ON-LOAD VOLTAGE REGULATION IN THE LOW VOLTAGE GRID

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ABSTRACT

In the electrical distribution grids the complexity of power flow increases due to increasing penetration with small and distributed power generation plants. In the future distribution system operators (DSOs) are requested to build up an efficient and up to date grid infrastructure by integrating the end consumers with their fluctuating power generation, their load and their storage capabilities in the system. In most European countries government subventions and the obligation to connect small solar and bio mass power generation lead to necessary extensions and strengthening of the LV grids. Depending on the generation and load scenarios in the LV and MV grids, a fluctuation of the power flow is expected, which can even result in back-feeding power into the MV and HV grid. This causes large voltage fluctuation in the grid.

One possibility to remain compliant with the reduced voltage range of +/- 10% according EN 50160 in grids with a high share of distributed generation is the use of a regulated distribution transformer. Especially in the case of homogeneous grids this measure is promising. Thereby the challenge is the development of an on-load voltage regulation for distribution transformers by keeping the accustomed performance and dimensions to ensure the changeability und comprehensive operation wherever it's needed.

Siemens AG has developed a regulated distribution transformer with an on-load voltage regulation on the low voltage side which fulfills all these requirements. Together with the German DSO E.ON Mitte AG a functional model was installed and field tested in an existing grid.

ANALYSIS OF THE APPLICATION OF THE REGULATED DT IN A LV GRID

Overview of existing regulations

In a first step various aspects of voltage behaviour in low voltage (LV) grids are discussed, which are derived from different regulations, standards and guidelines. Then possible applications of regulated distribution transformers (DTs) to improve the power quality and voltage behaviour in PV networks and the compliance with existing grid codes are discussed.

In LV grids the following technical aspects are important with regard to existing regulation:

- Steady-state voltage profile
- Steady-state voltage changes
- Transient overvoltages due to switching actions

For Germany and Europe there are different standards and technical guidelines existing, which define limits for the absolute voltage and voltage changes due to switching actions. These guidelines are for example DIN EN 50160, DIN EN 61000-2-2, D-A-CH-CZ – Technical Guidelines, VDEW-grid code, etc.
All regulations define slightly different limits. As a summary it can be derived that the steady-state voltages at all nodes in LV grids should always remain inside +/-10 % of the nominal voltage (400V resp. 230V). Due to switching actions – especially when they take place only a few times a day – the maximum change in voltage at all nodes should be limited to 5 % according DIN EN 50160. Thus the impact on customers and sensitive loads is minimized.

DSO and grid introduction

The grid of E.ON Mitte AG

E.ON Mitte AG is supplying nine rural districts in Hessen, four in Niedersachsen incl. the city Göttingen and one in Nordrhein-Westfalen with electricity. In the past five years a significant increase of decentralized power generation has been noticed. Due to the rural structure of the grid this increase is higher than the average trend in Germany. Currently 435 MW photovoltaic power plants are installed in the LV grid. Out of that 110 MW were installed in 2011. Additionally in the medium voltage (MV) grid the installed capacity of wind turbines currently reaches 292 MW.

Details of the selected grid

The regulated distribution transformer (DT) prototype was installed in the LV substation „Kindergarten“ which is located in the area Bühne of the city Borgentreich (Nordrhein-Westfalen). This area belongs to the MV grid close to the power transformation substation “Borgholz” and the switching substation “Daseburg”.
The LV grid is located concentric to the 630 kVA substation and consists of a ring line and six single feeders

that supply the village with electrical energy. Currently 33 photovoltaic systems with 500kW are installed and further 140kW are in the approval procedure.

The maximum voltage increase at the critical point is calculated with 5.04% according the EEG criteria. The maximum voltage spike along the critical line is 4.02% related to the voltage at the bus bar of the transformer. Both values correspond to a calculation considering a PV power feed in with a simultaneousness of 0.95 and a light load of 0.2 kW for each house connection.

A monitoring of the grid shows a maximum returned feed in of 503 kW to the MV grid and a maximum load of 124 kW.

Theoretical analysis of the application of regulated DT in an existing LV grid

Before installation of the regulated DT prototype a theoretical analysis was performed.

Description of LV grid

For the analysis of the effect and behaviour of regulated DT the performance of the grid with and without the installation of the new transformer was analysed. Therefore the complete 400 V network was modelled in the power system simulation software PSS®SINCAL (figure 1). The MV grid will be modelled only using a Thevenin voltage source with constant voltage.

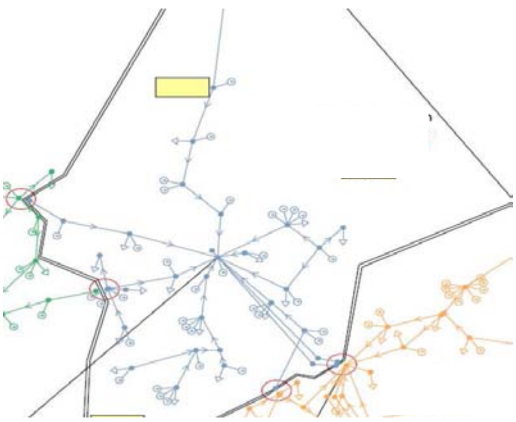

Figure 1: network model of the analysed LV grid in PSS®SINCAL

Three different operation scenarios are analysed:

a. Maximum demand without distributed generation
b. Minimum demand and maximum infeed of distributed generation
c. Minimum demand without distributed generation

The impact of a large amount of distributed generation on the MV grid is estimated by an increase of voltage by 1 % during maximum generation (scenario b.) and a decrease of 1 % voltage during maximum demand (scenario a.). These values indicate an optimistic assumption for the variation of the MV voltage.

Analysis of as-is grid

In a first step the as-is grid is analysed using with the existing conventional distribution transformer. The transformer has a no-load tap changer, which is set after installation and can not be activated during operation. Figure 2 shows the resulting voltages at all nodes in the LV grid for the analysed scenarios.

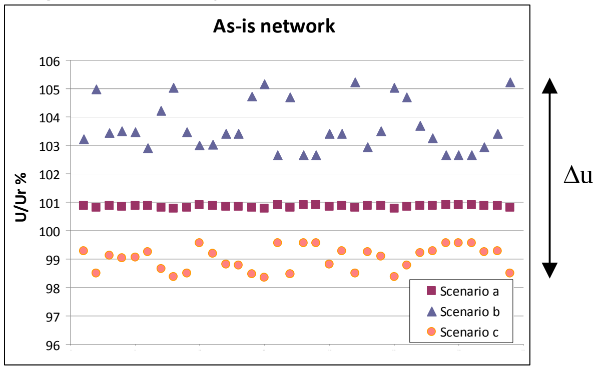

Figure 2: node voltages for the as-is LV grid for each scenario with conventional DT

During high demand without generation (scenario c) the voltages are reduced due to the voltage drop along the distribution lines. In maximum generation scenarios the voltages are increased. In this case the voltage difference between maximum and minimum voltages is about 7 %.

In the future this difference is likely to soar due to growing number of PV plants and distributed generation leading to increasing voltages, which can exceed the operational limits and thus leads to negative impact on customers and sensitive loads. Additionally the MV will be affected even more, thus reducing the available voltage range for the LV grid.

Analysis of regulated DT

Now a regulated DT of 630 kV is installed for the LV grid. This DT has an on-load tap changer of +/- 4.7 % additional voltage and can be controlled based upon the voltage at the LV side of the DT and of voltage meters distributed throughout the grid. The influence on the voltage in the LV grid can be seen in Figure 3.

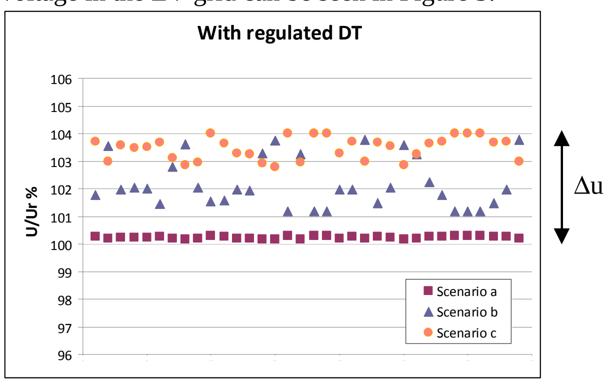

Figure 3: node voltages for the LV grid for each scenario with regulated DT

In comparison to the as-is grid, the voltage behaviour in the LV grid is well improved at all LV nodes. The maximum voltage difference at a single node is now reduced to Δu = 3.7 %.
If the additional voltage of the regulation range is reduced below 4.7 %, the maximum voltage difference at a single node can be reduced even further to about 2-3 %, if additional tap steps are introduced.
Considering the maximum voltage range of +/-10 %, this improvement has no relevance and there is no need to reduce the voltage difference below the indicated values. Furthermore with a solution with lower additional voltage a higher number of tap steps is needed leading to higher equipment costs and increased operation of the voltage regulation.
Thus a solution of a regulated DT with three tap positions and an additional voltage of 4.7 % as investigated in this paper is well sufficient to solve a large share of existing and future voltage problems in LV grids.

THE CONCEPT OF REGULATED DISTRIBUTION TRANSFORMER

The transformer model

IN order to realize the modification of voltage ratio in distribution transformers different tappings in the windings have to be provided. In this concept the LV winding was chosen.
The number of turns (N) in a LV winding of a common distribution transformer is in a range of 20 to 40 – the lower number belongs to higher ratings.
Deriving from physical and mechanical restrictions we can create a tapping after whole turns only. This fact defines the smallest possible difference between two tappings

$$\text{step [\%]} = 1 / N * 100,$$

expressed in % of the rated voltage. This means that in case of a 630 kVA transformer we can achieve approx. 4 – 5% steps, while in case of a 160 kVA transformer approx. 2.5 – 3 % is possible, depending on a number of turns in the real design.
The essential idea of the patented Siemens solution is to use existing electronic and electromechanical elements to build proper equipment (regulator) for the necessary connecting (switching) operation. These elements are designed for operation in air-filled cubicles. Therefore, as far as liquid-immersed transformers are concerned, we have to install standard bushings for every tapping in order to connect them to the outside regulator (figure 4).

The primary winding scheme can be seen on figure 4. Due to limited space on the cover we could realize 3 tappings for each phase.

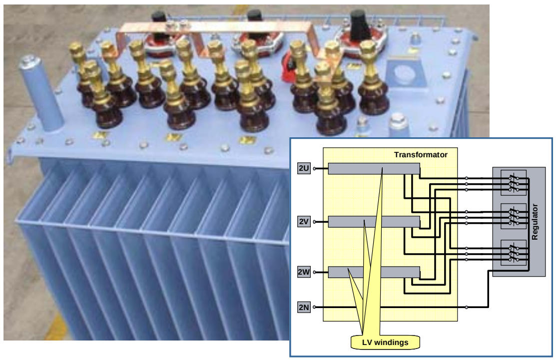

Figure 4: transformer and primary winding scheme

The regulation unit

The regulator unit was designed to form a separated mechanical unit, in fact the necessary measuring, controlling and switching elements were installed in a simple cabinet. The possibility to install the regulator not directly on the transformer allowed for safe inspection of the unit during the field test.
The main components of the regulation unit are vacuum contactors, solid-state relays (thyristor-based) and an appropriate control unit. The solid-state relay acts to ensure continuous current flow by conducting the current during the mechanical switching operations (Patent No. WO/2010/072622).
The regulation unit is governed by the control unit to achieve optimal coordination between mechanical and electronic switching elements. In order to reduce switching time to a minimum, voltages across the mechanical switchgear are measured in an effort to minimize the "on" time of the solid-state switch (figure 5).
Logical condition to fire thyristors:
|voltage across contact N| - |voltage across contact 2| > 0
Logical condition to extinguish thyristors:
|voltage across contact N| – |voltage across contact 1| = 0

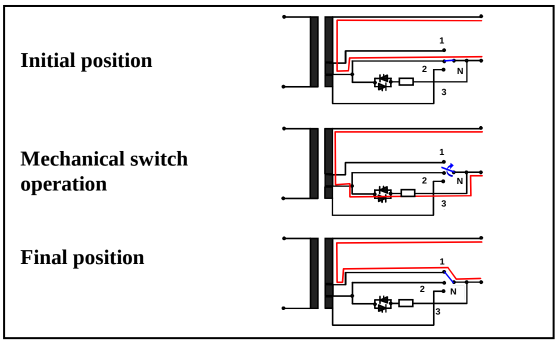

Figure 5: commutation process (schematic)

REALIZED LOCAL REGULATION CONCEPT

There are two aspects affecting the voltage: the first influence comes from the MV grid. If there is a lot of energy generation, such as WECS (Wind Energy Conversion System), the MV grid might has to use its full

range of tolerance of ± 5%. The second influence comes from the LV grid itself with consumption and generation of energy. The first influence is easy to detect by a voltage measurement at the secondary output of the transformer and so it is possible to regulate the nominal-actual value difference.
The quantification of the second influence is much more complicated due to the different LV grid structures with their individual location of energy consumption and energy generation. To measure all these influences complex equipment with a lot of communication is needed. To avoid these expenses an easier and local approach was investigated. Therefore a network calculation of the most critical points of the LV grid was performed. Based on this calculation it is possible to implement a superimposed current control in addition to the voltage controller. Thereby in the actual control unit it is possible to realize different delays between step-up and step-down. So the influence of a photovoltaic energy generation can be indicated much better because it is not wanted to step the transformer on all short generation differences on partly sunny days. If the calculated difference between the feeder with big consumption and the feeder with a lot of generation is very high it is possible to measure the current in each feeder and implementing a superimposed current control in the regulator.

So it is possible to check the actual power flow of each feeder and then the controller can calculate the actual voltage drops for all the feeders. This avoids quite a number of violations of limits also in more complicated distribution grids.

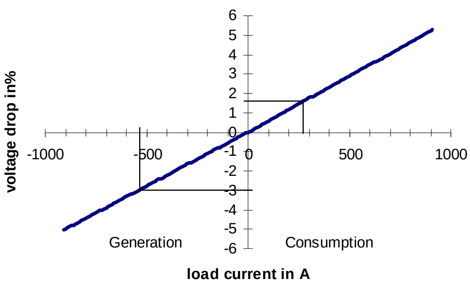

Figure 6: calculated voltage drops according to the load current in the given distribution grid

The considered grid has a voltage drop of 1.5% at 260A (current consumption) and -3% at -520A (current generation) at the end of the most critical feeder. So the given value for the voltage regulation must be increased by about 0.75% at 260A and must be reduced by about 1.5% at -520A, so that the influence of this voltage drop is eliminated in the middle of the feeder.

OPERATIONAL EXPERIENCE

To install the transformer with the separate regulation unit a transformer substation with enough space was chosen. The walk-in substation allows the installation of a second transformer and a large MV switch gear.
The change of the conventional transformer with the regulated transformer prototype was performed by the operational staff of E.ON Mitte AG without any problems. Due to the separate regulation unit, 18 single cables NYY 240mm² with a length of approx. 10m had to be installed. The structural condition of the substation allows an easy handling. The space which was originally foreseen for the second transformer installation allows the necessary bending radius for the cables. Half of the distance the cable were fixed in addition. Also the wiring of the electric sensors in the LV distribution of the substation which are placed in the same control cabinet as the regulating unit and the telecontrol follows the same installation. The size of the substation enables to install the control cabinet at the outer wall to perform a safe final installation and operational supervision away from the danger area of the transformer connection which was separated by a horizontal beam and a plexiglass panel in addition.
Despite the high amount of necessary connections and the assembling efforts for cables (power line, control and measurement) the change of the transformer and initial operation could be performed by the DSO in cooperation with the prototype manufacturer within one working day.
Beside the installation of the regulated prototype the substation was equipped with a remote controlled SF6 switch gear and a LV monitoring system with communication.
The present measurements show reliable and fast switching operation of the regulated distribution transformer prototype. The switching operation takes only approx. 200 ms until the required voltage is reached.
The pilot has been running since October hasn't really challenged the prototype so far. It has to operate only maximum of once a day to keep the voltage aint the LV bus bar in the substation within the limit of 220V and 235V.

OUTLOOK

Based on the experience of such projects as stated in this paper with E.ON Mitte AG, Siemens developed a regulated distribution transformer called "FITformer® REG" by keeping the accustomed performance and dimensions to ensure the changeability und comprehensive operation wherever it's needed (figure 7).

Figure 7: new Siemens product "FITformer® REG"