VOLTAGE CONTROL IN INTELLIGENT SECONDARY SUBSTATIONS BY VOLTAGE OBSERVATION METHODS BASED ON LOCAL MEASUREMENTS

Daniel SCHACHT
FGH e.V. – Germany
Daniel.Schacht@fgh-ma.de

Hendrik VENNEGEERTS
FGH e.V. – Germany
Hendrik.Vennegeerts@fgh-ma.de

Adam SLUPINSKI
ABB AG - Germany
Adam.Slupinski@de.abb.com

Björn KEUNE
TU Dortmund University - Germany
Bjoern.Keune@tu-dortmund.de

Robert FRINGS
INFRAWEST GmbH – Germany
Robert.Frings@infrawest.de

ABSTRACT

The increase of distributed power infeed in medium voltage grid level causes the risk of exceeding prescribed voltage range limits. The modernization of secondary substation technology and the corresponding integration of voltage controllable transformers offer a prominent technical solution. This paper gives a detailed description of a novel voltage control method and evaluates its benefits for grid operation. Thereby, the voltage control application has been modelled in a load flow calculation software tool and simulations have been carried out for a selection of representative low voltage grids.
Simulation results show on one hand the additional amount of distributed generation units, which can be integrated due to the voltage control, and on the other hand the efficiency of the novel control concept compared to common approaches.

INTRODUCTION

The long term objective of Europe to set up a system of electrical power supply based on renewable energy resources has led to a widespread promotion of distributed generation units. These units are often connected to the low voltage (LV) and medium voltage (MV) level. High penetration levels of distributed generation (DG) in LV and MV grids may cause problems in the areas of voltage control and grid loading and therefore influence the planning process of power distribution systems in a great manner. High grid loading can, in general, only be reduced by grid reinforcement. A high variation in voltage however can be reduced through other solutions apart from grid reinforcement.
In this context a collaborative research project sponsored by the German federal ministry for economic affairs and energy investigates solutions for an intelligent secondary substation. The focus of this project lies on efficient voltage control in LV grids, partly. The newly developed control algorithm is therefore based on local measurements available within in the substation and requires no additional external measurements. However, a communication link to the system control center would be a recommended additional feature to inform the grid operator in case of critical voltage levels.

In this paper the developed voltage observer as well as the control algorithm for the secondary substation transformer will be described. Special attention will be paid to the benefit, which this control algorithm creates for the integration of additional DG units and for an efficient utilization of the online tap changer (OLTC).

VOLTAGE CONTROL IN DISTRIBUTION GRIDS

In LV and MV grids high voltages can be caused by DG units and their resource-bound often simultaneous generation of power. Especially in LV grids, this phenomenon is a problem, because the great majority of units are based on photovoltaic generation.
Those generation units will not be available in situations with low solar radiation and therefore the voltage will be low and defined by the grid load. Besides, MV and LV grids are usually connected via a transformer with a fixed transformation ratio. Therefore, the total tolerable voltage variation in LV girds is linked to the voltage variation in the overlaying MV grid. Overall, the variation of voltage in distribution grids should not breach the limits defined in the European Standard EN 50160 [1]. Under normal operating conditions, the voltage variation must not exceed ± 10% of the nominal operating voltage in 95% of the 10-minute-means of the measured root mean square value within the interval of one week. This requirement usually leads to a split of the total tolerable voltage variation between the LV and MV level.

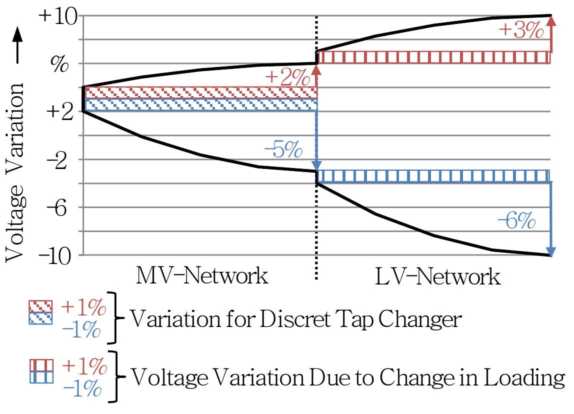

Figure1: Deviation of the Tolerable Voltage Variation

Since the voltage variation at a single node in the grid is influenced by a great number of factors, grid operators tend to use guidelines [2] defined by national organizations such as the forum grid technology / grid operation (FNN) in Germany to divide the tolerable voltage variation between LV and MV level as well as voltage increase and decrease. Figure 1 shows an example for the split of the tolerable voltage variation.

For a precise evaluation of the voltage variation, a detailed model of the MV gird and underlying LV grids including loads and generators needs to be established in a load flow calculation program. This process requires a significant amount of time and effort and is therefore used rarely. Instead of this, grid operators usually connect small DG units based on a rough estimation of the resulting voltage variation. Figure 1 shows the default values for the tolerable voltage increase caused by generators for the MV level (2%) and the LV level (3%), which are defined in German grid codes. This practice may on one hand lead to voltage levels, which exceed the tolerable variation, and on the other hand limit the installation of DG units significantly, because the voltage rise is limited to a small amount of the total tolerable voltage variation. Both of these problems will be addressed in the following paragraphs. First, an evaluation process for grids with a critical number of DG units will be described. Later, a control algorithm for an online tap changer will be introduced, which optimizes the voltage level and thereby reduces voltage induced constrains limiting the total installable power in DG units.

EVALUATION PROCESS FOR TOLERABLE VOLTAGE VARIATION

According to [3], the vast majority of LV grids require a division of the evaluation process in several steps as shown in figure 2. A grid will only be taken to the next evaluation step, if it has previously been classified as critical.

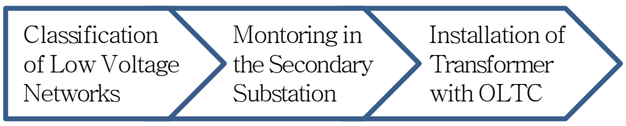

Figure 2: Process to Evaluate Critical Grids

In the first step of the evaluation process the grid is classified based on certain structural characteristics and its penetration with DG units. If a grid is classified as potentially critical, the second phase of the evaluation process is started. In this monitoring phase the maximum and minimum voltage in the grid is being monitored using a so called voltage observer, which will be described at a later stage. In case the voltages in the grid come close to the limits defined in EN 50160, the last phase of the evaluation process is started. The grid will be earmarked for the installation of a transformer with OLTC in the future.

Classification of Low Voltage Grids

In the first step, the grid is classified in regard to its critical voltage. This procedure requires the following structural characteristics of the grid:

- Number of house holds
- Number of house hold connections
- Radius of LV grid
- Number of DG units
- Total installed power in generation units

A detailed description of the classification process has been published in [4].

Monitoring with Voltage Observer

If a grid has been classified as critical, measurement equipment is installed within the secondary substation. For the setup of the whole monitoring system the following additional steps have to be considered [3]. At first, the grid is modelled in a load flow calculation program. Afterwards, load flow calculations are made to calibrate the voltage observer. At first the maximum voltage caused by maximum generation and no load is determined. Secondly, the minimum voltage for cases of no generation and maximum load are calculated. In both of these calculations the voltage variations in every feeder as well as the power flow into the feeders at the secondary substation are recorded. An example of such a calculation is shown in figure 4.

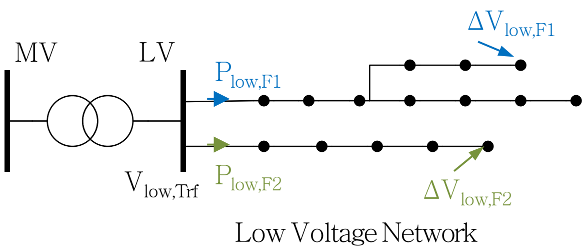

Figure 4: Parameters for Estimation of Lowest Voltages

Based on the calculation results, the voltage observer can be calibrated for every feeder. During operation, the voltage observer will use the following formula together with the measurements to estimate the voltage in a single feeder of the grid:

$$V_{low,F1} = V_{current,Trf} + \Delta V_{low,F1} * {}^{P_{current,F1}}\!/_{P_{low,F1}}$$

Whereas $V_{current,Trf}$ is the current voltage at the LV side of the transformer and $P_{current,F1}$ is the current power flow into feeder Nr 1, both values are measured values. The parameters $\Delta V_{low,F1}$ and $P_{low,F1}$ are part of the calibration of the voltage observer.

By using this method to estimate the voltages in every feeder, the voltage observer is able to determine the lowest and highest voltages in the complete LV grid. During operation the estimation of the voltages is repeated in case of significant changes in input data to give the observer a most accurate view at any given time.

Installation of Transformer with OLTC

If the set limit for highest and lowest tolerable voltage is frequently exceeded for certain duration, the installation of a transformer with OLTC ability should be considered. In this case, the voltage observer can be used to enhance the efficiency of the OLTC control. The algorithm used to realize this benefit is described in the next paragraph.

CONTROL ALGORITHM WITH VOLTAGE OBSERVER

Since the voltages in LV and MV grids can now be controlled separately by means of OLTCs in primary and secondary substations, the grid operator can define a tolerable voltage band for the LV level, which is based on the limits of EN 50160. These new limits for highest and lowest voltage can be used as input for a new control algorithm. Based on the results calculated by the voltage observer and this additional input, the OLTC control is able to determine if any of the set limits are overstepped. Voltage settings included in this algorithm are as follows:

1. upper voltage limit (e.g. 110% U_n)
2. lower voltage limit (e.g. 90% U_n)
3. highest tolerated voltage (e.g. 107% U_n)
4. lowest tolerated voltage (e.g. 93% U_n)

The control algorithm tries to keep the voltage always within the bandwidth defined by the lowest and highest tolerated voltage as shown in figure 5.

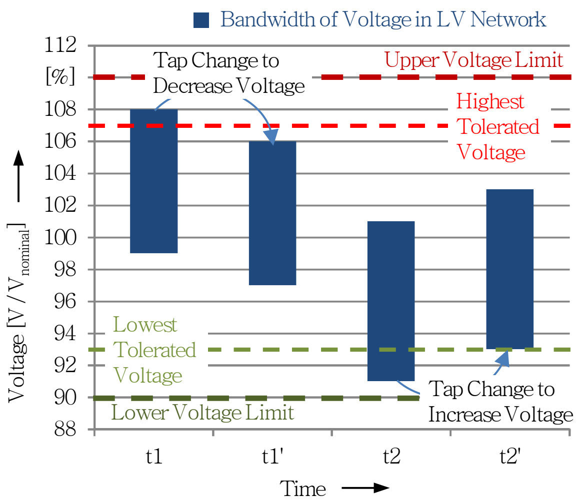

Figure 5: OLTC Control with Voltage Observer

Since the OLTC has in general a specific number of fixed steps, a priority level has to be defined in case the voltage cannot be kept under the highest and over the lowest tolerated voltage simultaneously. Therefore, the order of the settings in the list above also represents their priority. If the upper voltage limit is exceeded, the voltage level will be decreased even if it means that the lower voltage limit will be breached. If the lower voltage limit is breached, the voltage level will be raised even when the highest voltage will be above the highest tolerated voltage afterwards.

If the voltages calculated by the voltage observer are located within the bandwidth defined by the highest and lowest tolerated voltage, the tap position of the transformer will not be changed. This methodology leads to a significant decrease in changes of the tap changer position as will be shown by the simulations in the next paragraph.

SIMULATIONS AND RESULTS

In the simulations, synthetic LV grid models are used to evaluate the benefit of the new control algorithm in a great variety of different potential use cases. For the generation of these grids, an enhanced version of the generation tool described in [5] is used. The input parameters for the different types of LV grids as well as the number of feeders and the length of the feeders in these grids are derived from [6]. The input parameters for types and diameters of cables and overhead lines are taken from publications regarding grid concessions, which, in general, contain specific data concerning the grid assets such as cable type and installation year [7].

According to [6], LV grids can be classified in types and in groups such as: rural (2 types), suburban (4 types) and urban (3 types). For the simulations, grids of all types are generated and DG units are integrated into these grids. In three different scenarios the total number of household connections with DG units is increased from 10% DG to 35% DG to 60% DG. The installed power of the DG units is increased until the ampacity limits of lines/transformers or a voltage increase of 3% V_n compared to a case without DG units is reached. For the simulation of load and generation in LV grids, real and synthetic time series are used. Each simulation covers the time period of one year in a 15-minute-sequence.

Based on this setup, the benefit of the new control algorithm is evaluated with specific focus on the increase in installable power of DG units and on the efficient utilization of the OLTC.

Increase in Installable Power of DG Units

An evaluation of the limiting factor for the installation of DG units shows significant differences between the three groups of LV grids. For rural grids the limiting factor is in 90% of the grids among all three scenarios the voltage increase. In urban grids only for the first scenario (10% DG) 90% of the grids have reached their limit of installable power of DG units because of voltage increase. In scenarios two (35% DG) and three (60% DG) only in 25 – 90% of the grids the installable power is limited by the increase of voltage depending on the grid type. In suburban grids the corresponding shares are 5% up to 40% and depend on the grid type as well as the scenario. Overall, this analysis shows that the voltage increase limits the installable power of DG units

especially in rural and specific urban grids.
In the next step, transformers with an OLTC are integrated in those grid models, where the voltage increase limits the installable power. Afterwards, the new limit for installable power is determined in an iterative process by means of load flow calculations.
Figure 6 shows the results of the increase in installable power due to additional tolerable voltage variation in rural LV grids.

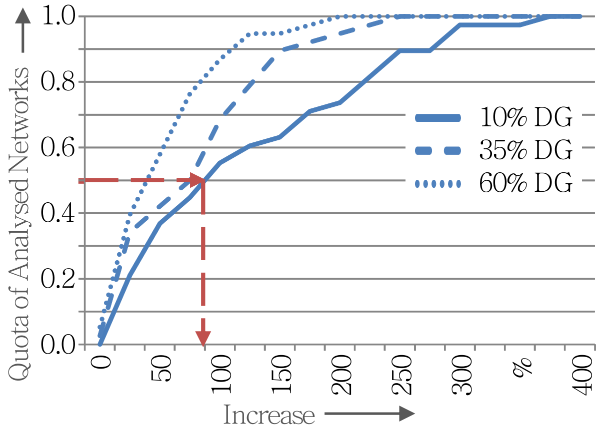

Figure 6: Increase in Installable Power in DG Units

The results show that for this particular kind of rural LV grid type in 50% of the analyzed grids the installable power can be increased by approximately 80% based on the installable power without the OLTC.
The relative increase in installable power varies between the scenarios 10% DG, 35% DG and 60% DG because of a variation in the installed power before the installation of the transformer with OLTC functionality. Since in the 60% DG scenario the installed power is more evenly distributed between the feeders and over the length of each feeder, the total capacity of the grid for the integration of DG units is already utilized in a better way. This leads to a lower relative increase in installable power compared to the 10% DG and 35% DG scenarios for most of the analyzed grids.
For the second type of rural LV grids the results are almost similar to the results shown in figure 6. For other grid types the relative increase in installable power is, in general, significantly lower. Especially in suburban grids, a transformer with OLTC functionality is only able to increase the installable power in approximately 15% of the analyzed grids depending on the scenario.

Efficiency of new control method

For the evaluation of the efficiency of the new control method simulations of all previously mentioned LV grid types are made. The installed power in DG units is increased to the previously determined maximum defined by tolerable voltage variation and ampacity of the grid equipment. Since the biggest effect of the OLTC on the installable power occurs in rural grids, only exemplary results for these grids are shown in the following.

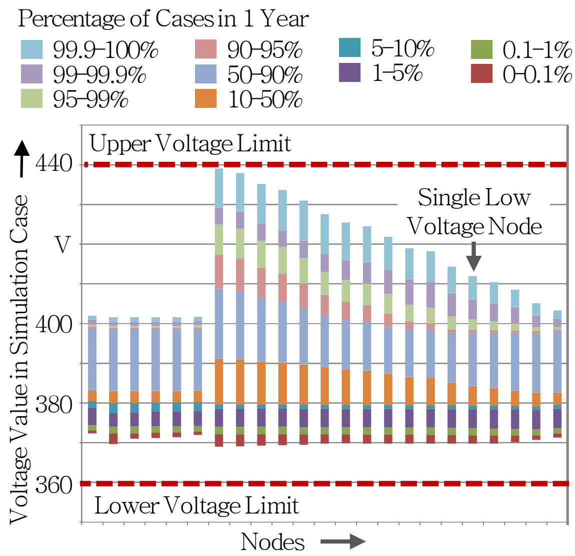

Figure 7: Distribution of Voltages in Exemplary Grid

Figure 7 shows the distribution of voltage values at every node in an exemplary LV grid over the simulation period of 1 year. As can be seen in the graphic, the voltages at each node are held within the boundaries defined by the upper and lower voltage limit. The utilization of approximately 90% of this bandwidth shows how effectively the algorithm works. The boundaries for the tolerated voltage were set to 107% and 93% V_n. The voltages are not constantly kept within these boundaries due to simultaneous occurrence of high voltages in one feeder and low voltages in the other feeder.

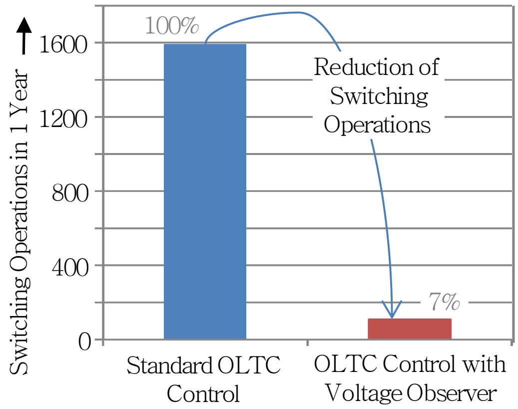

Figure 8: Switching Operations of OLTC

Besides the better utilization of the tolerable voltage variation, the new control method for the OLTC can promote operational calmness. As shown in figure 8, the number of switching operations in this exemplary grid can be reduced by approximately 93% compared to a standard OLTC control, which tries to keep the voltage at the secondary side of the transformer constant.
Another feature of the new control algorithm is its automatic standard tap position adjustment. Since the algorithm tries to reduce switching operations, the

standard position of the tap changer will be placed on a tap position which will require the least switching operations over the year. For the exemplary grid the frequency of tap positions over one year is shown in figure 9.

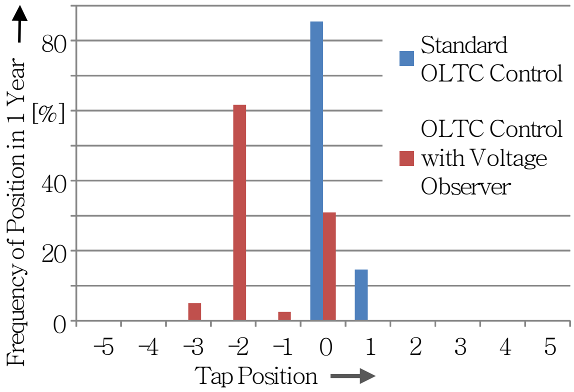

Figure 9: Frequency of Tap Positions over 1 Year

The figure illustrates that the new control algorithm defines position -2 as best position for the grid in contrary to position 0, which is most frequently chosen by the standard algorithm. This selection of standard tap position shows clearly that the new algorithm reacts significantly more sensitive on voltage increase due to power injection by DG units. The new algorithm tries to control the voltage variation in the LV grid and at the same time compensates voltage variations in the medium voltage grid. The standard algorithm is almost exclusively triggered by voltage variations in the medium voltage grid and high load in the LV level.

Overall, it can be concluded that the new control algorithm has significant advantages over the standard algorithm.

CONCLUSION & OUTLOOK

In a collaborative research project sponsored by the German federal ministry for economic affairs and energy the benefit of the voltage observer and its combination with a transformer with OLTC has been analyzed with quasi-stationary simulations of LV and MV grids. The results show that on one hand the number of voltage induced constrains decrease significantly and on the other hand the total tolerable voltage variation can be utilized frequently without leaving the set voltage limits. Furthermore, the control of the OLTC based on input from the voltage observer is more efficient and switching operations can be reduced to a minimum. This leads to a more efficient use of grid equipment, fewer restrictions for the installation of further DG units and, hence, increases flexibility during the planning process.

For future research works the impact of the combination of voltage observer and OLTC in secondary substations and a further development of the control algorithm for the reduction of losses in LV and MV networks should be analyzed.

ACKNOWLEDGEMENTS

This scientific work carried out as part of a collaborative project including ABB AG, FGH e.V., INFRAWEST GmbH and TU Dortmund University has been partly sponsored by the German Federal Ministry for Economic Affairs and Energy under grant 03ET7007B [8]. The authors thank all consortium partners for their engagement and support.

REFERENCES

[1] German Institute for Standardization, 2011, *DIN EN 50160:2011-02 – Voltage characteristics of electricity supplied by public distribution networks; German version EN 50160:2010 + Cor. :2010,* Beuth Verlag, Berlin, Germany.

[2] VDE Association for Electrical, Electronic & Information Technologies, 2011, 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 (VDE-AR-N 4105:2011-08), VDE Verlag, Berlin, Germany.

[3] A. Slupinski, et al, 2013, "Neue Werkzeuge zur Abschätzung der maximalen Spannung im Niederspannungsnetz", International ETG-Kongress (ETG-FB 139), VDE Verlag.

[4] Maximini, M., et al, 2013, „Abschätzung der Spannungsanhebung in Niederspannungsnetzen ohne Netzberechnung - Neue Prozesse bei der Stadtwerken Duisburg Netzgesellschaft mbH", ew - Magazin für die Energiewirtschaft, vol. 13, 72-75.

[5] S. Dierkes, et al, 2013, "Active and Reactive Power Behavior of Distribution Systems with a Significant Share of Distributed Generation", International ETG-Kongress (ETG-FB 139), VDE Verlag.

[6] J. Scheffler, 2004, „Bestimmung der maximal zulässigen Netzanschlussleistung photovoltaischer Energiewandlungsanlagen in Wohnsiedlungs-gebieten", VDI Verlag, Düsseldorf, Germany.

[7] BerlinOnline Stadtportal GmbH & Co. KG, "Technische Daten Stromverteilnetz Berlin", URL: www.berlin.de/sen/finanzen/dokumentendownload/vermoegen/konzessionen/strom/vattenfall_technische_daten_stromverteilnetz_berlin_09122011.pdf, Viewed 20 May 2014.

[8] Research Project *„Smart Area Aachen: i3S – Intelligente Ortsnetzstation – System- und messtechnische Untersuchungen zum Vorteil von intelligenten Ortsnetzstationen* ", www.smartarea.de.