ANALYSIS OF VARIOUS VOLTAGE CONTROL METHODS FOR LOW VOLTAGE NETWORKS WITH DISTRIBUTED GENERATORS

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ABSTRACT

In this paper the impact of distributed generation units on the load flow in the electrical power system is analysed, by taking a typical German LV network configuration into account. The impact on the network parameters voltage and loading of the network equipment is investigated to identify the limiting network parameter.

Because a high penetration of the considered distributed generators causes mainly voltage problems, the possibility to regulate the voltage in the LV network is analysed. Thereby, the effects of changing the tap position of the MV/LV transformer is presented as well as the reactive power control by photovoltaic systems.

INTRODUCTION

The objective of the European Union to reduce carbon dioxide emissions till the year 2020 about 20% as well as the increase of the share of power generation by renewable energy recourses and the energy efficiency by 20% referring to the year 1990 leads especially to different load and generator profiles in the future [1].

To reach given climate objectives, the German government promotes different technologies. In the last years an increasing number of photovoltaic (PV) systems became apparent, that were integrated to the electrical power system [2]. Also the new efficient technologies for heat generation are promoted by the German government. In this context micro combined heat-and-power (CHP) plants and electrical heat pumps (HP) have to be mentioned. In the last years an increasing share of these units was recognised as well. In the following, PV systems, micro CHP plants and electrical HP will be summarised to distributed generators (DG). HP can also be mentioned as DG, which are generating thermal heat. From the view of the electrical network they are handled as negative generators.

Connecting a huge number of DG to the electrical urban network may result in an inadmissible loading of the network equipment and in the exceeding of given voltage limits [3]. This effect will be analysed in this paper. At first, the impact of DG on network equipment loading and network voltage profiles are investigated. Secondly, methods to adapt existing LV networks to the new circumstances are analysed, avoiding an extraordinary extension of the electrical network to limit the costs. The investigations in this paper are based on an existing urban LV network structure, built up in the last decades. Also aspects of the new German LV grid code are taken into account [4].

METHOD OF ANALYSIS

In order to analyse the impact of DG on the LV network, a typical German metropolitan distribution network is considered. Therefore, data of Dortmunder Energie- und Wasserversorgung - Netz GmbH (DEW21-Netz) are used.

Considered Distribution Network

The typical German low voltage network is built up as a meshed network, but operates as a radial system [5]. The number of feeders per MV/LV substation is depending on the household structure as well as the number of households per LV feeder. By analysing the existing urban LV network structure of DEW21-Netz, the typical network configuration can be determined. In fig. 1 the determined LV network structure is presented.

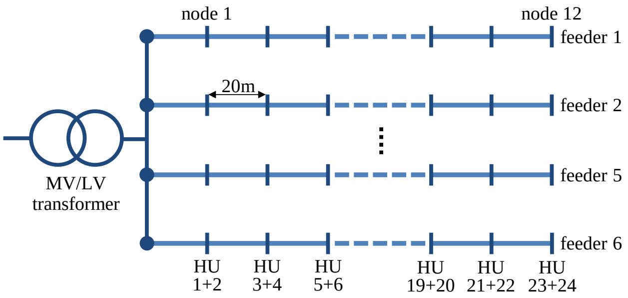

Fig. 1. Structure of the considered distribution network

The nominal power of the MV/LV transformer is assigned to 630kVA. The LV cables (NA2XY, 4x95mm²) between the points of connection, which feed 2 housing units (HU) each, are determined to a length of 20m. Thus the total length of a feeder is 240m. As shown in fig. 1 the considered distribution network consists of 6 feeders with 12 nodes and thus 24 HU per feeder.

Configuration of Loads and Distributed Generators

The load flow simulation in the considered LV network requires the definition of the network connection capacity (NCC) of HU and the nominal power of DG.

The maximum NCC of one HU can be assumed to 30kW [6]. Because of the stochastic behaviour of consumers, the actual NCC results by multiplying the maximum NCC with the simultaneity factor g(n).

$$g(n) = g_\infty + \frac{1 - g_\infty}{n^x} \qquad (1)$$

The parameters of g(n) can be determined with $g_\infty = 0.028$ and $x = 0.75$ [7]. Considering the impact of the load on the loading of the network equipment and the voltage profile, the number of customers, which are subordinated to the specific equipment, has to be estimated.

The number of HU per feeder is set to 24. To calculate the loading of the LV cables and the voltage at the terminal node, the maximum NCC has to be multiplied with g(24), which results in an actual NCC of 3.5kW per HU. A number of 6 feeders per MV/LV substation results in a g(144), which has to be considered to calculate the loading of the MV/LV transformer. In this case the actual NCC per HU has to be set to 1.5kW. The determined configurations of the loads and the DG are summarised in table 1.

Table 1. Assumed loads and DG for load flow simulations

	P_{max}	cos φ	calculated parameter
maximum load per HU	3.5kW	0.95 ind.	voltage
	3.5kW	0.95 ind.	cable loading
	1.5kW	0.95 ind.	transformer loading
electrical HP	1.5kW	0.95 ind.	all parameters
micro CHP plant	1.5kW	1.00	all parameters
PV system	7.0kW	1.00	all parameters

Based on the represented values the load flow simulations are executed.

Operational Network Limits

In order to guarantee safe energy supply, the loading of the network equipment must not exceed given limits. The maximum admissible loading for MV/LV transformers and LV cables is 100% [5].

According to EN 50160, the voltage at LV customers must not exceed a deviation of ±10% of the nominal voltage [8]. This deviation can be divided in a deviation of ±4% in MV networks and ±6% in LV networks. Thus the voltage at the terminal node has to be within the limits of 0.94 p.u. and 1.06 p.u..

DETERMINATION OF THE LIMITING NETWORK PARAMETER

In this paragraph the impact of DG on the loading of the network equipment and the voltage profile is analysed. In order to identify the limiting network parameter two cases are regarded. In table 2 the configuration of these two cases is presented.

Table 2. Configuration of different cases to identify limiting parameter

	regular household load	considered DG
case 1	no	PV systems micro CHP
case 2	yes	electrical HP

The maximum values of the used load and generator profiles are scaled to the determined values of table 1.

In case 1 the upper voltage limit is exceeded, if 12 of 24 HU are equipped with PV systems and micro CHP plants. The loading of the network equipment is still below the acceptable limit (about 59%). Only the loading of the transformer is near to the admissible limit (about 91%).

In case 2 the lower voltage level is exceeded, if 5 of 24 HU are equipped with electrical HP in addition to the regular household load. The loading of the MV/LV transformer as well as the loading of the LV cables is far below the acceptable limit (about 45% and about 60%, respectively).

Based on the results of the load flow simulations it can summarised, that a high penetration of DG exceeds voltage limits first, before the loading of the network equipment reaches inadmissible limits. Because of this, the following focus is on voltage and its control.

To show the time dependency of the voltage, fig. 2 illustrates the voltage profile at the terminal node, if 50% of the HU are equipped with electrical HP.

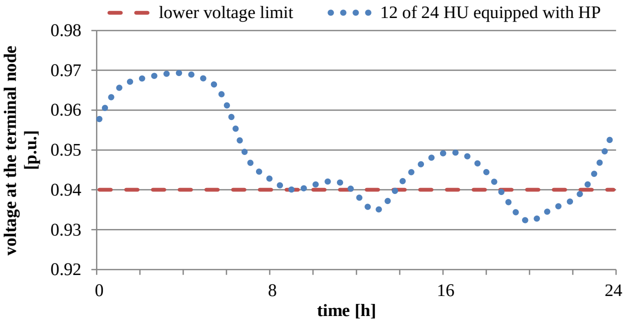

Fig. 2. Time dependency of the voltage profile at the terminal node

It can be seen, that the limits are exceeded at several time periods of the day. Therefore, the regulation of the voltage has to be executed dynamically based on the current load flow situation in the electrical network. In the following, two different methods to control the voltage in LV networks will be discussed. In addition to the use of an on load tap change (OLTC) transformer, the reactive power control by PV systems is considered.

VOLTAGE REGULATION METHODS

The maximum voltage deviation in a cable depends on the active power P and the reactive power Q. The nominal voltage deviation ΔU_n depends also on the impedance of the electrical network [9] (considered LV network: cable resistance R: 0.69 Ω, cable reactance X: 0.15Ω, R/X: 4.6):

$$\Delta U_n = \frac{PR + QX}{U_n} \tag{2}$$

P is determined by electrical loads and distributed generation units. To influence the voltage deviation, an adaption of the reactive power is required, as it is prescribed in the German standards. In this context two different methods of influencing the voltage profile in LV networks are examined.

On Load Tap Change Transformer

Because conventional MV/LV substations have fixed tap positions, the HV/MV transformer is the last active equipment in the power system to adapt the voltage. To deal with the problem of exceeding voltage limits caused by a huge number of DG, the application of new network equipment is necessary to change the tap position of the MV/LV transformer on load as well. Thereby, the tap changer has to be automatically, depending on the actual voltage situation in the subordinated LV network. The tapping of the transformer can be illustrated as an additional voltage to the actual voltage in the equivalent circuit diagram. Through this additional voltage a reactive current is impressed, which influences the voltage deviation in a cable.

Reactive Power Control by Photovoltaic Systems

Actually PV systems operate at cos φ of 1.0. According to EN 50438, the new German grid code requires PV systems to operate dynamically at cos φ between 0.90 capacitive and 0.90 inductive, depending on the nominal power of the PV systems [4].
The displacement power factor (DPF) can either be adjusted depending on the generation of active power, or a fixed DPF can be adjusted. By varying the reactive power, the voltage of the LV feeder can be adapted. Adapting the DPF in the required range is no technological problem for the pulse width modulated inverters, which are typically used to connect PV systems to the electrical network [10]. The possibility how to adjust the DPF automatically is described in [11].

EVALUATION OF VOLTAGE REGULATION METHODS

In the following the two different methods to control the voltage in LV networks will be discussed. Thereby, the effect of the autonomous use of an OLTC transformer and the autonomous reactive power control by PV systems will be investigated. To exploit the advantages of both methods a combination of them will be considered.

Method of Evaluation

Based on the structure of the considered network without any DG, the number of DG will be increased step by step up to the maximum number of 24 units per LV feeder. The voltage at the MV/LV substation is affected by the upper MV network. In order to take the voltage level at the substation into account, two different starting points of the voltage are assumed (1.012 p.u., 0.985 p.u.). The voltage level at the terminal node can be represented as a function of the number of DG and the chosen voltage regulation method.
There is a different influence on the voltage profile, whether the number of connected units is raised from the terminal node or from the first node of the feeder. This correlation is illustrated in fig. 3, where both proceedings are compared to each other.

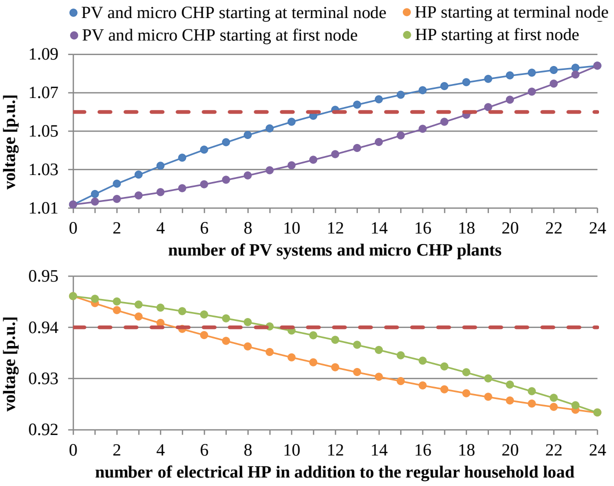

Fig. 3. Voltage level depending on different connection starting points

The voltage limit is exceeded at a lower number of DG, if the connection of the DG starts at the terminal node. Because the worst case has to be assumed, the connection of the DG starts at the terminal node in the following.

Evaluation of Results

To analyse the considered voltage regulation methods, the voltage profiles of three different cases are regarded. Table 3 presents the configuration of these three cases:

Table 3. Configuration of different cases to analyse regulation methods

	regular household load	considered DG	voltage at MV/LV substation
case A	no	PV systems micro CHP	about 1.012 p.u.
case B	yes	electrical HP	about 0.985 p.u.
case C	3 feeders: no 3 feeders: yes	3 feeders: PV + micro CHP 3 feeders: electrical HP	about 0.985 p.u.

Fig. 4 shows the voltage profiles of case A without voltage regulation and by using the two voltage regulation methods independent to each other.

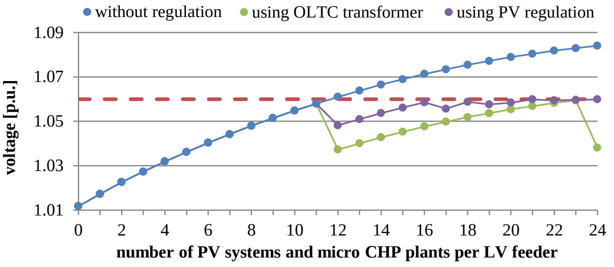

Fig. 4. Voltage profiles of case A

Without voltage regulation the voltage exceeds the admissible limit at a number of 12 PV systems and 12 micro CHP plants. By using the OLTC transformer the tap position of the transformer changes automatically, if the voltage in the LV network exceeds the given limit. The DPF of every 12 PV systems is set automatically to 0.95 capacitive, if the voltage limit is reached. While connecting more PV systems to the network, the DPF of these units is set to 0.95 capacitive as well, when the voltage is too high. PV systems and micro CHP plants can be connected to every single HU without exceeding the voltage limit, by using one of the considered regulation methods.

In fig. 5 the voltage profiles of case B without voltage regulation and by using the OLTC transformer are illustrated.

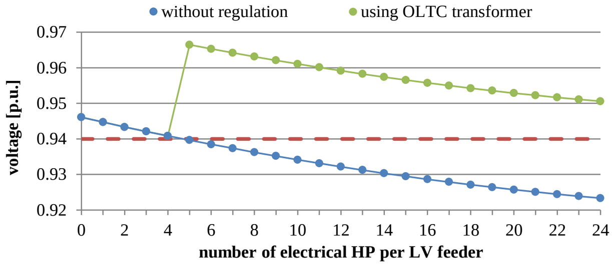

Fig. 5. Voltage profiles of case B

By using the OLTC transformer the voltage profile can be raised, if the voltage limit is reached. One tapping of the transformer is sufficient to hold the voltage within the acceptable limits, so that a HP can be connected to every single HU in the LV feeder without reaching the limit.

In case C two different load flow situations are assumed in the LV network. Fig. 6 illustrates the impact of both voltage regulation methods on two feeders with different load flow situations.

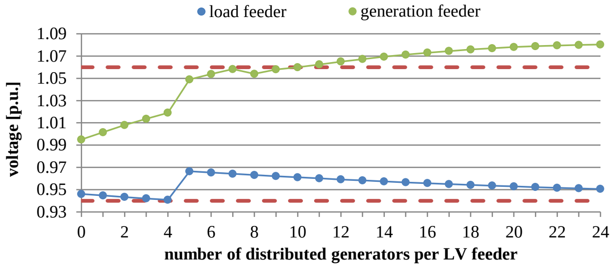

Fig. 6. Voltage profiles of case C

Because the voltage in the load feeder would exceed the lower voltage limit at a number of 5 HP, the tap position of the OLTC transformer has to be changed to raise the voltage. The changing of the tap position has also an impact on the voltage in the generation feeder. The voltage comes near the admissible limit. Connecting more DG to this LV feeder increases the voltage. The maximum number of DG is reached at a number of 10 units.

It is obvious, that totally different load flow situation in the same LV network cannot be managed by the considered methods. In this case other methods have to be used to hold the voltage within the limits.

CONCLUSIONS

It has been shown, that a high penetration of DG causes mainly voltage problems. The voltage level at the terminal node is deciding for the number of DG, which can be connected to the LV network without exceeding the given limits. The impedance of the upper MV network and the LV network as well as the active and reactive power in both parts of the network are the determining factors for the voltage deviation at the last HU of the feeder.

By using the considered voltage regulation methods the number of DG, which can be connected to the LV network can be increased without exceeding given limits. By using an OLTC transformer in the MV/LV substation, the voltage of each subordinated LV feeder is influenced in the same way. This causes problems, if the load flow situation is unsymmetrical in the LV network (see fig. 6). Also the required frequently change of the tap position, which results from the time dependency of the voltage (see fig. 2), is problematical.

In contrast to the MV/LV OLTC transformer the reactive power control by PV systems enables the autonomous variation of the voltage in LV feeders. The DPF can be set depending on the load flow situation of each feeder.

In the worst case the considered voltage regulation methods are insufficient. Because of this other methods to regulate the voltage are necessary. In this context series controllers and other methods which are applied in the MV network have to be considered [12] [13]. Also the possibility to regulate the voltage by active power control has to be mentioned (see eq. (2)).

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