VOLTAGE CONTROL IN SMART DISTRIBUTION GRIDS – OVERVIEW AND PRACTICAL EXPERIENCE OF AVAILABLE SOLUTIONS

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ABSTRACT

Ensuring voltage stability according to EN50160 has become a major challenge in today's distribution grids due to the increasing number of fluctuating distributed energy resources (DER) connected on the medium and low voltage level.

On the 2012 CIRED workshop EnBW Regional AG presented the regulated distribution transformer (RDT) as a powerful tool to achieve voltage control at the MV/LV-substation. Line voltage controllers complement this solution and are especially useful to avoid voltage problems when large loads or generation units are connected at the end of a long feeder line.

This paper discusses different technological approaches to voltage control and provides use cases for the application of substation-based solutions as well as voltage regulators for single feeders. Moreover, a hands-on example from the grid of EnBW Regional AG is discussed. This includes actual on-site measurement data and a simulation on the expected operation of the first line voltage controller which was only recently put into operation.

INTRODUCTION

An eighty percent share of renewables in the overall power consumption by the year 2050 – this is the ambitious goal of the German "Energiewende". Significant portions of this power will be generated by small distributed energy resources (DER) and fed into the low and medium voltage grid. Connecting these generation units to an infrastructure originally designed for a load-flow that was strictly one-way is not an easy task for the local distribution system operators (DSO). As of today the biggest challenge is the voltage increase caused by large numbers of DERs in LV-feeders. In accordance with the international standard EN50160 [1] voltage must not exceed ±10 % of the rated value at any terminal point and most inverters will stop feeding energy into the grid if this threshold is exceeded (see Figure 1).
The German regulator obligates DSOs to ensure a preferred grid connection for renewables which often results in the need for grid reinforcement (usually by means of additional cables or secondary substations) before a new DER can be put into operation. This is especially unfortunate from an economic point of view considering that the existing grid infrastructure would often be able to transport much higher amounts of energy with respect to the allowed maximum current. Simply changing the static ratio of substation transformers does not go well with the fluctuating nature of renewables like photovoltaic power. The voltage at one and the same terminal point can significantly rise and drop within a day depending on the current levels of locally generated and consumed energy.

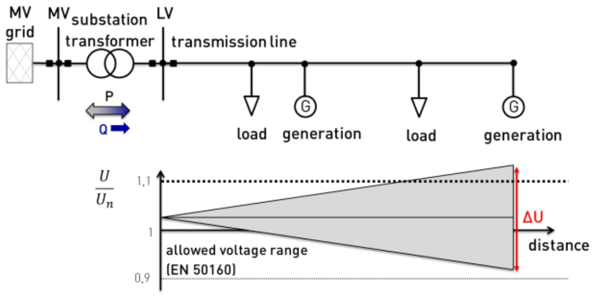

Figure 1: Voltage range along an LV-feeder line

With a dynamic voltage control this issue could be solved in a technically and economically reasonable way. The following will describe existing technical solutions and practical experience to achieve this goal.

SOLUTIONS FOR VOLTAGE CONTROL IN DISTRIBUTION GRIDS

There are two major technical solutions to ensure voltage stability in the low voltage network, depending on the grid layout and the nature of the voltage problems. The regulated distribution transformer (RDT) can be used in secondary substations to control the voltage level of the entire underlying LV-grid. Line voltage controllers on the other hand are used to regulate the voltage of a single feeder line.

Regulated Distribution Transformer

Using on-load tab changers to dynamically change the ratio of transformers is not a new concept in energy distribution. On the high and very voltage levels these solutions have been used to great success for decades. At the MV/LV-level RDTs have only recently become available. There are basically four different technical solutions to achieve the voltage regulation:

1. Mechanical switches on the low voltage side of the transformer (see [2] for details)
2. Mechanical switches on the medium voltage side of the transformer
3. An additional inductance which changes the magnetic flow of the transformer core
4. Voltage management via power electronics (thyristor voltage regulation)

All of these concepts have different advantages and disadvantages concerning for example the attainable voltage range, losses, reliability or the mean life of their components.
From a network planning perspective, however, it does not really matter which type of RDT is used as long as it serves the purpose of regulating the voltage at the MV/LV substation. In cases when the distribution of loads and generators in the underlying LV-grid is relatively homogenous in all feeder lines, as shown in Figure 2, an RDT can achieve very good results in voltage regulation.

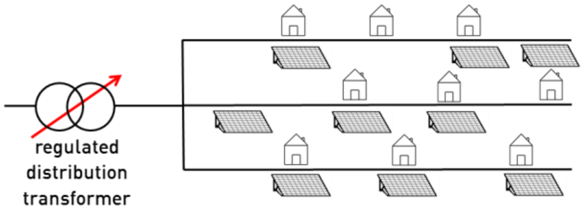

Figure 2: LV-grid with RDT

Line voltage controller

As opposed to the former case, Figure 3 shows a layout with unbalanced feeders in the LV-grid which provide a typical use case for the line voltage regulator.

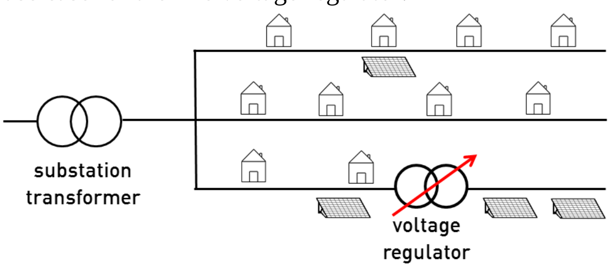

Figure 3: LV-grid with line voltage controller

This grid layout can often be found when a secondary substation supplies at the same time residential areas and a far-off farm with many photovoltaic panels on its roof. While the high consumption of households leads to a voltage drop in some feeders, the PV-supply simultaneously increases the voltage in another feeder. Replacing the substation transformer by an RDT would obviously do no good in this case as some feeders require a higher and others a lower voltage level. Line voltage controllers which can be placed anywhere along a feeder line solve this issue, as will be discussed more in detail in the following sections.

This short comparison shows that the RDT and the line voltage controller are two solutions with clearly defined use cases. Both approaches complement each other and might in some situations even be used in combination to efficiently solve voltage problems.

TECHNICAL SPECIFICATIONS OF THE VOLTAGE REGULATOR

The effect of line voltage controllers is to reduce or increase the voltage on the secondary side of the controller with respect to the primary side. We define the primary side as the one connected to the substation transformer. Figure 4 shows the effect of a line voltage controller on the voltage distribution along an LV-feeder line with several generators and loads connected to it.
The grey area highlights the possible voltage range along the line. In this example the terminal voltage at the substation transformer is 3 % above the nominal voltage. Depending on the supply and load situation the voltage rises or falls along the line. In case of feed-in, the voltage would rise along the line and exceed the upper voltage limit of +10 % allowed for low voltage grids (compare Figure 1).

Close to this point, the line voltage controller is installed. Here the controller can decrease the voltage level so that the voltage on the secondary side of the controller has a sufficient margin to increase further without exceeding the allowed upper voltage limit.

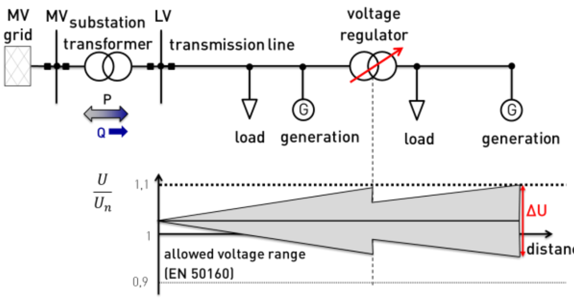

Figure 4: Voltage range on LV-feeder with line voltage controller

There are different technical solutions for the design of line voltage controllers. The following shows the function principle of three different commercially available solutions. All have in common that the secondary voltage V_{sec} is influenced by inducing a voltage ΔV lengthwise in the line with a transformer so that $V_{sec} = V_{pri} - \Delta V$. Two concepts lead to controllers which can by design either only increase or only decrease the secondary voltage while a third solution allows a dynamic control of V_{sec} in both directions.
In any case the voltage regulation is achieved at the expense of some additional losses due to the operation of the controller itself.

1. Control by variation of inductance

In this case the voltage induced lengthwise in the line (ΔV) is determined by a voltage divider consisting of one winding of a transformer and a variable inductance. The inductance is varied by affecting the ferromagnetic core material of the coil with a magnetic field perpendicular to the main field of the coil. The perpendicular magnetic field can be strengthened or weakened by a variable DC-current in a second coil. Thus the inductance and as a result of this also the voltage V_{sec} can be controlled continuously.

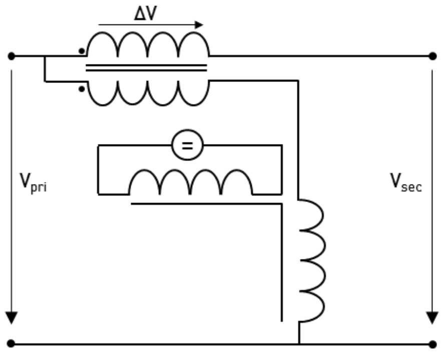

Figure 5: Circuit diagram of line voltage controller with varying inductance

Advantages: Continuous control, long lifetime (expected)

Disadvantages: voltage control only in one direction (either increase or decrease)

2. Control by electric contactors

In this case ΔV is varied stepwise by switching on and off transformers with electric contactors. Thus the voltage is controlled stepwise. In the circuit diagram shown in Figure 6 the number of steps is 3. By changing the direction of the voltage along the secondary winding the operation can be switched between voltage in- and decrease. Here ΔV is the sum of $\Delta V = \Delta V_1 + \Delta V_2$.

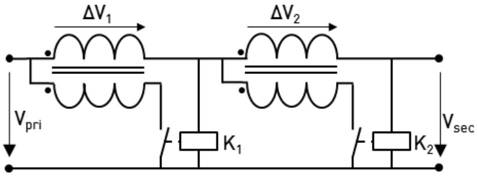

Figure 6: Circuit diagram of line voltage controller with electric contactors

Advantages: Simple maintenance, voltage control in both directions possible

Disadvantages: Stepwise control

3. Control by thyristors in separate circuit

In this case ΔV is varied by an AC-current in the secondary winding of a transformer. The current is controlled by thyristors and thus ΔV can be varied continuously. Depending on the direction of the current in the secondary circuit the voltage can theoretically be both in- and decreased. Currently only regulators for a voltage decrease are commercially available.

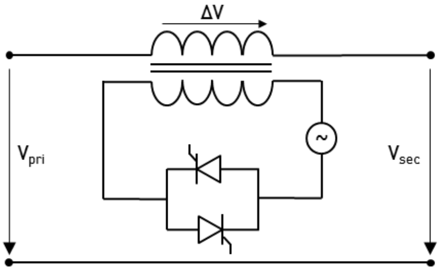

Figure 7: Circuit diagram of line voltage controller with thyristor control

Advantages: Continuous control, lower losses

Disadvantages: Lower expected lifetime of active parts, voltage control only in one direction (either increase or decrease)

LAYOUT OF THE PILOT INSTALLATION

In order to evaluate the practicability and the reliability of these technical solutions EnBW is currently field testing several line voltage controllers of different manufacturers using all of the three presented technical solutions. In the following one case example for solution no 1 (variable inductance) is shown exemplarily.

The first prototype of a line-voltage regulator in EnBW Regional AG's low-voltage grid was put into service in October 2012. The voltage controller can be found in the small town Wolpertswende (Oberschwaben) in Baden-Württemberg, Germany. At this site two PV generators with a combined capacity of 30 kWp are connected to the end of a long feeder line, which, according to network calculations, would have violated the voltage constraints at times of high feeding. Without the voltage regulator a new secondary substation and additional MV-cables would have been necessary to ensure the connection of the generators.

Figure 8 shows the double-size cable distribution cabinet which holds the voltage regulator on site. The stone pillars left and right were added for mechanical protection.

Figure 8: Installation site

MEASUREMENTS AND SIMULATION

Since an on-board measurement and recording of the data is not supported by the current prototype, several measurement cycles using a mobile power quality device are planned to be conducted until end of 2013. During the first recording period from 9th Oct. till 15th Nov. 2012, the low solar irradiation didn't lead to a control action of the line voltage controller because the feed-in power was so low that the power flow didn't cause a voltage rise that exceeded the allowed voltage margin.

In order to nevertheless illustrate the effect of the controller, its operation was simulated using voltage values recorded during the test phase and assuming more restrictive settings for the voltage control algorithm. The control setup used for this simulation is shown in Figure 9.

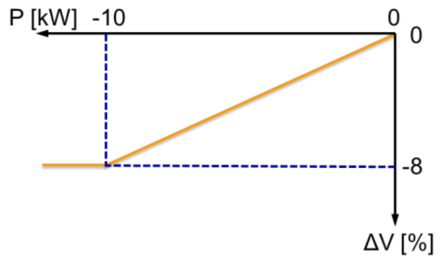

Figure 9: Exemplary Control Setup

As can be seen, the set voltage level on the feeder is adjusted depending on the prevailing load flow. If, for example, the load flow is P = -10 kW (reverse feeding), the voltage in all phases would be reduced by 8 % (referred to the nominal value of 230 V) so that, as a result, V_{sec} is 8 % lower than V_{pri}.

Figure 10 shows a simulation of a control action. The dashed light blue line shows the voltage V_{pri} in phase 1 recorded on-site on October 14th 2012. The corresponding power flow can be deducted from the orange line. The dark blue line then represents the calculated voltage V_{sec} which would be the result of a controller set to the algorithm shown in Figure 9.

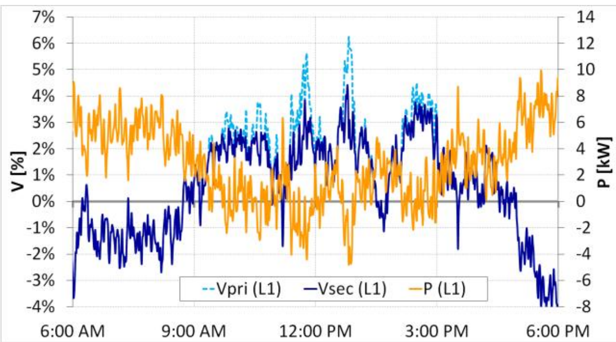

Figure 10: Simulated voltage characteristic

At times when the power flow is negative, reverse feeding occurs which causes the voltage to be reduced by the controller. This setup allows the voltage rise on the secondary side to be kept below 5 % at all times.

In the coming months EnBW will perform further tests with different setups for the pilot voltage controllers to gain more experience with the performance and practical implications of the competing technical concepts.

SUMMARY AND OUTLOOK

In this paper it three different technological approaches to line voltage control have been introduced and evaluated with respect to their specific advantages and disadvantages. Assuming that all of these solutions ensure the desired voltage regulation, additional factors like reliability, maintainability, losses, and of course price will determine the products' commercial success.

EnBW Regional AG is currently testing pilot installations for each of the presented technologies. Since these were only recently installed, there is not yet enough data to finally evaluate the efficiency and technological robustness of the controllers. This is why in this paper the operation of the introduced exemplary controller could so far only be shown by way of a simulation based on measured values. The plan is to further test different control algorithms and monitor the operation of the regulators during the summer months with higher PV-supply.

Eventually the line voltage controller, alongside the regulated distribution transformer, is to be added to the portfolio of smart grid tools used by EnBW's grid planning department. These tools are meant to allow the connection of a high amount of distributed generators in a more flexible and cost-efficient way than traditional grid reinforcement.

REFERENCES

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[2] Körner, C. et al., 2012, "Gaining Experience with a Regulated Distribution System Transformer in a Smart Grid Environment", *CIRED Workshop 2012*, paper No. 0161