Increasing grid capacity to connect renewable energies

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ABSTRACT
Contrary to large centralized power plants, many of the renewable energy generators feed into the local distribution grid, either at LV, which is mostly for PV or at MV level, which is mostly for wind power. Traditional distribution grids are designed to cope with the existing and expected future power flow of connected consumer loads, but were not designed for decentralized infeed, which can sometimes be much higher than the load power. Especially in rural areas, generation of renewables can quickly exceed the planned load power by a factor of 2 to 3 but can be as much as a factor of 10. Instead of voltage drop along the electricity line from transformer to consumer, voltage increase occurs near the producer.

However, because generation is higher than the load power, the voltage rise can be very pronounced and exceed the allowed voltage band. This may result in the need to disconnect the generator. There are different solutions to the voltage rise problem, like grid extension or installation of a voltage regulator. Which solution is the most economically efficient depends on the specific case.

By using a line voltage regulator (LVR), the available voltage range is significantly increased and additional power can be fed into the grid without exceeding the allowed voltage range. LVR is able to automatically adjust the voltage of LV or MV line in the part of the grid subsequent to the LVR, within a certain range, to desired value and prevents the need for costly grid extensions. LVR can be installed in standard LV cable distribution cabinets or MV compact substation, completely mounted and tested. In both cases, LVR can easily be relocated and installed at another location if the situation in the grid is changing or further connection of generators requires a reinforcement of the grid.

KEYWORDS
Distribution Automation, line voltage regulator, distribution grid, voltage control, photovoltaic power generation, wind power generation, biogas power generation, small water power generation
INTRODUCTION

A high load on a medium or low voltage distribution grid causes a voltage drop along the line, especially in case of long radial lines. On the other hand, introduction of decentralized power production in distribution networks results in an increase of the voltage. This sounds like an ideal combination, but unfortunately load and generation are happening differently in time and location and to keep the voltage within a certain range becomes a real challenge.

Decentralized power production based on solar or wind power generation can easily become a multiple of the typical power rating of the load for which a distribution grid was originally designed. The voltage rise can therefore be very significant and require the generators to stop in-feed and to disconnect. Many countries have ambitious targets to increase the amount of renewable energies and voltage variation in the distribution grids will increase accordingly. For utilities in some countries as e.g. in Germany, this has already become a daily issue.

The European CENELEC standard EN 50160 [1] defines the requirements for the voltage in public distribution networks. Under normal operating conditions the voltage at the customer has to be within a range of +/-10% of the nominal voltage. In other regions, demands can be even more stringent. In the US for example, ANSI C84.1 [2] requires the utility to deliver power within the building’s service entrance within a range of +/-5% for low voltage and within -2.5% to +5% in case of medium voltage. NRS 048-2 [3] of South Africa requires that supply voltages <500 V do for 95% of the time not deviate more than +/-10% from the standard voltage and never more than +/-15%. For higher voltages the requirements are +/-5% and +/-10% respectively.

By introducing a line voltage regulator (LVR) into a power line, the voltage can be adjusted and it is possible to match the voltage requirements under all load and generation conditions. A line voltage regulator is a series element in a low voltage or medium voltage line, able to increase or decrease the voltage by a certain amount. It can be placed close to a distribution transformer or somewhere further down the line. LVRs are making distribution grids “smarter”.

The paper starts with presenting purpose and effect of a LVR in low and a medium voltage grids. It continues with presenting functionality and technology behind a LVR. The device is based on a feeder/booster concept, voltage regulation is step-wise and happens automatically. During the design, focus was put on achieving low losses and to allow simple and easy integration into the grid. Several examples of successful installation of a low and medium LVR in rural area are shown and described in details, including measurement data.

PURPOSE AND EFFECT OF LINE VOLTAGE REGULATOR

When considering today’s methods for the design of distribution grids it gets evident that low voltage and medium voltage levels are firmly coupled and individual network levels do not have the full voltage bandwidth available. The last transformer able to adjust the voltage is the HV/LV substation power transformer. The total voltage bandwidth must therefore be distributed between the subsequent medium and low voltage grids. This results in a reduced voltage available for voltage rise caused by the local generation or for voltage drop due to loads.

To increase this bandwidth a device is needed, which can modify the voltage and so decouple the operating voltage in a medium voltage line from HV/MV power transformer voltage and so increase the potential for power in-feed from distributed generation into the line [4].

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 medium voltage connection points of large photovoltaic and wind generation units. Positioning somewhere 1/3 to 2/3 down the line is often a good choice. Note that in case several medium voltage feeder lines are connected to the HV/MV power transformer, tap changing at this transformer will influence all medium voltage 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 1 shows that the introduction of a
A line voltage regulator in the medium voltage line allows to “recalibrate” the voltage and to increase the available voltage band according to EN50160 standard requirements. In this example the band is doubled.

**Figure 1: Available voltage bands in MV and LV grids**

The additional bandwidth in medium voltage grid can also be used to increase the voltage bandwidth for the low voltage grid (Figure 2). This eliminates the need for installing regulated distribution transformers (RDT). A single MV-LVR can therefore be installed in a medium voltage 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 2: Possible shifting of available voltage bands from MV to LV grids with MV-LVR**

By analogy to the application in the medium voltage grid, LVRs can also be used in the low voltage grid. In case of several low voltage 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.

Since various countries require the distribution system operator (DSO) to be able to take up all renewable generation, in situations like the above, the DSO needs to provide a solution. Grid extension, i.e. adding additional cables or overhead lines, is the most straightforward approach, but it is also very costly. In many cases, the current carrying capacity of the existing lines is not a limiting value, and the line is not thermally limited. In some cases use of reactive power can improve the situation and reduce the voltage.

The use of regulated MV/LV distribution transformers (RDT) is another solution. However as described before, there are a number of cases, where a RDT is not providing the required functionality of maintaining the voltage in the acceptable range for all the relevant nodes. This is the case, when the decentralized production is not homogeneously distributed in the grid. In many such cases a line voltage regulator (LVR) is able to solve the problem by regulating the voltage on a single branch. Which solution is economically most efficient depends on the specific case.

**FUNCTIONALITY OF A LINE VOLTAGE REGULATOR**

An LVR creates an additional voltage which is overlaid the existing line voltage $U_L$. The additional voltage $U_B$ can be additive or subtractive. The LVR therefore “recalibrates” the voltage in the part of the grid subsequent to the LVR. An LVR can be installed in a medium voltage or a low voltage line of the distribution grid. The respective effect on the voltage is shown in Figure 3. Note that voltage stays below the maximum voltage of 110%, EN 50160 standard.

Note that in case several medium voltage feeder lines are connected to the HV/MV power transformer, tap changing at this transformer will influence all medium voltage lines, whereas a LVR only regulates the specific line from which the problem arises.
This is important since load and in-feed can be very different on different lines. In case the LVR is installed in a medium voltage feeder line, the use of costly RDTs at transformer stations or of LVRs in the low voltage grid becomes unnecessary.

Figure 4 shows how the voltage bands are enlarged when a LVR is introduced. Dependent on the regulation range of the LVR, the additional range can be different from the one shown in Figure 4. Positioning the LVR somewhere 1/3 to 2/3 down the line is mostly the best choice.

TECHNOLOGY OF THE LINE VOLTAGE REGULATOR

Figure 5 shows the operations principle of an LVR installation. A variable voltage supply, fed by the line itself, creates a voltage $U_{RB}$, which is transmitted via a booster transformer ($U_B$) into the line, resulting in the regulated voltage $U_R = U_L +/- U_B$.

A transformer with on-load tap changer (OLTC) is used as variable voltage source. It allows to change the transformer voltage step-wise between zero and one hundred percent. The OLTC has a linear configuration and uses mechanical switches and resistors in his diverter. The switches of the OLTC allow up to 3 million mechanical operations without need for maintenance. Dry-type transformers of the RESIBLOC technology are used, eliminating any risk for fire or explosion. The variable voltage source is galvanically separated from the line. This feature makes the LVR equally suitable for usage in grounded, impedance-grounded, or insulated grids. On the other hand the ABB LVR does not create a galvanic separation of the regulated line and introduces a minimal additional impedance.
LVR contains additionally disconnecting and/or earthing switches at input and output side, sensors for the measurement of voltage and current, as well as a by-pass switch, which allows to completely shunt the LVR. The same functional principle is used for low and medium voltage grid.

Figure 3: MV-LVR (left) installed in a compact substation and LV-LVR (right) in a cabinet

LV-LVR can regulate the voltage for a transmitted power of up to 250 kVA (Figure 6). A more detailed description of its operation modes is given in [5]. The medium voltage LVR (MV-LVR) is mounted in compact substation (Figure 6). MV-LVR can regulate the voltage for a transmitted power up to 8 MVA and for voltage up to 24 kV. A more detailed description of the MV-LVR can be found in [6].

LVR is able to operate in a completely autonomous mode, or via remote or local control. 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 line.

EXPERIENCE WITH LOW VOLTAGE LVR INSTALLATION

In a rural area in Switzerland, an investor intended to rent the roof of two farmhouses for the installation of a photovoltaic power plant. The PV modules are providing a maximum power output of 134 kW. The farm is connected to the distribution transformer by a 250 m long 400 V cable. Several other customers are connected to the same transformer (Figure 7).

Figure 4: Grid situation and with PV plant and LV-LVR

Customer E is served by a second feeder from the distribution transformer. The peak load in this grid used to be in the order of 50 kVA and the grid was originally designed according to this requirement. The grid simulations performed by the utility company showed that when connecting the 134 kW PV installation, the requirements of EN50160 can no more be fulfilled and the voltage would exceed
110% of nominal voltage at customer B, and potentially also at customers A, C and D. On the other hand the investigation did also show that the cable does not have a thermal limitation.

A 250 kVA LV-LVR was therefore installed in the middle between distribution transformer and PV inverter (Figure 7). The LVR controls the voltage of customers A-D. The installation of a LVR was much less expensive than adding additional cables.

Figure 8: Active (top) and reactive (bottom) power measured at the LVR during 1 week. Negative values mean that power flows from the PV generator into the grid.

Figure 8 shows one minute values of active and reactive power at the location of the LVR measured during a one week period at the end of August 2014. The differences in the daily power profile represent mainly the different weather conditions: while August 23 and 25 were only partly sunny and on August 26 there was very little sun, on the other days the varying active power indicates that there was broken cloud cover. During night there is regularly a load of 20 kW getting connected. The lower curve shows how the PV inverter absorbs reactive power when high in-feed occurs.

Figure 9 shows the “in” voltage (towards transformer, non-regulated) and “out” voltage (towards PV, regulated) at the LVR. While the non-regulated voltage increases up to 434 V, the regulated voltage stays all the time in the range 400 - 409 V, according to the 1.2% voltage hysteresis. Note that without voltage regulation, the voltage at customer B respectively the PV inverter would well exceed 450 V.

Figure 9: Input and output voltage of phase-to-phase voltage U-V and step position of the line voltage regulator.
EXPERIENCE WITH MEDIUM VOLTAGE LVR INSTALLATION

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 a LVR are voltage conditions close to the limiting threshold values combined with a low current load of the power cable. 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/MV power transformers, will quickly reach their limits.

One of the most important influences is the length of the medium voltage line and should be noticed. 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.

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.

Figure 10: Input and output voltage of the line voltage regulator during a one week period

Figure 10 shows 15 minutes values of its input and output voltage. The set-point value for the voltage is $U=20.5$ kV. The MV-LVR output voltage stays within a voltage range of +/-1.5%, defined by the stepping hysteresis. The MV-LVR is in operation already a one year. The non-regulated voltage (input voltage) at the location of the LVR (km 10) already increases above 21 kV. Without a LVR, the voltage at the end of the line (km 26) would further increase significantly. Note that during the measurement period in February 2015 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.
SUMMARY AND CONCLUSION

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. 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. In case of long feeder lines and substantial loads, significant voltage drop can occur. A rather new phenomena is that with increasing amounts of renewable and decentralized power generation connected to the distribution grid, also large voltage rise occurs.

Rising voltages can become a major problem and limit the in-feed of renewables, although the cable or overhead line are far from their thermal capacity. A line voltage regulator recalibrates the voltage, and is able to handle both, large voltage drops and rises. The use of a LVR allows to increase the power which can be feed into an existing grid, without the need for a costly grid extension. Its installation is simple and fast.

The results presented from an LV-LVR installation in Switzerland, for adjusting the voltage rise caused by a PV plant, shows that the device works correctly and keeps the voltage well within the allowed voltage range.

A pilot installation of an 8 MVA MV-LVR was realized in the 20 kV grid of Westnetz. The medium voltage 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 more economical solution and significantly increases the connection capacity of generation power. It was possible to realize the installation within a few months. 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.

Presented installations successfully showed that utilization of a line voltage regulator can easily solve described grid demands. Such a device is able to adjust the voltage of a medium or low voltage 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 a 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.

BIBLIOGRAPHY

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