully as a component according to the relevant technical standards. Thus the following chapter describes in particular the firstly designed and applied verification method and the challenge of meeting requirements and certification standards are highlighted including proposals for adaption.

III. COMPLIANCE PROCEDURE

For a broad use of new technologies a high level of valuable and reliable functionality is necessary. Therefore the clear definition of operations modes of VRDT and the valid verification of its reliability in constantly changing operation conditions are of primary interest. It was therefore of highest priority that quantitative and qualitatively conformity is verified in order to allow system operators or other users of the VRDT to assess its characteristics based on a proven validity of information. The assessment of the electrical characteristics of the VRDT is closely related to the certification procedure of power generating units, which is already established in Germany since 2009. The approach according to the newly designed certification guideline Z 417 by FGH certification office is consequently derived from process of unit certification for high- and medium-voltage levels. It contains the development of product certificates based on type tests for the operating equipment [5]. Furthermore the procedure includes the complete assessment of conformity taking into account the relevant normative standards. These standards contain existing product norms and if applicable rules of grid operator for the connection to, or operation in electrical power systems with paying attention to legal and technical requirements. In addition, the process defines further requirements to control units that have not been determined in general standards yet, because general requirements for such innovative technologies do not exist so far. The evaluation criteria of such certificate are generally limited to electrical characteristics and the electrical robustness of secondary technical equipment, which have a relevant influence on power flow, grid stability and quality of supply in the electrical power system. Finally, the product certification includes a sovereign expert vote. Therefore the result represents an independent verification of compliance with grid code requirements, product standards as well as of provisions for controllability.

Basic parts and characteristics of the assessment within the framework of certification of VRDT are:

1) Successful performance of type testing of transformer, tap changer and voltage controller, e.g. normative compliance to DIN EN 60076 or DIN EN 60214

2) Consideration and inclusion of specifications and standards of distribution system operators for type testing (e.g. for distribution transformers)

3) Evaluation of the VRDT in terms of relevant requirements for connection to distribution grids integration into the system

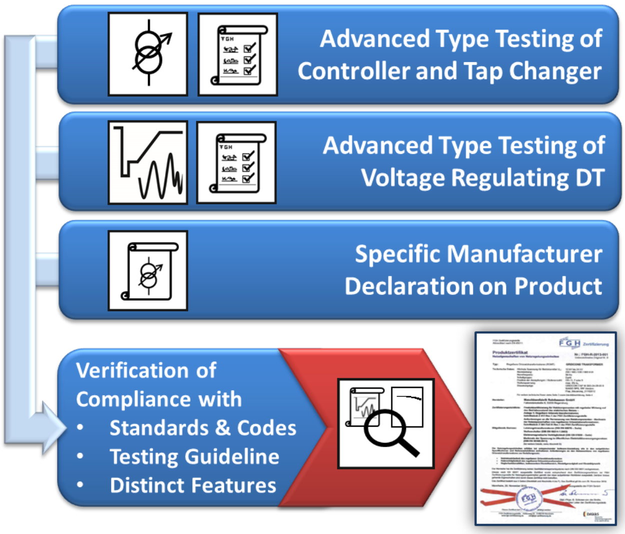

Figure 5: Certification scheme for VRDT according to FGH certification guideline Z 417

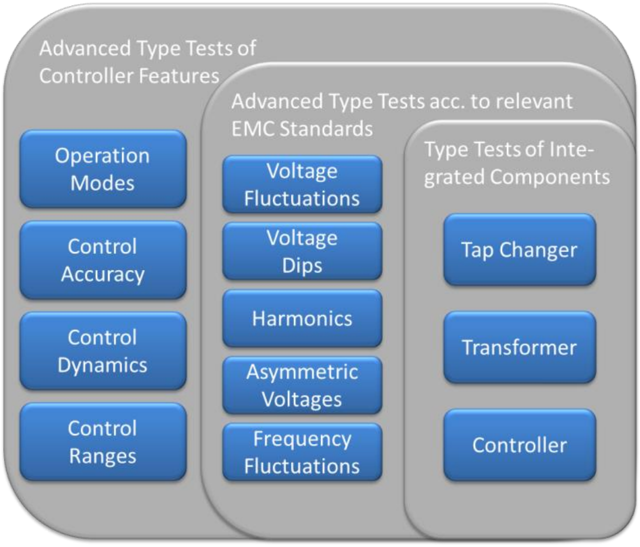

Figure 6: Advanced and product type tests of the VRDT according to FGH testing guideline Z 501 Part IV

Furthermore within the pilot project with Maschinenfabrik Reinhausen a remote controllability of the VRDT by using standardized control protocols like IEC 60870-5-104 was tested and evaluated positively.

As far as normative guidelines define requirements for the electrical characteristic of VRDT that are fundamental for certification but no specification for verification is given, type testing according to the testing guideline Z 501 Part IV of the certification office of FGH for voltage control units has to be performed. These tests focus on real normal as well as critical operating conditions during grid operation and identify the capability of the components [6]. They refer on the one hand to components of the VRDT and on the other hand to the entire VRDT as voltage regulating unit (see Figure 6). The tests in the latter case are subjected to be performed during full load operation.

In detail the tests include the following aspects while predefined success criteria must be fulfilled:

a) Evaluation of control accuracy and dynamics for voltage regulation at low voltage terminals

This includes the verification of the control range, set-points and transition function as well as the validation of delay time and parameterization.

b) Control characteristics and switching modes

In this regard the assessment refers to possibilities of operation modes for triggering a switch signal. Furthermore in case of e.g. autonomous operation the detection values and reaction time have to be identified.

c) Extensive testing of the component's behavior at critical external electrical influences and its robustness against failures

This category of tests considers in particular the performance of the VRDT during disturbances. The may occur in terms of frequency or voltage deviations and can be summarized by EMC standards of the EN 61000 for e.g. immunity against voltage fluctuations, harmonics, voltage dips, voltage unbalances and frequency fluctuations.

IV. PILOT PROJECTS AND EXPERIENCES

Certification of the VRDT as a voltage regulating unit was conducted successfully according to the relevant technical standards and the newly designed verification guidelines of FGH. However, with an application of the VRDT as an integrated component of a PGU specific adaption of the compliance procedure has to be made based on the individual setup and adjustments. In this context the evaluation of particular control strategies or system behavior of previously certified PGU without VRDT may have to be retested and reassessed again while the majority of electrical characteristics remain unaffected. Derived from ongoing pilot projects these reassessments may refer to system perturbations like flicker and switching operations, reactive power supply or protection systems. With respect to protection equipment for instance, a testing of the entire PGU with VRDT is necessary again because voltage monitoring of the PGU's protection systems refer to low voltage. Due to the variable transmission ratio of the VRDT and harmonized low voltage, the reference voltage is measured incorrectly which leads to conditionally changing tripping thresholds. Hence, adaption has to be made otherwise the selectivity of protection tripping as well as cascaded redundancy is not give anymore. However, this problem can be solved by either implementing the voltage measurement on medium voltage side or by integrating a dynamic calculation algorithm that identifies the medium voltage by measuring low voltage and utilizing a signal for the identification of the actual tap position.

For future projects an important aspect in terms of operational strategies can be seen in further developments of control algorithms. Current projects focus on integration via compatible interface however advanced interdependence concepts promise to have additional advantages in order to optimize the entire PGU system.

V. CONCLUSION

A successful implementation of the paradigm shift in energy policy is associated with a massive growth of grid connections of mostly volatile power generating units to low and medium voltage grids. The transition requires cost-effective alternatives to conventional grid expansion. In this regard new and innovative regulating technologies have great potential to contribute to increased ability for grid integration of dispersed power generators.

The advantages of supplementary voltage regulating grid units have been introduced and VRDTs were highlighted as effective solution of combined applications. On the one hand VRDTs can be integrated into transformer stations and on the other hand they can be included as component in distributed power generating units. In both cases, VRDTs represent an innovative and cost efficient approach that provides advantages in flexibility, performance and costs. With application of VRDT in PGUs even stringent requirements of grid codes with respect to operation voltages or reactive power capability can be fulfilled.

Nevertheless, it is important to rely on safe operation of power equipment. Hence, new verification standards were developed and certification was firstly and successfully carried out. The article emphasizes correspondingly the used procedure and assessments in the context of grid regulating components. The independent verification contains type evaluation of individual integrated components as well as special grid compatibility testing and scrutiny of control capability of VRDT in case of normal and disturbed operation conditions. For grid operator the successfully concluded certification means the provision of the independent and proved evidence, which describes the compliance of the product with guidelines and standards. For manufacturers of PGUs, not only the certification as component is possible, but also as combination with the PGU. The combined certificate includes additionally the standards of grid connection like e.g. the German BDEW medium-voltage directive without the necessity of repeating the entire verification procedure.

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