LINE VOLTAGE REGULATION IN LOW VOLTAGE GRIDS

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ABSTRACT

Despite volatile distributed energy resources and numerous variable loads, low voltage microgrids are required to ensure the permitted voltage range through an optimized operation and coordinated control. In order to resolve voltage violations, this paper presents a research on a novel line voltage regulator for distribution grids and microgrids which is characterized by a high degree of robustness and minimum side effects on power quality. The paper deals with its setup and features as well as its performance and influence on power quality, which is demonstrated by laboratory tests.

INTRODUCTION

Microgrids based on low-voltage AC often contain highly volatile distributed generation (DG), e.g. photovoltaics, and consumers with limited controllability. Maintaining the line voltage within the permitted range becomes a major limiting factor for the performance of these grids [1]. Reinforcement and extension of the grid are options, but typically require significant investments. An objective of a microgrid is to resolve the volatile impact of DG through an optimized operation and coordinated control [2]. In order to achieve an efficient supply and to resolve voltage violations, this paper presents a research on a novel line voltage regulator (LVR) as a part of the InLiNe[1] Project and carries on previous studies [3]. For LVRs various technologies can be used and, therefore, the common ones are briefly introduced in this paper. The voltage control of these common technologies is either robust but stepped or less robust although continuous. According to this study, a novel line voltage regulator is developed and established in the laboratory, which operates with a magnetically controlled inductor. This technology merges a continuous voltage control with a robust and cost-effective design. Additional requirements for the development are low maintenance costs, easy installation and parameterization, good interoperability with other grid devices and regulators as well as minimum side effects on power quality.

LINE VOLTAGE REGULATORS

An LVR appends an additional control voltage to the line by use of a series transformer. This additional voltage leads to rise or reduction of the line voltage. Figure 1 shows the voltage impact of an LVR along a feeder. Due to high distributed generation (Figure 1a)) or a high demand of power (Figure 1b)) there would be a voltage violation without further action. The LVR adjusts the line voltage to keep it in the permitted range. To vary the additional voltage, different technologies can be used and are briefly introduced in the following. However, what all technologies have in common is the use of one series transformer per phase to append the voltage and to enable an interruption-free operation even during switch-on and -off processes in the regulator.

Transformer Cascade

This LVR technology is characterized by a high degree of robustness. Its setup contains several series transformers. Their secondary circuit is connected in series with the line while their primary circuit is switched on or off according to the required regulation. The primary circuits are supplied by the line voltage and can be connected in phase or in opposite phase to rise or reduce the line voltage. To switch off a series transformer, the primary circuit is short-circuited. [4] [5]
Figure 2a) shows a possible setup for this LVR technology. The voltage control is always stepped whereby the step size is determined by the transformer ratio. Hence, for a wide control range with a low step size many devices are necessary. A combination of different suitable ratios can remedy to use less devices [6]. In [7] the operation of such an LVR technology is compared with grid reinforcements in a field test. In this case, the LVR technology amplifies flicker and unbalances.

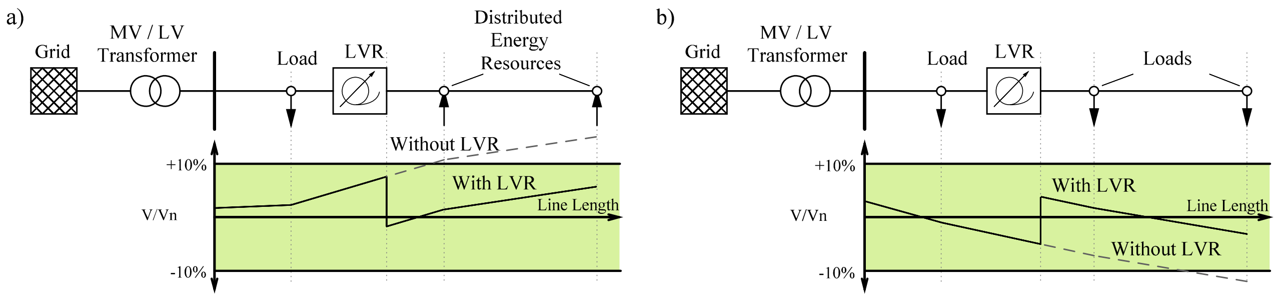

Figure 1 Operation Principles of an LVR   a) Voltage Reduction via the LVR   b) Voltage Rise via the LVR

1 The InLiNe Project is funded by the German Federal Ministry for Economic Affairs and Energy

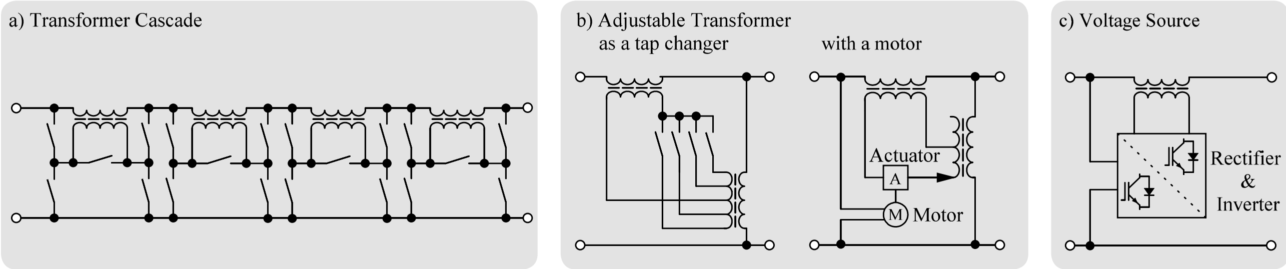

Figure 2 LVR Technologies a) Transformer Cascade b) Adjustable Transformer c) Voltage Source Technology

Adjustable Transformer

A possibility to reduce the number of devices is the use of adjustable transformers. They can replace the series transformer or are installed as a second transformer in the control circuit. The second version has the advantage that the adjustable transformer has to carry less current. An adjustable transformer can be built up as a tap changer [8] or with a motor and slip ring [9]. The second style enables a continuous control range, but makes the device also less robust, due to the mechanical elements. Thus, this style is not commonly used as an LVR, but as a voltage stabilizer at costumer's side, where a regular maintenance can be ensured. Figure 2b) shows two configurations of this technology.

Voltage Source Technology

Voltage source technology based on power electronic enables a quick control by a continuous control range. Therefore, in the first step, the supply voltage is rectified and in the next step, converted to the requested voltage by an inverter. [10] [11]
Figure 2c) shows a setup for an LVR based on this technology. This kind of regulator is a quite powerful device. However, the use of power electronic devices always contains a side effect of high frequency harmonics. Furthermore, the technology is less robust and even costly. Due to this and the high control speed, currently the application of this technology is rather at costumer's side for improving power quality. Nevertheless in [12] such kind of LVR is proved in a medium voltage (MV) grid for voltage adjustments.

A NOVEL LINE VOLTAGE REGULATOR

Two main requirements for an LVR are, on the one hand, a high robustness so that there is no maintenance needed while operating in an LV grid and, on the other hand, a minimum of side effects on power quality. By the LVR technologies mentioned above, it is striking that the technologies, which have a high level of robustness, only allow a stepped voltage control range. This causes side effects like voltage jumps and flicker. The LVR technologies, which enable a continuous voltage control, are conversely less robust. According to this, a novel line voltage regulator is developed and established in laboratory, which merges a continuous voltage control with a robust and cost-effective design. The requirements for the development are low maintenance costs, easy installation and parameterization, good interoperability with other grid devices and regulators as well as minimum side effects on power quality. The novel LVR operates with magnetically controlled inductors (MCIs) and is based on a first prototype presented in [3].

Setup and Features

The novel LVR consist of a series transformer (Tr_{Sr}), which appends an additional control voltage to the line and an inductive voltage divider in a control circuit, consisting of a pair of MCIs. Figure 3 shows the single-phase circuit of the LVR.

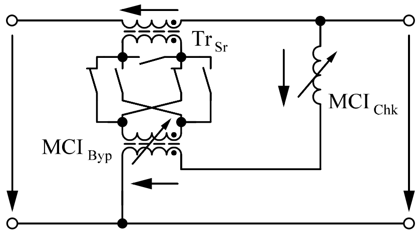

Figure 3 Single-Phase Circuit of the Novel LVR

The inductivity of the MCI's can be varied by a factor of approximately 300 by inducing an additional magnetic DC flux in the MCI core, causing a partial saturation of the magnetic core. The DC flux is generated by a current in a DC coil. MCI geometry and coil wiring are optimized to avoid coupling of AC to the DC coil. By variation of the DC currents in each MCI, the voltage divider ratio and thereby, the voltage appended by the series transformer can be controlled precisely. A typical control range is 0 % to 10 % of the input line voltage. Control of the output voltage is completely stepless - no flicker events are produced by the LVR. Further, with no moving parts, a maintenance-free design is achieved. Due to the series regulator principle, the power in the control circuitry is only a fraction of the power throughput of the LVR, which allows for compact and cost effective components and minimizes thermal losses. No active cooling is required. In a typical setup, a device controller is used to establish a control loop, which keeps the LVR output voltage within a predefined voltage range.
The LVR works independent of the direction of power flow in the LVR. A typical grid setup contains both en-

ergy consumers and energy producers on the feeder connected to the LVR output. The main application of the LVR is to compensate voltage drops on a line, caused by highly volatile producers (photovoltaics) and consumers (industrial & residential). The LVR is capable to step-up and step-down the voltage by means of a switching circuitry. In case of no voltage regulation demand, the control winding of the series transformer can be short-circuited, in order to minimize standby losses. The control speed is variable. A time constant of one second is achievable, but often not permitted in a specific grid setup. A single-phase control is possible, which is useful in grid environments facing volatile phase imbalances.
Summarizing, the features of the novel LVR are:

- Avoiding voltage band violations in LV grid branches, especially with bidirectional power flow
- Increasing the capacity of distribution grids / microgrids and reducing grid reinforcement efforts
- Continuous voltage control avoids voltage stepping and flicker phenomena
- Compensation of voltage unbalances

Performance and Influence on Power Quality

By means of laboratory measurements of the prototype its performance as well as its influence on power quality are analyzed and presented in the following.
First, the control performance of the LVR as a voltage booster is depicted. The buck operation acts similar to this. As already mentioned, the novel LVR appends an additional control voltage to the line with a continuous range of adjustment. Figure 4 shows this additional voltage depending on the DC control currents, which regulate the MCIs. The additional voltage is determined from the subtraction of the input voltage to the output voltage. If both MCIs are deactivated, it appears that there is a voltage drop across the series transformer caused by the line current (in this case 100 A by 230 V phase - neutral). However, the operation of the bypass MCI can compensate this voltage drop to a certain point. By reducing its inductance, the series transformer gets approximately short circuits and cannot effect the line any longer. By activating the choke MCI a continuous voltage boost up to 19V is achieved by a maximal DC control current of 1800 mA.

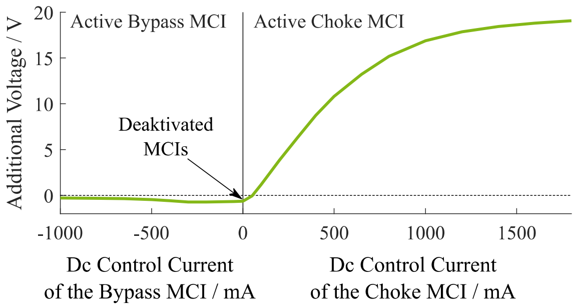

Figure 4 Operation Range of the novel LVR

Hereinafter the advantage of the bypass MCI is presented in more detail. Therefore, Figure 5 compares a switch-off process with and without bypass MCI during a line current of 140 A; meanwhile, the choke MCI is deactivated. It can be seen that without bypass MCI there is a voltage jump of 1,8 V when the primary side of the series transformer is switched to short circuit and thereby the series impedance of the transformer is rapidly eliminated. In contrast, by using the bypass MCI, the voltage can increase continuously up to 1,4 V and there is just a voltage jump of 0,4 V due to the short-circuiting of the primary side of the series transformer. So in this case the short-term flicker factor is always smaller (< 1) than the emission limits specified in IEC 61000-3-3 [14], whereas this does not apply to the case without bypass MCI.

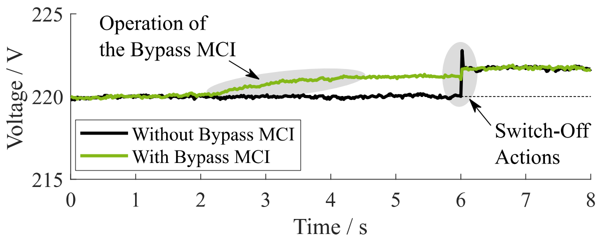

Figure 5 Switch-Off Operation With and Without Bypass MCI

Beside voltage jump, the additional impedance of the series transformer also increases the necessary short-circuit power of the grid. Due to that, the impedance needs to be as small as possible. However, it is a multi-objective optimization to find the balance between minimal impedance/inductance, maximal magnetic coupling as well as low size and costs. Moreover, this phenomenon occurs at all LVR technologies, as they all operate with a series transformer. The novel LVR operates with one autotransformer per phase, which is constructed as a toroidal core. The use of an air gap optimizes the saturation effects and inductance by a small size. Therefore, the maximal additional grid impedance created by the novel LVR is 0.01 Ω.
The previous presentation shows that all operation points and switching processes can be enabled in a continuous way, whereby side effects are avoided. Nevertheless, due to the saturation effects in the MCIs, the LVR generates harmonics. Although the LVR does not violate any standard (< 8 %)[15], summing up multiple emission sources can cause violations in grid operation. Therefore, the objective is to reduce the emission of harmonics. An analysis of the novel LVR in Figure 6 shows that the total harmonic distortion (THD) of the output voltage depends on the operation point of the MCIs. The maximal factor is 3 %, while the basic THD of the supply voltage varies between 1 % and 1,4 %. Figure 6 also shows the spectra for two exemplarily selected operation points, which show that especially the 3rd, 5th and 7th harmonic are pronounced.
The first improvement approach involves the connection of the primary side of the series transformer to a delta connection. This extinguishes the 3rd harmonic and multiples of it. However, by this a single-phase control is not

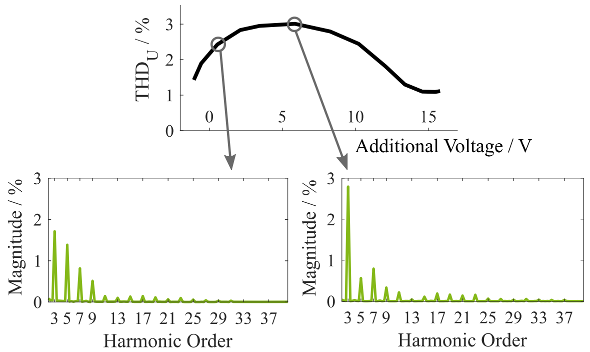

Figure 6 THD$_U$ and Two Exemplary Spectra Depending on the Operation Point

feasible. Another approach, which admittedly also restriction in the single-phase control, is the use of a three-phase-transformer as a series transformer. It is constructed as a three-legged core; hence, it also extinguishes the 3rd harmonic and multiples of it via the magnetic paths in the core. However, grid voltage balancing can be achieved by an additional delta winding. The last approach involves an interaction of the bypass MCI and the choke MCI. A control strategy is developed where both MCIs are active for voltage control and their interconnected operating range is optimized for a minimum THD. In Figure 7 the THDs of these approaches are compared with the THD of the starting prototype. It can be seen that the THD by a transformer with delta connected windings and by a three-phase transformer acts similar, since they both just extinguishes the 3rd harmonic and multiples of it. This effected especially the THD at higher additional control voltages. In contrast, by the THD-optimized control the THD at lower additional control voltages is effected more. In total, all approaches reduces the THD to less than 2.3% and are thus suitable for improving.

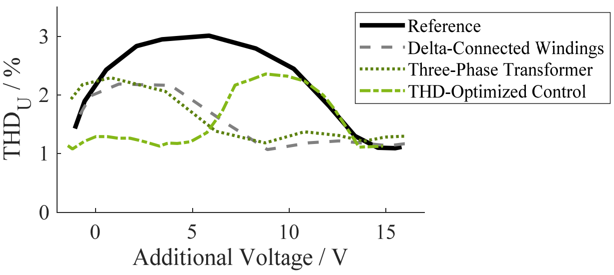

Figure 7 THD$_U$ of the Different Approaches

CONCLUSION

This paper dealt with the research of a novel LVR, which is distinguished by a high degree of robustness and minimum side effects on power quality due to a continuous voltage control. Since a single-phase control is possible, voltage unbalances can be compensated in addition to voltage fluctuations. The analysis of the laboratory tests shows the performance of the LVR and its advantages in terms of its influence on power quality. The continuous control range of the LVR is presented in the same way as its continuous switching-processes, so that no voltage jump occurs during the entire operation of the LVR, which can lead to flicker. Although the saturation behavior of the MCIs results in a slight harmonic distortion of the output voltage, this emission can be reduced by suitable optimization variants. Whereby the distortion factor is far below the factor forced in the norm. Therefore, it can be concluded that the novel LVR is regarded as excellent equipment for reducing voltage violations without causing any negative impact on power quality and thus increasing the capacity of distribution grids.

Further laboratory tests will concerned with another form of MCI, which is characterized by a more cost-efficient design. Additional, there will be a focus on the controller design and its dynamic investigation, since the control behavior of the LVR is not linear. Finally, a field test will carried out to examine the LVR under real conditions

REFERENCES

[1] García de Vicuña, Luis et al., 2015 "Voltage security in AC microgrids. A power flow-based approach considering droop-controlled inverters" *IET Renewable Power Generation,* vol. 9, 954–960.

[2] Dayi Li, Z. Q. Zhu, 2015 "A Novel Integrated Power Quality Controller for Microgrid", *IEEE Transaction on Industrial Electronics*, vol. 62, 2848-2858

[3] M. Holt, J. Maasmann, C. Rehtanz, 2017, "Line Voltage Regulator Based on Magnetic-Controlled Inductors for Low Voltage Grids", *CIRED, 24rd International Conference on Electricity Distribution*, Glasgow, 12-15 June, Paper 0207

[4] Walcher GmbH & Co. KG, 2011, "Voltage Regulator", Brochure, Germany; Download: http://www.walcher.com/en/products/power-transmission/voltage-regulators.html (22.02.2018)

[5] Eisenmann Thermal Solutions GmbH & Co. KG, 2016, "Nessy – Network Voltage Stabilisation System", Brochure, Germany; Download: https://www.ruhstrat.com/files/pdf1/Broschuere_NESSY_GB_04_2016_012.pdf (23.02.2018)

[6] A. Eberle GmbH & Co. KG, 2017, "Low voltage regulation system LVRSys", Data Sheet, Germany; Download: https://www.a-eberle.de/en/download-center-categories/datenbl%C3%A4tter-1 (22.02.2018)

[7] U. Wanner, M. Finkel, A. Aigner, 2011, "Technische und wirtschaftliche Betrachtung eines Netzregelgeräts im Vergleich zu einem Netzausbau aufgrund EEG", *Internationaler ETG-Kongress*, 8-9. November, Würzburg, Poster 15

[8] A.Eberle GmbH & Co. KG, 2013, "Schaltung zur Regelung und/oder Einstellung einer Wechselspannung", Patent Number: DE 10 2012 010 115 A1 2013.11.28

[9] Eisenmann Thermal Solutions GmbH & Co. KG, 2017, "Voltage Optimization – For Industry, Trade, Business and Local Networks", Brochure, Germany; Download: https://www.ruhstrat.com/files/pdf1/Brochure_Voltage_Optimization_GB_04_2017_011.pdf (23.02.2018)

[10] S. Kempen, 2013, "Voltage Control in Distribution Grids", *ECPE Workshop*, 12-13 March, Kassel Germany, Presentation, https://www.aegps.com/en/products/product-archive/thyrobox-vr/ (22.02.2018)

[11] Eisenmann Thermal Solutions GmbH & Co. KG, 2017, "Oliver – Online Voltage Regulation", Brochure, Germany; Download: https://www.ruhstrat.com/files/pdf1/Brochure_OLIVER_GB_08_2017_012.pdf (23.02.2018)

[12] Martin Carlen, 2015, "Line Voltage Regulator for voltage adjustment in MV-grids", *CIRED, 23rd International Conference on Electricity Distribution*, Lyon,15-18 June, Paper 1230

[14] IEC 61000-3-3, 2013, "Electromagnetic compatibility (EMC) – Part 3-3"

[15] EN-50160, 2011, "Voltage characteristics of electricity supplied by public distribution networks"