APPARENT POWER DEPENDENT VOLTAGE CONTROL IN THE LV GRIDS WITH DISTRIBUTED GENERATION USING ON-LOAD TAP CHANGING TRANSFORMER

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ABSTRACT

This paper deals with the voltage control in the LV grids with distributed generation using On-Load Tap changer. An innovative cost-effective voltage control schemes based on the locally measured signals at the substation is presented. In this approach not only the active power, but also the reactive power injection are taken into consideration. The functionality of this method is demonstrated via simulation based upon real measurements from a German DNO. The results confirm the advantage of the apparent power dependent voltage control in contrast to other proposed approaches in the literature.

I. INTRODUCTION

Concern over global climate change the Germany government has decided to support more renewable energy. According to the study from German Energy Agency (DENA) the installed photovoltaic (PV) power should rise from 38 GW in 2015 to 62 GW in 2030, and the most PVs will be directly connected to the low voltage (LV) grids [1].
The connection of such distributed generation (DG) to the present LV grids often experience voltage rise problem due to reversed power flow. Regarding the voltage maintenance there are two guide lines/standards, which the German distribution network operator (DNO) should follow [2], [3]. According to [2] 95% of the 10-minute average effective voltage within a week should be kept in the range $U_n \pm 10\%$. In [3] another criterion is regulated, the voltage rise due to the connection of DGs in the LV-grid should not be over 3% of the nominal voltage on all buses.
In order to meet these requirements, the traditional solution is network expansion, but this can be quite cost intensive and make the connection of DG uneconomical. One of the effective methods is the application of On-load tap changing (OLTC) transformer [1]. Hereby the algorithm of the voltage controller plays an important role in the voltage control of the whole LV grid. Some control algorithms have been investigated and applied in the practice.
In this paper the most applied control algorithms will be introduced and analysed. Thereafter, the proposed method will be described in detail. Finally, the functionality of all approaches will be presented via simulation based upon real measurements from a Germany DNO.

II. ALGORITHMS OF VOLTAGE CONTROL

Different strategies of voltage control via OLTC have already been introduced. In the following the functionality and the limitation of these methods will be shortly explained. Based on the analyse an innovative control algorithm will be proposed.

a. Secondary bus voltage control (SB)
This is the simplest and traditional method. The single input signal is the measured voltage on the secondary bus of the transformer. By means of the OLTC, the controller tries to keep the secondary voltage near the constant reference voltage, and the high (HL) and low limit (LL) should not be violated.
One of the disadvantages bundled with this approach is that the voltage rise/drop along the cable is not taken into consideration at all, so that the voltage limits in some buses may be violated.

b. Voltage control with distributed measurements (DM)
In this approach the voltages on several critical buses for voltage rise/drop should be measured and transmitted to the voltage controller at the transformer station. Via OLTC these voltages on these critical buses can be kept between HL and LL.
Compared with other approaches this method is quite cost intensive due to the necessary distributed voltage measurements as well as the data transmission.

c. Active power dependent voltage control (AcP)
In the practice this method has already been applied in several projects. In this method the reference voltage is not constant any more like methods SB and DM, it depends dynamically on the active power at the moment as shown in Fig. 1.

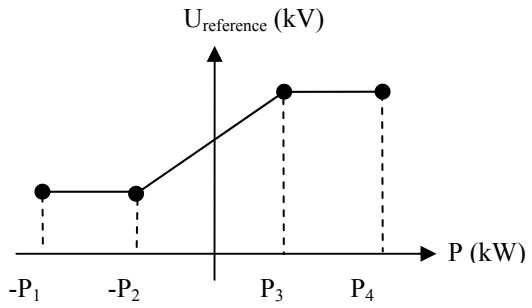

Fig. 1: Active power dependent voltage control

The advantage of this method is that the reversed active power flow is taken into account. A problem that arises in this kind of voltage control system, however, is the reactive power control. According to the guide line for DG connection to the LV-grid [3], all DGs whose power is larger than 3.68 kVA must have the ability, dynamically to control the power factor according to the momentary active power as shown in Fig. 2. Another drawback lies in the fact that this approach does not work in heterogeneous network, i.e. the feeders have different characteristics, which the most networks belong to.

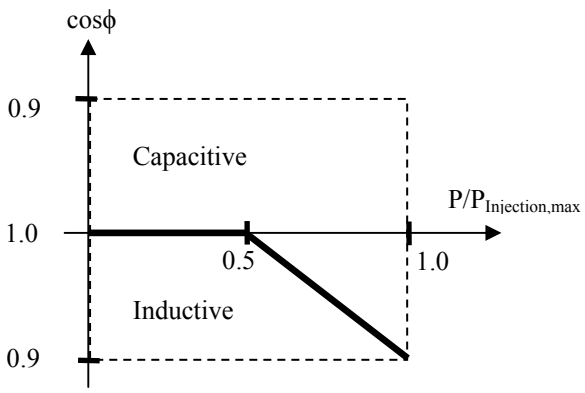

Fig. 2: cosϕ/P control

d. Apparent power dependent voltage control (ApP)

Based on the above analyse an apparent power dependent voltage control method will be proposed here. The system structure is presented in Fig. 3.

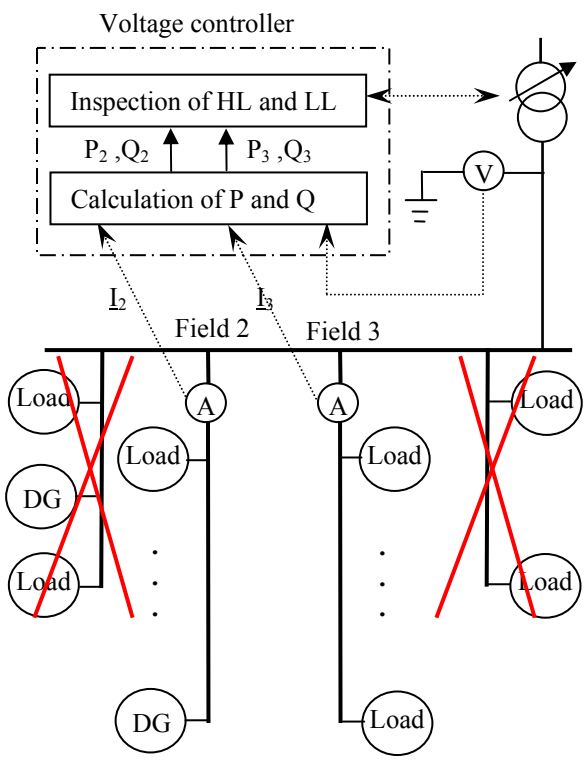

Fig. 3: System Structure

1) Measurements

All measurements are carried out locally at the substation. The necessary measurements are voltage on the busbar and currents on the critical out-going-feeders. The critical feeders are those feeders whose buses along the connected cable may have the highest/lowest voltage in network during operation. These feeders can be easily distinguished from the rest by the following characteristics: large DG/consumer at the end of a power line, or the power line has large impedance, etc.....

2) OLTC Control

At first, the apparent power of all critical feeders can be calculated from the measured busbar voltage and feeder currents. Then HL and/or LL violation will be inspected respectively according to the apparent power of the critical feeders (Fig. 4).

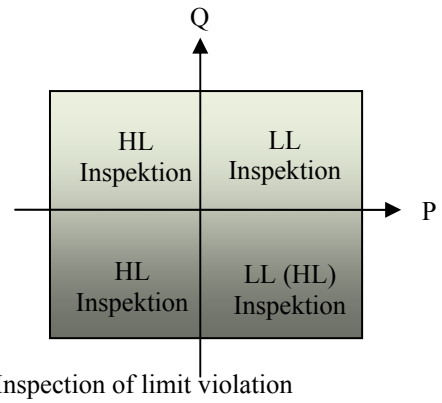

Fig. 4: Inspection of limit violation

The positive direction of power flow in Fig. 4 is defined as consumer. In first quadrant LL will be checked, because both P and Q are consumed in this region, only LL could be violated. In second and third quadrant, the DG characteristic dominates in these areas, i.e. DG injects P into network, at the mean time injects or consumes Q from the grid, in order to support the reactive power in the network or reduce the voltage rise along the power line. In the fourth quadrant LL should be checked, optionally HL can be inspected as well.

The inspection of HL and LL will be executed for each critical feeder. The maximal/minimal voltage of the power line which connects with the critical feeder will be estimated with the following equations:

HL inspection

$$\left|\underline{u}_{\max}\right| = \left|u_{bb} - \underline{Z}_{\max} * \underline{I}_{feeder}\right| \quad (1)$$

LL inspection

$$\left|\underline{u}_{\min}\right| = \left|u_{bb} - \underline{Z}_{\min} * \underline{I}_{feeder}\right| \quad (2)$$

Here u_{SS} and $\underline{I}_{feeder}$ are measured busbar voltage as well as feeder current. The estimation of $\underline{Z}_{\min}$ and $\underline{Z}_{\max}$ will be explained in the next section.

If HL is violated on any bus, then OLTC should be stepped down after dead time. In the case of only LL violation, then the OLTC should be stepped high.

3) Estimation of equivalent impedance

A scenario with voltage rise is given in Fig. 5 for a simplified feeder.

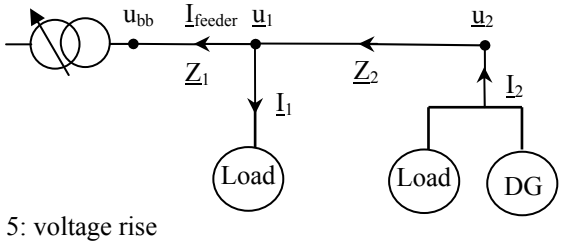

Fig. 5: voltage rise

$$\underline{Z}_{\max} = \frac{\underline{u}_2 - u_{bb}}{\underline{I}_{feeder}} = \frac{\underline{I}_2 * \underline{Z}_2 + (\underline{I}_2 - \underline{I}_1) * \underline{Z}_1}{\underline{I}_2 - \underline{I}_1} \tag{3}$$

$$= \underline{Z}_1 + \frac{\underline{I}_2}{\underline{I}_2 - \underline{I}_1} * \underline{Z}_2$$

$$|\underline{I}_2 - \underline{I}_1| \le |\underline{I}_2| \Rightarrow |\underline{Z}_{\max}| \ge |\underline{Z}_1 + \underline{Z}_2| \tag{4}$$

In the case of voltage rise, the equivalent impedance $|\underline{Z}_{\max}|$ is larger than the physical impedance $|\underline{Z}_1 + \underline{Z}_2|$

The scenario with voltage drop is shown in Fig. 6

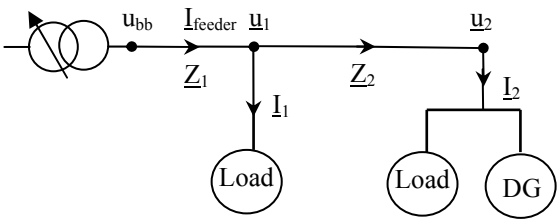

Fig. 6: voltage drop

$$\underline{Z}_{\min} = \frac{u_{bb} - \underline{u}_2}{\underline{I}_{feeder}} = \frac{\underline{I}_2 * \underline{Z}_2 + (\underline{I}_2 + \underline{I}_1) * \underline{Z}_1}{\underline{I}_2 + \underline{I}_1} \tag{5}$$

$$= \underline{Z}_1 + \frac{\underline{I}_2}{\underline{I}_2 + \underline{I}_1} * \underline{Z}_2$$

$$|\underline{I}_2 + \underline{I}_1| \ge |\underline{I}_2| \Rightarrow |\underline{Z}_{\min}| \le |\underline{Z}_1 + \underline{Z}_2| \tag{6}$$

In the case of voltage drop, the equivalent impedance $|\underline{Z}_{\min}|$ is smaller than physical impedance $|\underline{Z}_1 + \underline{Z}_2|$

Therefore $\underline{Z}_{\max}$ and $\underline{Z}_{\min}$ have to be separately estimated. These parameters can be estimated either from the synchronized measurements with GPS timer or directly from the probabilistic power flow calculation.

The estimation can be mathematically stated as:

$\underline{Z}_{\max}$ subject to: i) $|\underline{u}_2| > u_{bb}$ and

ii) $|\underline{I}_{feeder}| > I_{threshhold}$ and

iii) $\max(|u_{bb} - \underline{u}_2|)$

$\underline{Z}_{\min}$ subject to: i) $|\underline{u}_2| < u_{bb}$ and

ii) $|\underline{I}_{feeder}| > I_{threshhold}$ and

iii) $\max(|u_{bb} - \underline{u}_2|)$

III. CASE STUDY

The different algorithms have been tested on a real LV-grid from a German DNO. This network has 6 feeders, supplies up to 300 Households, and several commercial loads. Approximately 800 kW_p of PV-equipments are connected also to this grid, which are operated at cosϕ=1. The whole LV-grid is supplied by a transformer with off-circuit tap changer (OCTC) and OLTC, these parameters are shown in table 1.

Trans-former	Sn (MVA)	Un1 (kV)	Un2 (kV)	u_k (%)	P_k (kW)	i_0 (%)	P_0 (kW)
	0.63	20	0.4	4	5.4	0.1	0.57
OCTC	Step	Step voltage (%)	Centre Tap	Tap at beginning			
	-1 ~ 1	4	0	1			
OLTC	Step	Step voltage (%)	Centre Tap	Tap at beginning			
	-10~10	2	0	0			

Table 1: Parameters of transformer

In order to evaluate these different control algorithms quantitatively, an improved *"Backward Forward Sweep"* (BFS) method is applied for the power flow calculation. The BFS-method is robust and stable, compared with the traditional Newton-Raphson-method.

Based on the measurements the simulation is carried out in an interval of 1 minute, and overall 231200 consecutive time sequences from the power flow calculation have been evaluated.

According to our measurements in further German DNOs in duration of more than 2 years, the mean voltage in the medium voltage network is about $1.02U_N$. In accordance with [3] the voltage rise should not be over 3%, so we set HL as $1.05U_N$. LL was chosen symmetrically at $0.95U_N$. This is the setting for the methods DM and ApP. Three critical buses have been selected as the distributed measurements.

Because only the busbar voltage will be observed in the methods SB as well as AcP, the HL and LL are chosen respectively as $1.02U_N$ and $0.98U_N$.

IV. SIMULATION RESULTS

The histogram of the voltage on a critical bus with different control algorithm is shown in Fig. 7 as an example. Whereas the voltage is successfully kept between LL and HL with the DM method, there is more or less HL violation with the rest three methods.

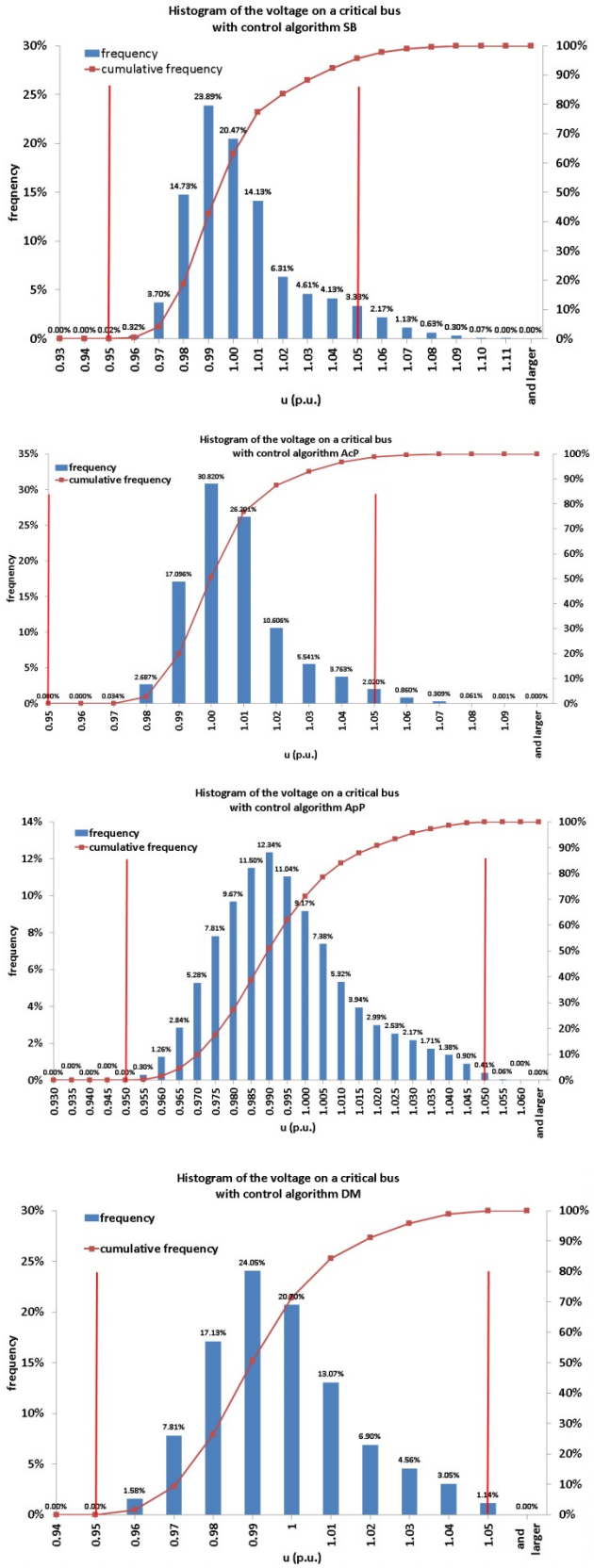

Fig. 7: Histogram of the voltage on a critical bus

The performance with the SB algorithm is not satisfied, because about 5% of the voltage is over the HL. The performance can be improved with the AcP, but it has to be pointed that the cosϕ/P control of PV-converters is not taken into the simulation yet, if this is applied in the simulation, the HL violation will rise consequently. The performance with the proposed ApP method is satisfied und meets the requirement in the practice, only 0.06% voltage is over the HL limit.

	SB	AcP	ApP	DM
Used step	-1 ~2	-2~3	-1~5	-1~5
Number of switching	628	1360	397	419
costs	Low	Low	Low	High
engineering	Medium	High	High	Medium
Voltage maintenance	95.68%	98.77%	99.94%	100%

Table 2: Evaluation of different algorithms

The technical and economical evaluation for the four control algorithms is presented in Table 2. Although the essential OLTC switching with ApP and DM is much less than with AcP, the performance is however better. Whereas the DM method is bundled with high invest and operation costs because of the measurements on the critical buses as well as the data transfer between voltage controller and the distributed measurements, the ApP method does not need any communication equipment, because all measurements are locally carried out at the station. The necessary equivalent impedance $\underline{Z}_{max}$ and $\underline{Z}_{min}$ in the method ApP can be either directly estimated from power flower calculation, or from the once-only measurements.

V. CONCLUSION

In this paper, the different methods for the control of OLTC have been studied and tested with a network of a German DNO and the real measurements over years.

The simulation results show that the proposed ApP method reaches the best compromise between technical and economical evaluation. With this method, the voltage maintenance is almost the same as with the DM method, better than with the methods SB and AcP. The invest and operation costs with this method is comparable with the methods SB and AcP, and much lower than with the method DM.

The precondition for the application of the ApP method is the estimation of the equivalent impedance $\underline{Z}_{max}$ and $\underline{Z}_{min}$ in each critical feeder. Theses parameters can be easily achieved via probabilistic power flower calculation in the LV-grid. An appropriate approach has already been developed and tested, which will be presented in another paper.

REFERENCES

[1] Dena Verteilnetzstudie: http://www.dena.de/projekte/energiesysteme/verteilnetzstudie.html

[2] European Standard EN 50160: Voltage characteristics of electricity supplied by public electricity networks, *July 2010*

[3] VDE-AR-N 4105 Anwendungsregel: Erzeugungsanlagen am Niederspannungsnetz – Technische Mindestanforderungen für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Niederspannungsnetz, *August 2011,VDE Verlag*

[4] H. Y. Li, 2008, "Increasing Distributed Generation Using Automatic Voltage Reference Setting Technique", *Conversion and Delivery of Electrical Energy in the 21st Century IEEE,* 10.1109/PES 2008.

[5] Anna Kulmala, 2007, "Active Voltage Level Management of Distribution Networks with Distributed Generation Using On Load Tap Changing Transformer", *Power Tech, 2007 IEEE,* 10.1109/PCT.2007.4538360.

[6] An D.T.Le, 2007, "Response Coordination of Distribution Generation and Tap Changers for voltage Support", *Power Engineering, 2007 IEEE,* 10.1109/AUPEC.2007.4548108.