ANALYSIS OF LOW VOLTAGE NETWORKS WITH HIGH DISTRIBUTED POWER GENERATION

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ABSTRACT

Nowadays the operational limits of existing power distribution networks are likely to be reached due to the strong and increasing integration of renewable generation facilities. Conservative solutions for the upcoming but also for the existing situations in low voltage (LV) grids, which are mostly given by overloads of the network components or by exceeding the predefined voltage levels in some nodes of LV grids, are network development and reinforcement. For the network planning only extreme scenarios with principally very low occurrence probabilities are considered. Therefore such a solution is primarily not justified economically. For that reason some further opportunities for voltage and load control have to be investigated theoretically and practically.

Voltage control, active (P) and reactive (Q) power management by means of different kinds of storage components and their integration in real networks, as well as a realization of a real-time measurement and control system are some of the key subjects of interest in an EU-supported smart grid project called "Smart Grid Solar"(SGS). In this paper network analyses within the frame of this project have been carried out. The focus is on the voltage and load behaviour in LV networks with a remarkable share of photovoltaics (PV), possible solutions for voltage control and P/Q-management. Moreover, the most attention will be directed at voltage control by a storage device that was dimensioned and located especially for this purpose in a real LV network.

INTRODUCTION

The existing electrical power distribution networks were primarily designed to realize a power flow from the central power plants to the end consumers. The always increasing integration of renewable energies confronts network operators with new challenges, e.g. in the LV grids in terms of the reversal of the power flow and the associated rise of voltage.

Differing to traditional power plants, the electrical energy generated by photovoltaic or wind turbines is defined by various nonmanipulable factors (e.g. season, time of day, weather conditions, etc.) that allow only limited controllability and cannot be used to ensure the base load. Moreover, a high feed in LV networks, e.g. by PV-systems during times of high solar irradiation, and concurrently low load can lead to a reversal of the load flow compared to the original planning of the network, resulting in two major problems: higher loads of the components and exceeding of the voltage limits.

Although an overload of the power equipment that can occur in LV as well as in MV networks is not so common and thus not the primary problem, high currents can lead to accelerated aging of the equipment. Then again an increase of the voltage due to the reverse power flow is an already well known problem that could lead to further complications. Besides the standard regulations of valid voltage limits of 207V-253V in LV networks (DIN EN 50160), there is also a recommendation of the Association for Electrical, Electronic & Information Technologies in Germany (VDE-AR-N 4105) defining a maximal permissible voltage increase of 3% in LV network due to the particular installed PV-System.

Keeping the voltage within these limits also has to be ensured with further integration of renewables with the goal to cover 50% of the total electricity demand of Bavaria (Germany). Furthermore higher loads of the equipment and the reduction of the equipment lifetime is of great economic importance.

With this background an EU supported project "Smart Grid Solar" (SGS) has been initiated, researching the implementation of both technically and economically optimized solutions for network planning and development, the integration of renewable energy sources, but also other novel components such as intelligent and effective integration of storage units.

RESEARCH ON SMART GRIDS

In order to provide important system services (such as power reserves, voltage and frequency regulation) in an optimal infrastructure and for power networks with a significant number of renewable sources and energy consumption in 2050, it is primary necessary to address requirements for LV networks. Therefore the main technical aspects in the project SGS concern network topology and structure, communication structure (needed data, number of measurement units – network nodes, measurement locations and frequency), predictions of PV-feed and consumption profiles based on weather forecast and empirical values, predictions of the network state as well as regulation and control of generation and consumption such as storage units (central or distributed) or other available and controllable network components, etc.

Network Analysis & Network Management

In the main working group of SGS called "network analysis and network management" real LV networks (urban and rural) with high PV-power will be analysed on the basis of network simulation, network models and measurements to allow a better planning of the smart grids and to optimize the total system. Besides control of the power flow and voltage levels, also local use of fluctuating renewable energy will be analysed.

Moreover, a measurement system for online data acquisition is positioned in preselected low- and medium-voltage network nodes, at defined households as well as in power equipment nodes (e.g. transformers, storage units, etc.).

The three-phase measurements of voltage, current and cosφ will be carried out simultaneously in a 15 s cycle (1s cycle on power equipment) including measurement on total harmonic distortion. Such a system enables analyses of available methods or the development of novel approaches for optimisation of the network state estimation and prediction, of approaches for network regulation, but also optimization of the positioning of the LV measurement equipment and simultaneously minimisation of the needed number of measurement units.

One of the basic problems concerning state estimation in distribution grids compared to the transmission system is the lack of measurement nodes. Due to the high costs of measurement devices and high number of nodes in LV networks, one of the tasks is to find the minimum necessary number of devices and their optimal position within a given network to enable a reliable state estimation.

In the first step measurement devices will be located in all available network nodes. Besides the validation of the developed network models, it is therefore also possible to analyse measurement placement methods. The goal is to find the minimal necessary number of measurement units dependent on the distribution in the network and network structure (topology) to ensure the demanded maximal estimate error at all nodes, as it is suggested in e.g. [1].

Options for Voltage Regulation

Due to the structure of LV and especially networks in rural areas with high PV-feed there is a higher risk of exceeding the voltage limits. In one of the example networks of this study, the problem of keeping the voltage within the permissible voltage range already occurs today. In this certain case, the stabilization of the voltage will be regulated by a central energy-storage unit that has been dimensioned for this particular network.

To understand the influence of active and reactive power management on the voltage, simplified calculations based on the circuit shown in figure 1 are described. The corresponding vector diagram is presented in figure 2.

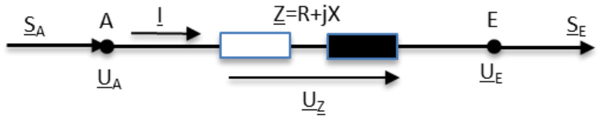

Figure 1. Simplified network for voltage calculation of an electrical line

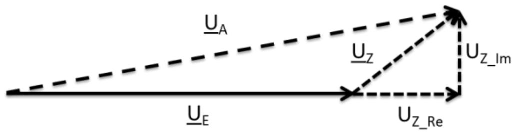

Figure 2. Vector diagram for load flow from *A* to *E* in network shown in figure 1

For the calculation, the voltage at node *E* concurs with the real axis and a load flow from node *A* to node *E* is assumed. The correlation of the voltages at *A* and *E*, is described by equation 1:

$$\underline{U}_A = U_E + \frac{P_E R + Q_E X}{U_E} + j\frac{P_E X - Q_E R}{U_E} \quad [1]$$

where are: $\underline{U}_A$ = complex voltage at node *A* (start of the regarded line); $\underline{U}_E$ = real part of voltage at node E (U_{E_Im} = 0V); P_E = active power flowing from *A* to *E*; Q_E = reactive power flowing from *A* to *E*; *R* and *X*= resistance and reactance of line *A*-*E* respectively.

In this equation, the second and third addends represent the real and imaginary part of $\underline{U}_Z$ ($\underline{U}_{Z\_Re}$ and $\underline{U}_{Z\_Im}$ in figure 2). It can be seen, that $\underline{U}_Z$ depends on the load flow as well as on the impedance. Assuming a load flow according to figure 1, figure 2 shows an increased voltage at node *A* compared to $\underline{U}_E$. By active and reactive power management the voltage can be influenced by changing the load flow $\underline{S}_E$.

Because of the usually high *R*/*X* ration in LV networks, reactive power management does not have such an influence on the voltage level as active power control, as confirmed in [2]. Anyhow, by reached limits of the storage unit for active power management, regulation of the voltage could be still achieved by reactive power management in some cases.

It has to be noted that voltage regulation by reactive power management also means an increased stress of cables and transformers caused by higher currents. Active power management on the other hand lowers the stress of the equipment, as will be shown later in this paper.

A further and essential question is the positioning of the storage unit. The selection of the most suitable location of the storage unit is dependent of its purpose. For example, if used to enhance self-consumption of a local area, it should be placed at the transformer station. Or in another case for regulating a voltage in a critical node, it is recommended to position the storage unit as close as possible to the critical voltage node within the network or at the end of a critical power line.

In addition to the central unit also distributed storage units can be used to increase the self-consumption of a household, in this way minimizing the network load and load reversal.

SIMULATION OF VOLTAGE REGULATION BY CENTRAL STORAGE UNITS

To illustrate the voltage regulation by active and reactive power management, the operation of a storage unit in a real network will be shown in the following.

The considered subnetwork is shown in figure 3, where node E is the end of the main line while A is the LV busbar of the transformer. PV-facilities are connected by supply lines to node numbers 5a, 5, 4, 3 and 7, where the largest one is connected at number 5 (highlighted in fig. 3). Five more PV-facilities are connected to node A. Those are not shown in the figure 3 but are considered in the following calculations.

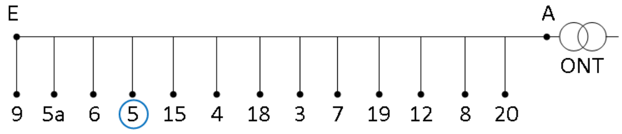

Figure 3. Simplified illustration of the main line (A-E) and house connections of a real LV network

Stationary considerations in real LV-grid

In order to identify the critical nodes or lines in the network, a stationary calculation has been carried out.

For calculating the worst-case-scenario, the minimal load of 172,4 W is assumed for all households, [3]. Simultaneously, it is assumed that the PV-facilities feed into the grid with maximum power of 100 %. Moreover, for more realistic results, especially for calculations with load and generation profiles, 85 % of the installed power can be assumed, [4].

The results of the worst-case study show that critical voltages (>103 % U_n) occur for both cases (85 % and 100 % PV feed) at the end of the main line (E) and at house connection 5, as shown in table 1. The voltage increases of the other nodes are presented in figure 7 for 85 % of PV-feed.

Table 1. Rise of voltage at node 5 and node E for stationary calculations

Node	PV-feed P/P_{inst} [%]	Voltage increase U/U_n [%]
5	85	104,5
E		103,28
5	100	105,26
E		103,84

In order to control the voltage, a central storage unit is placed in the network. Considered locations are node 5 or node E, in both cases with the goal of lowering the voltage level at critical node 5 to a maximum of 103 % U_n. The necessary power of such a storage device for P- or Q-management at the stationary operating point (worst-case) is presented in table 2.

Table 2. Necessary power of a storage device for reducing the voltage to the valid level by P/Q-control

PV-feed P/P_{inst} [%]	Installation node	Storage (P-Control) [kW]	Storage (Q-Control) [kVar]
85	5	25,5	58,7
	E	42,3	66,6
100	5	38,8	87,1
	E	64,2	99,1

The results show that a higher power is needed at node E to lower the voltage at house 5 to the same level. Furthermore it becomes clear that higher values are necessary for voltage reduction by reactive power management.

Dimensioning of the Local Storage Unit

The calculations for the stationary operating point are the basics for further considerations using load and generation profiles. To get realistic results for the storage units the maximal PV-power is assumed to be 85 % of the installed power. Generation profiles for the PV-facilities for 24 h of a sunny day have been created using the software PVSyst 6.1.2 and can be seen in figure 4.

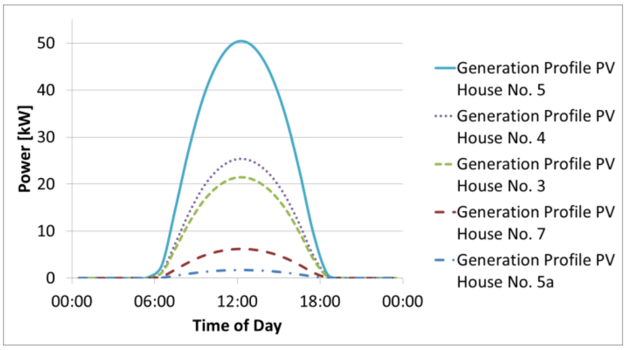

Figure 4. Generation profiles of all PV-devices of the main line on a sunny and cloudless day

With these assumptions voltages at the nodes over a period of 24 h can be calculated. Additionally the power flow from the main line to the MV grid can be generated, which, together with the stationary consideration, provides the base for estimating load profiles of storage units for voltage regulation by active or reactive power management.

Voltage control by Active and Reactive Power management of a local storage unit

With the knowledge of the maximum power of the storage devices (table 1) and of the power flow to the MV grid, the load profiles for active power control of storage units placed at node 5 or node E that are necessary to keep the voltage within the predefined limits (103 % U/U_n in the critical period from 9 a.m. to 3:30 p.m.) at all nodes can be determined (figure 5). In the following the charge profiles of the storage units are defined by the voltage level at the critical node 5.

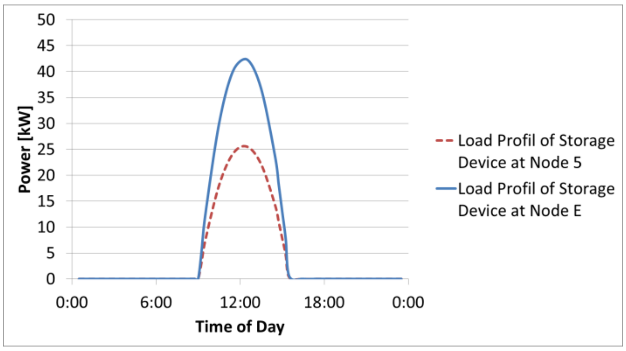

Figure 5. Load profile of a storage device connected to node 5 or node E for reduction of voltage at node 5

For power management a storage device with a capacity of 108 kWh or 181 kWh, placed at the critical node 5 or at the end of line (E) respectively, is needed to provide voltage control over a period of 24 h.

Figures 6 and 8 show the voltage curves at the two regarded nodes over the period of 24 h with and without operating storage devices (P- and Q-control respectively) located at the given nodes 5 or E.

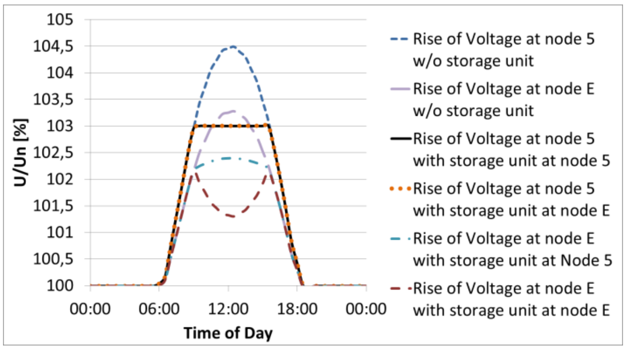

Figure 6. Comparison of the voltages with and without storage unit (P-Control) connected to node 5 or node E

It can be seen in figure 6 that for both possible locations of the storage unit the voltage at node 5 remains constantly on the desired 103% U/U_n within the critical time interval while the voltage at node *E* is below that value. As it can be expected the voltage at node *E* is lower in case of applying active power management at the end of the main line compared to an application directly at node 5.

The effect of the P-management, voltage reduction to 103 % U/U_n at node 5 (for given network at the time of the highest PV-feed), is shown in figure 7. It can be noted that by positioning the storage unit at node *E* and P-management the voltage level in the complete main line is reduced.

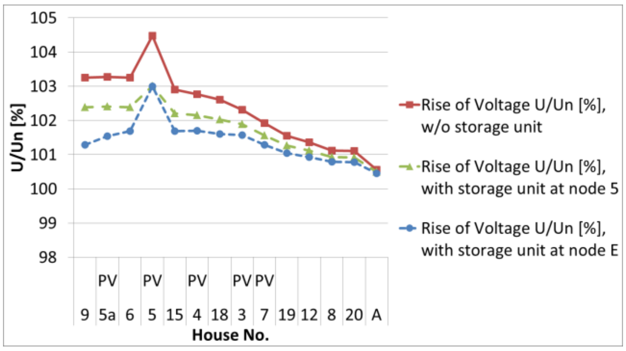

Figure 7. Voltage increase along the main line without storage unit as well as with storage unit at node 5 and at the end of line E

Accordingly, the voltage curves shown in figure 8 for reactive power management closely resemble the results for active power control seen in figure 6. While the voltage curves at node 5 are almost identical, a difference can be seen in the voltage curves for node *E* with storage unit at node 5. Due to the higher R/X ratio of the supply line of node #5 compared to the cables of the main line, the supply line's length specific voltage drop is lower when using Q-management. In order to keep the voltage at node 5 constant at 103% U/U_n by Q-management, the voltage in the complete main line has to be reduced more compared to P-management.

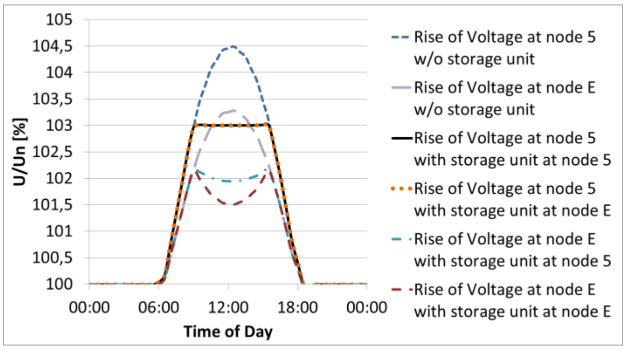

Figure 8. Comparison of the voltages with and without storage device (Q-control) connected to node 5 or node E

As already mentioned, voltage regulations by P- and Q-management change the currents of the network and therefore the thermal stress of the power equipment. Table 3 and table 4 show the values of the currents (at the beginning of the main line and in the supply line of house #5) rated to the thermal limit I_b of the given cables.

Concerning the stress of the given cable lines, it can be concluded that differing to P-management the effect of voltage reduction by Q-management is an increase of apparent power of the network and therefore increased stress of power equipment. Furthermore, the necessary reactive power has to be covered by the MV grid.

Table 3. Comparison of currents in the main line and the supply line of house 5 with and without P-Control

	I/I_b w/o storage device [%]	I/I_b P-Control at node E [%]	I/I_b P-Control at node 5 [%]
main line	52,33	31,1	39,88
supply line of house 5	52,12	52,88	26,01

Table 4. Comparison of currents in the main line and the supply line of house 5 with and without Q-Control

	I/I_b w/o storage device [%]	I/I_b Q-Control at node E [%]	I/I_b Q-Control at node 5 [%]
main line	52,33	62,97	60,6
supply line of house 5	52,12	52,88	81,44

Combined use of storage devices for voltage control and self-consumption

Besides voltage control, an additional task for storage devices is increasing of self-consumption. To cover the demand of all households in the local network over 24 h, the storage device is filled while an oversupply of PV-power is available. Simultaneously it has to be ensured, that enough capacity is left to implement voltage control. The load and generation profiles at node 5 and E of a storage unit assuming 85 % PV-power and household load profiles, means worst-case load profiles for variable occasions within the 24h, are displayed in figure 9. While the last part of the curves shows the load profiles according to voltage control for the storage device located at node 5 or node E, the first part is to ensure the covering of the load when PV feed is below demand and is therefore equal for both nodes.

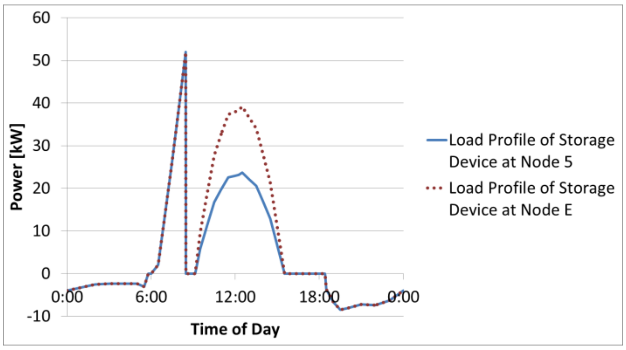

Figure 9. Profile of a storage device for combination of voltage control and own consumption in the local area

CONCLUSION

In this paper the analyses of the voltage and load behaviour in LV networks with a high level of photovoltaics (PV) and possible solutions for voltage control and P/Q-management are presented. For this purpose a real power grid has been considered. Additionally, dimensioning and positioning of the energy storage devices have been analysed.

Assuming the worst-case-scenarios the results of the load-flow calculations show a critical voltage increase as well as high currents in the network. When single-phase loads or PV feeds are expected, however, calculations may lead to voltage and current deviations.

In order to keep the voltage within the target limits, a storage unit can be located in the grid to influence active or reactive power flow. In both cases the device should be placed as close as possible to the critical node. Unlike P-control reactive power management leads to higher stress of the equipment and therefore to a reduction of the remaining lifetime. Active power management, however, improves the local use of renewable energies. One approach to increase local use in combination with voltage control is described in the last paragraph. The capacity and the control strategy of the storage device is defined by the ratio of PV feed and load demand in the particular grid and is a complex optimisation problem.

The voltage in a local network can be influenced by the effect of active power management, which albeit has high requirements of the capacity of the storage devices. However, if the limits of the storage capacity are reached, there is still a possibility of keeping the voltage within the limits by means of reactive power management.

Acknowledgments

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