LINE VOLTAGE REGULATOR FOR VOLTAGE ADJUSTMENT IN MV-GRIDS

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ABSTRACT

Based on the German way of changing the generation mix to renewables, a high amount of fluctuating and dispersed photovoltaic and wind power needs to be integrated into the distribution grids. This causes voltage rise problems especially in rural grids with low load density and long distribution lines [1]. In order to achieve an efficient supply with electrical energy this paper presents an innovative line voltage regulator (LVR) solution for prevention of voltage problems in medium voltage grids.

A LVR pilot installation is in operation in the 20 kV grid of Westnetz in Western Germany. The paper describes the grid situation at the LVR pilot installation, includes a detailed technical description of the LVR solution benefits compared to conventional grid expansion, and presents the technology of the LVR.

INTRODUCTION

During the last decade, Germany has experienced an unprecedented increase of renewable generation, especially of wind and photovoltaic (PV) power. There are regions where the peak generation power is a multiple of the peak power consumption. Electric distribution grids have been designed in the past for being able to scope with the forecasted load consumption. The massive introduction of distributed and strongly dispersed generation brings many grids to their limits and require additional actions and investments.

It is expected that in Germany the strong trend into renewables continues, backed-up by the political decision to shut down all nuclear power plants and the concerns about global warming. The share of renewables in electricity production is supposed to double within the next 15 years to 50% of the total consumption. Other countries experience similar problems in their distribution grids, although on a so far less pronounced level.

The European standard EN 50160 [2] defines the voltage requirements in distribution grids, and requires that the voltage stays within a band of +/-10% of the nominal voltage. Considering present practices [3], only a 2% voltage increase is available in the medium voltage (MV) grid. The exact value of the available voltage increase depends on the grid control settings of the grid operator. A generalized situation is sketched in in Figure 1. The indicated values include transformer voltage drops and deviations due to discrete steps.

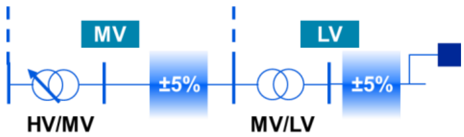

Figure 1: Available voltage bands in MV and LV grids

On longer MV lines, with distributed in-feed along and especially towards the end of the line, the 2% limit, can quickly be exceeded and some of the generators may need to be disconnected [4]. On windy and sunny week-end days with low consumption, the situation can be especially pronounced. In many cases the MV line is not limited by its capacity but by the voltage rise. A costly reinforcement of the grid is required, unless one could insert a device which is able to adjust the voltage.

PURPOSE AND EFFECT OF LINE VOLTAGE REGULATOR

The last voltage regulating unit in most distribution grids is the HV/MV transformer, which can influence the requested voltage band at connected customers of +/-10% of the nominal voltage. To increase this band a device is needed, which can modify the voltage and so decouple the operating voltage in a MV line from HV/MV transformer voltage and so increase the potential for power in-feed from distributed generation into the line [5].

Such a device is called a line voltage regulator (LVR). It can be placed anywhere along the line. Its optimal position depends on the specific distribution network and the MV connection points of large PV and wind generation units. Positioning somewhere 1/3 to 2/3 down the line is often a good choice. Note that in case several MV feeder lines are connected to the HV/MV transformer, tap changing at this transformer will influence all MV lines, whereas a LVR

will regulate only the specific line from which the problem arises. This is important since load and in-feed can be very different on different lines.
Figure 3 shows that the introduction of a line voltage regulator in the MV line allows to "recalibrate" the voltage and to increase the available voltage band. In this example the band is doubled.

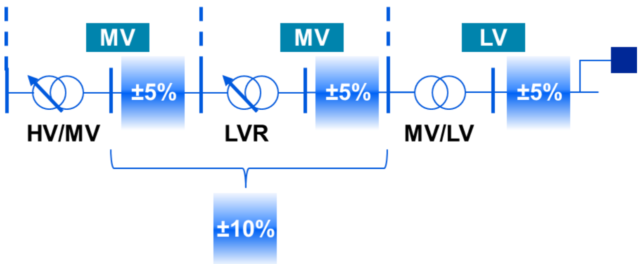

Figure 2: Available voltage bands in MV and LV grids with MV-LVR

The additional band in MV can also be used to increase the voltage band for the LV grid (Figure 3). This eliminates the need for installing regulated distribution transformers (RDT). A single MV LVR can therefore be installed in a MV line instead of replacing a large number of distribution transformers with costly RDTs, in particular if the average transformer power rating is small (≤ 100 kVA).

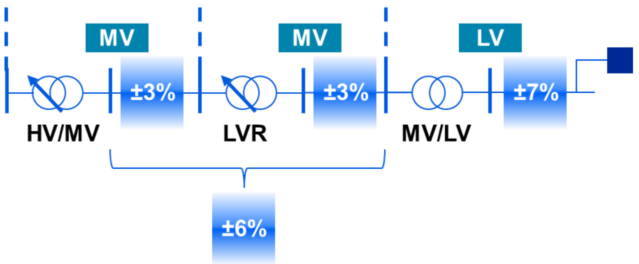

Figure 3: Possible shifting of available voltage bands from MV to LV grids with MV-LVR

By analogy to the application in the MV grid, LVRs can also be used in the low voltage grid. In case of several LV-feeder lines with different load/generation situation, a RDT is not able to appropriately adjust the voltage and voltage regulation in the specific feeder line is required.

SPECIFIC GRID SITUATION AT WESTNETZ

The economical usage of the LVR depends on various criteria, which are frequently found in rural electrical power grids, where the power feed is decentralized. Some of them are found in subareas of the German distribution system operator Westnetz. With a grid length of 190,000 km the company Westnetz GmbH supplies approx. five million people with electrical power over an area of 50,000 km². The requirement for an LVR are voltage conditions close to the limiting threshold values combined with a low current load of the power cable. The determination of these grid areas requires both, a network analysis of the maximum reachable power feed and a low consumption (worst case). Different technical improvements, like expanding the medium voltage grid, using voltage regulated distribution transformers, or a flow-dependent regulation of the voltage level of the busbar by the tap changer in the HV/MS transformers, will quickly reach their limits. Expanding the medium voltage grid or using voltage regulated distribution transformers to achieve a technical improvement are high level investments. Additionally a low synchronized flow in many power grids does not fulfill the technical requirements for a flow-dependent regulation of the busbar voltage.

There are different criteria which have to be fulfilled to justify the usage of LVR in medium voltage grids. A technical requirement is a high penetration of generation plants in the medium voltage grid. Additionally, the spatial arrangement of the generation units and their connection points to the grid have to be considered as well as the function of the reactive power control of the generation units. The less inductive reactive power is consumed by the generation unit the worse is its effect on the voltage level. At present the powerful renewable generation plants in Germany have to generate inductive as well as capacitive reactive power as a function of the active power or as a function of the voltage level with a maximum value of cos(φ) = 0.9. As a last criterion, the influence of the length of the medium voltage line needs to be mentioned. The greater the distance between the grid-connection points of the renewable power plants and the nearest voltage control unit in the substation, the more are the effects of the renewable feed on the voltage level at the connection points of the renewable power plants.

In this section the cost-benefit ratio of all alternative technical solutions is addressed to show the high economic efficiency. Because of its technical mode of action, the LVR is able to transmit electrical power up to 8 MVA by creating a new reference point for the electrical voltage. Thus, the LVR significantly increases the connection capacity of generation power. For a direct comparison with a technically equivalent effect caused by expanding the medium voltage grid, the capital investment for new electricity lines exceeds by far the capital expenditure for the LVR. In addition to this, many existing medium voltage lines will not amortize in the near future. In conclusion, in many cases the LVR is the most efficient economical solution.

Based on this, Westnetz GmbH made an analysis to determine the best place for an installation of a LVR prototype in medium voltage grids. To adapt the simulation close to reality, the theoretical model was enhanced by real measurement values. The analysis identified a circuit with a total length of 26 km in the medium voltage grid near to the city Bitburg that takes the generation power of approximately 200 generation units. The total power in this circuit is more than 5 MW, composed of photovoltaic-, biogas- and water power plants. This connection point of the LVR to the medium voltage grid is located in a distance of 10 km to the last voltage control unit in the substation and transmits a maximum of 4.7 MW generation power feed and about 3.0 MW consumption in the opposite direction. In the unregulated condition without using the LVR, the voltage at the end of the circuit at a distance of 26 km from the substation ranges between 19.6 kV and 21.9 kV. An additional analysis shows, that the effect of expanding the medium voltage grid achieves only a small voltage improvement combined with a high capital expenditure. The cost difference was evaluated to be several 100 kEUR.

In a first stage, the LVR operates with a nominal output voltage of 20.5 kV. The implementation of this control mode in the simulation environment shows that the new maximum values of the voltage are expected to be 19.8 kV and 21.1 kV, respectively. This results in a theoretical improvement of 800 V of the upper voltage value at a distance of 26 km from the substation.

The alternative flow-dependent operating mode of the LVR improves the results significantly: the simulation shows that the implementation of an output voltage value of 20.0 kV at 4 MW generation power and a second output voltage value of 21.0 kV at 3 MW power consumption results in new maximum values of 20.3 kV and 20.9 kV at a distance of 26 km from the substation. Thanks to this technology the future spatial arrangement of the generation units is only of minor importance. Thus, the LVR nearly totally compensates the restrictive criterion of the limited voltage values in medium voltage grids.

LINE VOLTAGE REGULATOR

The LVR is based on a circuit which adds or subtracts an additional voltage U_B to the non-regulated line voltage U_L (Figure 4). A variable voltage supply, fed by the line itself, creates a voltage U_{RB}, which is coupled into the line via a transformer (booster transformer). The regulated voltage is then $U_R = U_L +/- U_B$.

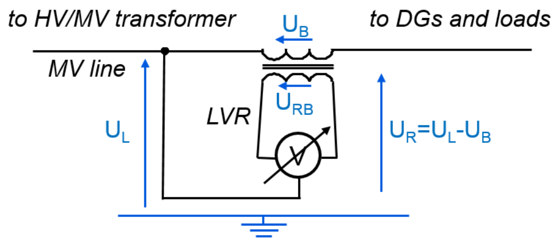

Figure 4: Operating principle of the line voltage regulator

A transformer (feeder transformer) is used as variable voltage source. The transformer has a number of taps so that its voltage can be changed step-wise between 0% and 100%. The on-load tap changer (OLTC) is based on a linear configuration with resistors used in the diverter during the commutation phase. The switches of the OLTC allow up to 3 million operations without need for maintenance. The direction of the current flow in the regulation circuit can be inverted, allowing to generate an additive or a subtractive voltage.

The variable voltage supply circuit is galvanically separated from the line. This feature makes the LVR equally suitable for usage in grounded, impedance-grounded, or insulated grids.

The LVR contains additionally disconnecting and earthing switches at the HV/MV transformer and at the DG/load side, instrument transformers for the measurement of voltage and current, as well as a by-pass switch, allowing to completely shunt the LVR.

The LVR does not introduce any galvanic separation into the line itself and adds only very low additional impedance. Protection procedures are therefore not influenced and existing protection settings do typically not need to be modified. Line voltage regulators with the same operating principle are provided for MV and for LV [1] applications.

Dry-type transformers of RESIBLOC technology are used as booster and feeder transformers. Thanks to the usage of dry transformers all components are free of oil, making them suitable and safe for outdoor or indoor installation and guaranteeing high fire safety.

The RESIBLOC transformers are especially suitable for this application since they offer high flexibility for providing any tap configuration, are mechanically very stable, not sensitive to quick changes in load or temperature, and qualified for temperature down to -60°C. The transformers also fulfil the new EU Regulation for transformer losses [6].

For the pilot installation at Westnetz, the whole LVR was mounted in a concrete substation, completely tested at the factory, delivered to the site and connected to the 20 kV cables (Figure 5). In case of different demands in future, the whole LVR can easily be relocated to another location. This gives flexibility for future changes in grid reinforcement or reconfiguration and allows to continue to make use of the investment.

The specification of the LVR is shown in Table 1. An important criterion for an LVR is the short-circuit current of the line. The grid simulations at Westnetz showed that at the installation site the short circuit current is less than 6.2 kA. The losses of the LVR depend on the regulation step and on the current on the line. In case no voltage regulation is required, the by-pass can be activated, resulting in negligible power consumption of the LVR.

Figure 5: 8 MVA line voltage regulator getting installed on 20 kV distribution line of Westnetz (pictures: Trierischer Volksfreund/Kimmling)

power rating (line)	8 MVA
system voltage	20 kV
short-circuit current	6.2 kA
voltage regulation range	+/- 10%
step voltage	2%
control settings	- fixed voltage - power flow dependent voltage
control modes	- automatic - remote or local
stepping hysteresis	1.5% (adjustable)
stepping time delay	60 s (adjustable)
efficiency	>99.75%
sound level L_p (1m)	<40 dB(A)
installation	outdoor
dimensions (LxWxH)	6600x3300x3600 mm³

Table 1: Characteristics of MV line voltage regulator installed at Westnetz

The LVR is able to operate in a completely automated and autonomous mode, or via remote or local control. In the case of Westnetz it is integrated into to the grid control system. Communication between local RTU and grid control system is done via a GPRS connection.

Different modes for the control settings are available. It is possible to select a fixed voltage set-point value. The set-point value can be modified via remote control, and e.g. be based on a voltage measurement at a different location. Alternatively, a control curve can be defined. The curve can for example be a function of the power flow and the flow direction on the MV line.

In order to avoid that small voltage changes cause frequent voltage stepping, a “voltage stepping hysteresis” is introduced. This parameter is adjustable. A typical value is 1.5%, meaning that a voltage step of 2% is taken only when the voltage deviates by at least 1.5% from the set-point value instead of 1%. Stepping back is happening only at a deviation of 0.5% from the original value. In order to also avoid stepping in case of short voltage variations, additionally a time delay is used. Those two parameters help to prevent flickers in the grid.

In case of operational disturbances, the by-pass switch is activated and the LVR is shunted. Disturbances may come from the power system (e.g. voltage exceeding the allowed range, large asymmetries between phases) or from the LVR (e.g. over-temperature). The fast, automatic activetion of the by-pass within less than one second guarantees a safe operation of the LVR and allows to detect special grid situations without being influenced by the LVR.

The actual grid status at the location of the LVR can be obtained at any moment via the RTU. Information on phase voltages, phase currents, reactive power, harmonic content, etc. is available and allows to determine the exact status and performance of the grid.

OPERATION OF MV-LVR

The medium voltage LVR is in operation since several months. **Figure 6** shows 15 minutes values of its input and output voltage. The set-point value for the voltage is U=20.5 kV. The LVR output voltage stays within a voltage range of +/-1.5%, defined by the stepping hysteresis.

The non-regulated voltage (input voltage) at the location of the LVR (km 10) already increases above 21 kV. Without LVR, the voltage at the end of the line (km 26) would further increase significantly. Note that during the measurement period in February there was only limited infeed from PV feed-in. The figure also shows periods where input and output voltage are identical. This occurs during night when PV feed-in is completely missing.

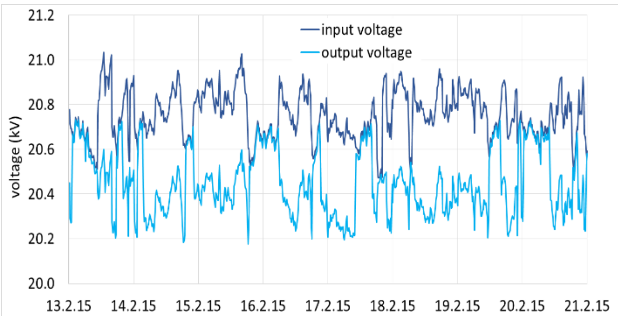

Figure 6: Input and output voltage of the line voltage regulator during a one week period

No problems have been encountered so far related to the communication via GPRS. All systems used by Westnetz must pass in advance an Information Safety Management System (ISMS) process. Due to use the RTU as a standard getaway the risk assessment did not reveal any special risk. Access to the LVR is only possible via the grid control system.

The selected "stepping time delay" of 60 s did appear so far as being an appropriate value. Since the MV grid covers a quite large geographical area, it is not expected that voltage changes occur very fast. If required, the delay can be adjusted to 1 s or less. The LVR control also has implemented a high-speed return/high-speed raise tap-change operation without waiting for delay time for cases where large voltage changes occur. Further operation experience will help to further optimize the delay time, while still keeping the number of voltage steps at a minimum. The eclipse of the sun on March 20, 2015, and the fast returning of the sunshine and PV power did not create any special problem to the LVR.

SUMMARY AND CONCLUSIONS

Distribution grids are traditionally designed to scope with the expected power of the load, taking into account that not all customers require peak power at the same time. While in-feed of renewable generation is increasing, the peak power of the generation can easily become a multiple of the peak load and occurring simultaneously from all generators. Distribution grids are getting to their limits, especially in rural areas with long lines. In many cases the limiting factor is not the transmission capability as such, but compliance to stay within the allowed range around the nominal voltage.

A line voltage regulator can easily solve this problem. Such a device is able to adjust the voltage of a LV- or MV-line within a certain range to a desired value and avoids the need for costly grid extension. It is difficult to give a general advise on when grid extension or the installation of an LVR is more economical since costs for the extension depends much on the specific situation, like cable or overhead line, topography, crossing of roads, rivers, number and rating of secondary substations, etc.

A pilot installation of an 8 MVA LVR was realized in the 20 kV grid of Westnetz. The MV circuit has a length of 26 km, peak load is 3 MVA and maximum generation feed is close to 5 MVA. The analysis had shown that the installation of a LVR is a much better economical solution than a grid reinforcement. It was possible to realize the installation within a few month. The whole device is mounted in a concrete substation and can be relocated to a different side in case the requirements from the grid would change in future.

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