# ASSESSING THE COMBINATION AND COORDINATION OF VOLTAGE CONTROL APPLICATIONS IN LV NETWORKS WITH SMART GRID METRICS

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## ABSTRACT

*In Germany, the enormous growth of distributed generation (DG), in particular from photovoltaic (PV) panels, pushes the low voltage (LV) networks to their limits. Over-voltages in LV networks limit the further absorption of DG, especially in rural and suburban areas. Several voltage control (VC) applications can be implemented to solve these issues. These VC applications can be further combined or even coordinated with the help of information and communication technology (ICT) to improve the control effect. This paper focusses on the combination and coordination of these VC applications. The control effects are evaluated are evaluated for a wide range of artificial synthetic LV networks. The assessment is made with the help of the Smart Grid Metrics framework (SGM).*

## INTRODUCTION

The absorption capacity of DG in rural and suburban LV networks is mostly limited due to possible over-voltages. In contrast to thermal overloads which can only be solved by storage, curtailment or network extension, advanced and relatively affordable technologies are available to maintain the voltage magnitude [1, 2]. The project LISA (Leitfaden zur Integration Spannungsstabilisierender Applikationen) aims at providing a guideline for the integration of VC applications in LV networks [3, 4]. The aim of this project is not only to investigate the various VC concepts but also to systematically examine application options in various LV networks. The project results will be summarized into a guideline for the implementation of different VC options. This guideline shall provide the distribution system operators with optimal solutions in both technical and economic aspects without the necessity of high-effort analysis. The guideline shall also provide suggestions to the equipment and controller manufacturers for their future development including the control concepts. In [3, 4], the simulation results of different VC schemes for various applications are presented and analyzed. The next step now is to investigate the interaction between the different VC schemes and technologies. Different combinations of VC applications are investigated with and without control coordination for different network situations. All costs of the investigated options are estimated and summarized and the results are assessed by the SGM [5] for a quantitative cost-benefit analysis.

## VOLTAGE CONTROL CONCEPTS

The VC applications in LV networks can be divided into two main categories: direct voltage regulation (DVR) and reactive power management (RPM). DVR includes transformers with on-load tap-changers (OLTC) and electric voltage regulators (EVR). RPM includes PV-inverters and reactive power compensation equipment (RPCE). The OLTC is installed at the distribution transformer. It decouples the voltage magnitude of LV networks from MV networks. The EVR is set up just behind the distribution transformer or at the distribution feeders. Both the OLTC and the EVR are not only able to decrease the voltage but also to raise the voltage during heavy load conditions. The reactive power can be managed by PV-inverters at the end users' side or with RPCE in the LV networks. The control concepts are essential for the stable operation of the voltage regulation equipment. Various control schemes are designed and tested and the results are given in [3, 4].

### Without Communication

As presented in [3, 4], the VC concepts without communication are shown in Table I.

TABLE I. VOLTAGE CONTROL WITHOUT COMMUNICATION [3,4]

| **Voltage Control** | **Without Communication** | |
|---|---|---|
| | **Without Measurement** | **Local Measurement** |
| **Inverter** | (1) **fixed cos(φ)** | (2) **cos(φ) (P)**, (3) **Q (U)** |
| **OLTC** | - | (4) Local voltage - $\mathbf{U_{local}}$,<br>(5) Power-dependent estimated voltage with tranformer measurement- $\mathbf{U_E(U_{local}, P_{local})}$,<br>(6)Power-dependent estimated voltage with feeder measurement - $\mathbf{U_E(U_{local}, P_{feeder})}$,<br>(7) Power-dependent characteristic line - $\mathbf{U_c(U_{local}, P_{local})}$,<br>(8) Solar-dependent set-point voltage - $\mathbf{U_E(U_{local}, G)}$ |
| **EVR** | | (9) Local voltage - $\mathbf{U_{local}}$,<br>(10) Power-dependent estimated voltage - $\mathbf{U_E(U_{local}, P_{local})}$,<br>(11) Power-dependent characteristic line - $\mathbf{U_c(U_{local}, P_{local})}$,<br>(12) Solar-dependent set-point voltage - $\mathbf{U_E(U_{local}, G)}$ |
| **RPCE** | | (13) **Q (U)** with steps |

The PV-inverters can be set to a fixed power factor. This VC concept requires no measurement and is the simplest concept considered. In order to reduce the consumed reactive power at PV-inverters, the power factor or the reactive power can be adjusted according to a cos$\varphi$(P) or a Q(U) characteristic line by using local measurements. Similar concepts can be applied to RPCE but only the Q(U) characteristic line with steps is investigated. With respect to DVR, set points according to local voltage [$U_{local}$], power-dependent estimated voltage [$U_E(U_{local}, P_{local})$], power-dependent characteristic line [$U_c(U_{local}, P_{local})$] and solar radiation [$U_E(U_{local}, G)$] can be implemented with local measurements only.

## With Communication

The price reduction in ICT and the rollout of smart meters enable communication for VC concepts. According to Table II, these concepts can be divided into unidirectional or bidirectional communications. OLTC and EVR receive the measured data from the last household [$U_{end}$] or all households to regulate the voltage. A coordination of components is possible if bidirectional communication is available. By optimizing the reactive power of PV-inverters network losses can be reduced. If the communication system is extended to the medium voltage (MV) networks, it is even possible to coordinate the components in MV and LV networks.

TABLE II. VOLTAGE CONTROL WITH COMMUNICATION

| Voltage Control | With Communication | | |
|---|---|---|---|
| | Unidirectional (from Remote Node) | Bidirectional (Coordination) | |
| | Remote + Local Measurement | Remote + Local Measurement | |
| Inverter | - | (14) Q-Optimal | Coordination of components in MV and LV networks |
| OLTC | (15) Data from last household - $U_{end}$<br>(16) Data from all households - $U_{all}$ | Coordination of VC applications in LV networks | |
| EVR | (17) Data from last household - $U_{end}$<br>(18) Data from all households - $U_{all}$ | | |
| RPCE | - | | |

## Voltage Control Coordination

In some networks, a combination of different options may be necessary. New installed PVs in distribution networks in Germany have to be able to consume reactive power according to [6, 7]. However, considering a further increase of PV feed-in in LV networks, when RPM by PV-inverters alone can no longer solve the over-voltage problems, a combination with OLTC and EVR are supposed to be the potential solution. In this case it is necessary to find suitable control concepts to improve the regulation effect for the combination of the different measures. Thanks to the price reduction in ICT, even coordinated control concepts with bidirectional communication might be feasible in the future. With regard to the simulation results from [3, 4], three combinations (OLTC and EVR, OLTC and PV-inverter, EVR and PV-inverter) are selected to investigate the VC coordination. Fig. 1 to 3 present their working principles. Fig. 1 shows a combination of an OLTC and an EVR in a LV network. The operation of the OLTC and the EVR is coordinated to avoid any negative interactions. The dotted lines represent the communication paths. The OLTC receives the measured data not only from the MV/LV transformer but also from the feeders. The data from feeders without EVR are collected at the end of the feeder. The data from feeders with EVR are collected at the node in front of the EVR. The EVR receives measured data from the end of the feeder. The OLTC acts as the control master and it works first to control the voltage. After the OLTC cannot further control the voltage, a start signal is sent from the OLTC to the standby EVR. Then EVR then starts to regulate the voltage at its respective feeder according to the local and remote measured data.

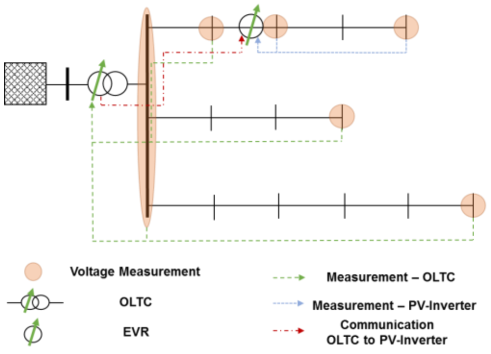

Figure 1 OLTC and EVR Coordination

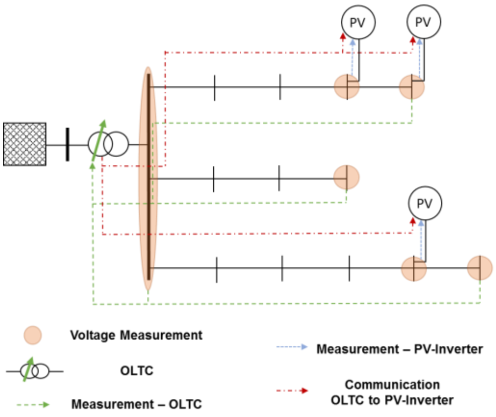

Figure 2 OLTC and PV-Inverter Coordination

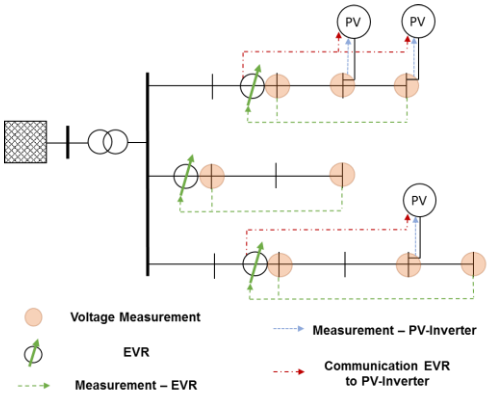

Figure 3 EVR and PV-inverter Coordination

Fig. 2 shows the coordination of an OLTC and several PV-inverters. The OLTC receives the local measured data and remote measured data from the end of the feeders. The PV-inverters collect only the local measured data. The OLTC is the control master and operates in the same way as in Fig. 1. If the OLTC cannot further control the voltage, the start signals are sent from the OLTC to the PV-inverters. The PV-inverters are required to consume inductive reactive power according to their Q(U) characteristics. In order to reduce the power losses from the additional reactive power in the network the PV-inverters are activated one by one starting from the end of the feeders. Fig. 3 illustrates the coordination of an EVR and PV-inverters. The working principle is similar to Fig. 2 but the EVR works as the control master. The EVRs coordinate only with the PV-inverters connected to the same feeders.

## APPROACH

In order to assess the combination and coordination of voltage control applications, the time-series power flow simulation technique (PFS) is applied. Fig. 4 illustrates the approach. The Monte Carlo method is used to generate probabilistic load curves and PV in-feed curves. The synthetic LV networks are modeled according to the settlement structures [8-10]. The combination and coordination of voltage control options are implemented into the synthetic LV networks and PV feed-ins to run the time-series PFS again. The SGM is used to compare the effectiveness of the combination and coordination of voltage control options. Both capital and operating cost are calculated as input for the cost/benefit analysis.

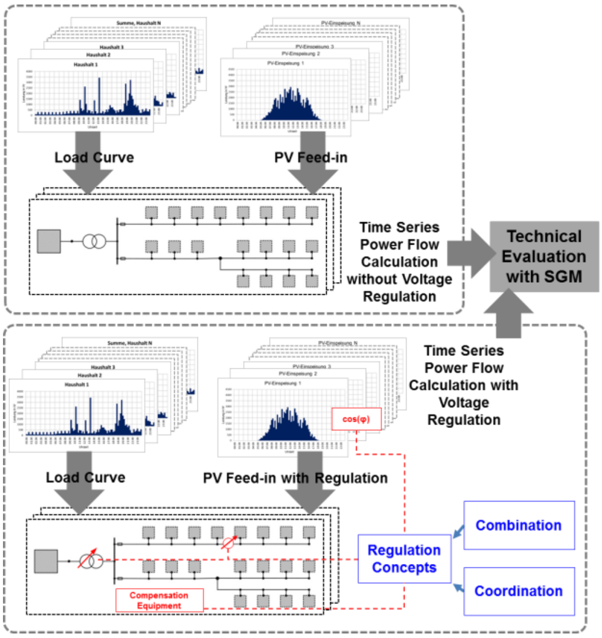

Figure 4 Approach of Assessment

## SYSTEM MODELS

The synthesis of household load curves with a bottom-up approach is widely applied to model the residential load from electricity consumption data or metering data. A probabilistic synthetic residential load model is applied based on domestic appliances [8-10]. The synthesis of PV feed-in curves is based on two models: the solar intensity model and the PV system model. PV systems show dominant daily generation patterns depending further on the season and short-term effects induced by clouds and other weather phenomena. A detailed explanation of the modelling approach can be found in [8-10]. LV networks reflect local settlement conditions. The settlement structure (SS) has a big influence not only on the network structure but also on the parameters of the LV networks. A set of synthetic LV networks based on settlement structures is used [8-10]. Table III shows a part of the SS types and the number of their service connections and households. For each SS, three further variants exist representing the spatial size of the networks. For SS2a, SS2b and SS3a, there are both overhead line (OHL) and cable networks.

TABLE III. SYNTHETIC LV NETWORKS

| Region | SS | Name | SC | HH |
|---|---|---|---|---|
| **Rural area** | 1a | Dispersed with individual house | 18 | 18 |
| | 1b | Dispersed with house cluster | 30 | 30 |
| | 2a | Linear town center | 80 | 80 |
| | 2b | Crossed town center | 100 | 100 |
| **Sub-urban** | 3a | Detached one-family house | 162 | 162 |
| | 3b | Detached two-family house | 108 | 216 |
| | 4a | Attached duplex house | 180 | 180 |
| | 4b | Attached row house | 162 | 162 |

## SIMULATION AND RESULTS

The worst-case PFS is carried out to select the synthetic LV networks with over-voltage problems and the optimum position of the EVRs in the networks [3, 4]. For the time-series simulation the maximum size networks for SS1a to SS3a including the OHL and cable variants are selected. PV penetrations from scenarios 2015 and 2035 are used with both homogeneous and inhomogeneous PV distributions to cover normal and extreme PV feed-in situations [3, 4]. In order to simulate the maximum influence from the MV network, two variants (102 % and 107 % of the nominal voltage) are applied for the voltage at the high voltage side of the MV/LV transformers. The individual VC measures according to Table I, as well as their combinations and coordination according to Table II are investigated.

For results analysis, the total over-voltage time per year is utilized and translated into SGM benefit points. The SGM benefit points for the over-voltage relieve targets are calibrated linearly to a scale from 0 to 10, where 0 marks the over-voltage duration without VC and 10 marks zero over-voltage hours. Both capital and operational cost are calculated as an input for the cost/benefit analysis. Capital costs are put into two categories: VC equipment and ICT devices. The operational costs include the ICT operational cost and the annual maintenance cost [11]. For cost comparison, annuities are calculated using the net present value calculation for a 20 year time horizon. The interest rate is set to 6 % per year. In order to present the cost/benefit analysis intuitively, the benefits and costs of the VC options are shown in Fig. 5 to 7. Only parts of the results are presented here due to the limit of the paper space.

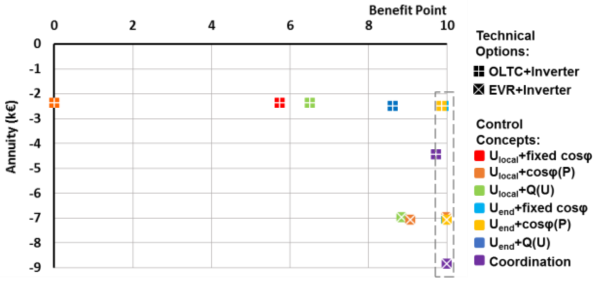

Figure 5 SGM for SS3a OHL, 2035, inhomogeneous, 102 % $U_n$

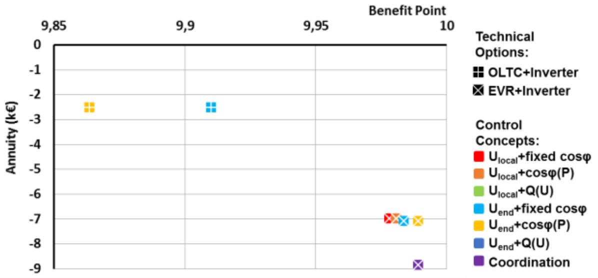

Figure 6 Detail from Fig. 5

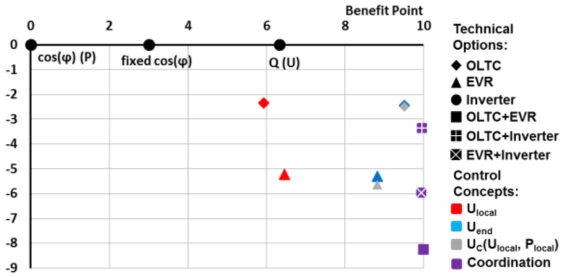

Figure 7 SGM for SS2a OHL, 2035, inhomogeneous, 107 % $U_n$

Fig. 5 shows SS3a with OHL, scenario 2035, inhomogeneous PV distribution and the MV set to 102 % $U_n$. The different label shapes represent the technical options and the colors indicate the types of control concepts, e.g. a red square plus means a combination of OLTC with the local VC concept and the RPM with a fixed cos*φ*, a green square cross means the combination of OLTC with voltage measurement from the most distant household and RPM with Q(U) control. The coordination options shown in purple represent the DVR options coordinated with Q(U) RPM. Both coordination options show an improvement of the benefit points compared to the combination options. However, they have higher investments in ICT. Fig. 6 shows the dashed area in Fig. 5 in more detail. The combination of EVRs and PV-inverters generally provides better technical performance than the combination of OLTC and PV-inverters, but the annuities are almost three times higher. Fig. 7 shows the results for SS2a with OHL, scenario 2035, and the MV set to 107 % $U_n$. In this extreme scenario it is not possible to solve the over-voltage problems with only PV-inverters. PV-inverters with Q(U) show better benefit points than fixed cos*φ* and cos*φ*(P). Using OLTC leads to better benefits than EVR in this scenario. The coordination options can further improve the benefit of VC and all over-voltages can be solved.

## CONCLUSION

In this paper, a time-series PFS is used to compare the combination and coordination of different VC options in the LV networks. Comparing to the individual measures the reasonable combinations of measures are able to improve the control effects and the coordination can solve almost all over-voltages even for extreme scenarios. Therefore, VC with coordination are recommended for networks with extreme situations. For future research, the dynamic behavior of the regulation concepts will be investigated. Furthermore, the effects of VC on a real LV network will be assessed in a field test.

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