Cost-effective and fail-safe integration of distributed grid infeed

Highly efficient, controllable distribution transformers and voltage regulators

ABSTRACT

Grid expansion represents a technically obvious but also very expensive solution for the infeed of renewable energy sources. A more intelligent solution is the implementation of controllable distribution transformers whose ratio can be controlled under load, as well as voltage regulators used in the medium voltage grid.

KEYWORDS

voltage regulation, renewables, distribution grid, regulated distribution transformers

1. Introduction

Photovoltaics, biogas and wind turbines save resources and reduce CO_2 emissions. However, they also result in fluctuating energy flow directions, as well as load and voltage fluctuations. Traditional distribution grids with their conventional distribution stations and classic transformers are not designed for these conditions. Capacity could certainly be expanded, but this does not resolve the core issue. The concept was developed for a world with a small number of large power generation facilities and a large number of loads. While expansion of the grid would cover this inherent system deficiency, it would not correct it. Grid operators are currently faced with completely different tasks, being obligated to provide for the infeed of renewable power sources. With no affordable intermediate storage devices currently available, they must also harmonize supply and demand of power, and smoothen peaks using power generation and load management.

> Decentralised energy production is on the rise, but its integration in the existing grid infrastructure is a challenge for distribution grid operators

With their variable voltage under load, regulated distribution transformers and voltage regulators can be used as a supplement in grids with voltage range issues

With their variable voltage under load, FITformer REG – a regulated distribution transformer – and voltage regulators are two of the available solutions providing a supplement for grids with voltage range issues. Both solutions offer a cost-effective alternative to traditional grid expansion and are easily integrated in existing structures.

2. Better voltage control with distribution transformers for the MV/LV grid (e.g. 20 kV/0.4 kV)

There are currently different concepts for regulated distribution transformers, where the integration of a tap changer on the high-voltage side of the distribution transformer appears to be the simplest solution for many operators. These units are essentially small versions of controllable power transformers – a concept known from large transformers and therefore easy to understand. The advantage of this solution is precise control enabled by the tap changer on the high-voltage side. However, this requires that the operator accepts somewhat higher losses, caused by the tap changer design. It includes additional reactors, as well as the risk of feedback loops with the medium-voltage transformer occurring when the regulation of the distribution transformer takes place in small steps once a small voltage change from the MV grid happens.

Designed with a different approach, FITformer REG is a regulated distribution transformer whose underlying philosophy is not to regulate voltage "exactly to the volt", but rather to very flexibly keep it within the allowed voltage range in accordance with EN50160 [1], with extremely low losses. In order to achieve this, the regulated distribution transformers has been supplemented with a load controller on the low-voltage side in addition to the load-free control range on the high-voltage side. This regulated distribution transformer enables voltage adjustment under load in three stages to ensure distributed infeed from micro power plants. The operating characteristics and dimensions of the distribution transformer remain virtually unchanged.

Figure 1 shows the results from the implemented regulation algorithm in an application case. As illustrated, frequent switching caused by the medium power transformer stepping is avoided (point 1) because the limits are not reached. However, when the voltage of the three phases in the grid increases (as shown by the green lines at point 2), the feed-in is negative (see the blue line at point 3), and the voltages reach the upper limit of the configured voltage level (point 4). The transformer lowers the voltage at point 4 by stepping from position 2 to position 1 shown on the right-hand axis, where the three steps of the regulated distribution transformer are indicated. After a while, the voltage reaches the lowest limit (point 5) and the transformer steps back from position 1 to position 2 on the right axis to increase the voltage.

Losses always play a major role when rating electrical machines and have a big impact on the lifecycle costs, defining the ecological footprint of the transformer. Therefore, in the development of this regulated distribution transformer both the control technology and economic factors were considered. In the available ratings from 250 kVA to 630 kVA, the transformer meets the loss requirements according to the European standard, e.g. a distribution transformer up to (not incl.) 1.25 MVA:

$$P_k = C_k + 5\,\% \text{ and } P_0 = A_0 + 20\,\%, \qquad [2]$$

where P_k defines the load losses and P_0 defines the no load losses.

Transformers are divided into classes where A is the class with the lowest and C with the highest losses. For regulated distribution transformers there are additional losses allowed, which enables replacement of transformers in existing substations with regulated distribution transformers, considering that losses have a direct impact on the design as well as the size of a transformer.

Depending on the product, utilities must accept that regulated distribution transformers not only cost more, but also imply higher operating costs . This transformer is designed with optimized losses, and therefore reduces these costs. Its control system causes only low additional losses, which could be compensated by an adapted design of the active section, so that it exhibits the same low losses as the standard distribution transformer. With an additional focus on keeping acquisition costs as low as possible, the development of this transformer resulted in a controllable distribution transformer with a shorter amortization time.

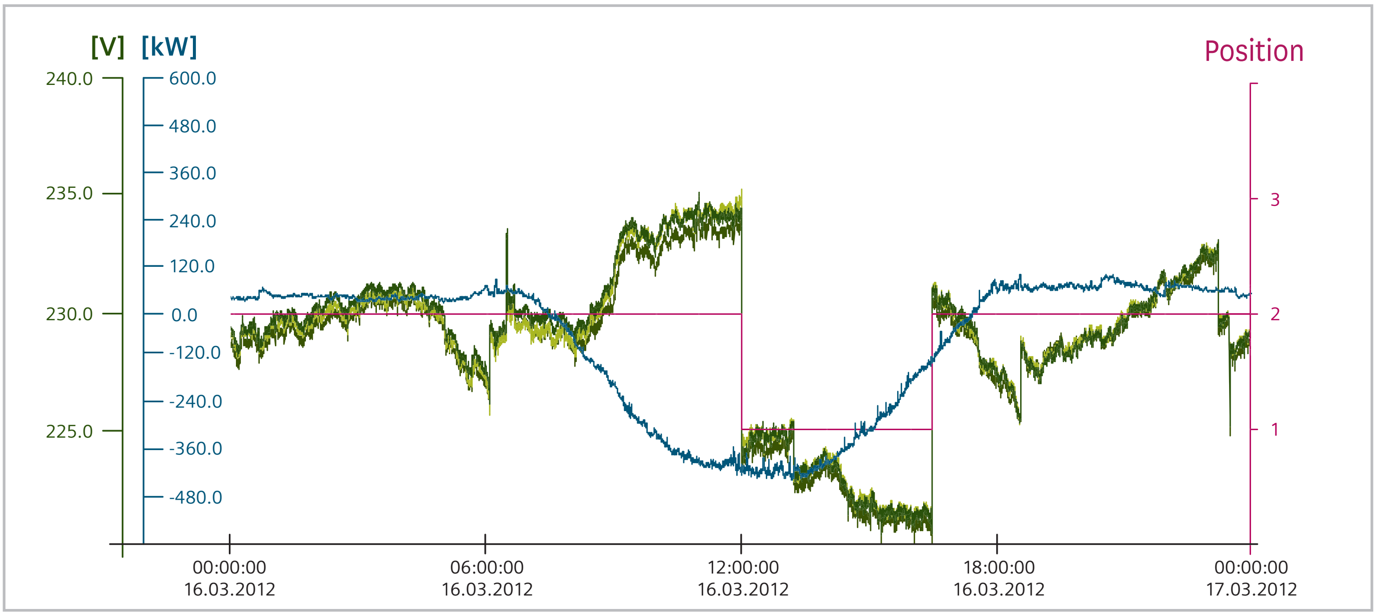

Figure 1. Measuring recording during operation of a regulated distribution transformer for 24 hours, starting point 00:00:00

> **Algorithm implemented in the regulated distribution transformer ensures that frequent switching caused by the medium power transformer stepping is avoided**

2.1. Technological details

The regulated distribution transformer presented in this paper is a special kind of transformer where the windings are produced with three low-voltage taps which are routed from the transformer through the hermetically sealed corrugated wall tank to the control unit. With its compact design, it can also be used to replace former traditional distribution transformers in commonly compact stations without difficulty.

Highly robust and reliable vacuum contactors are used, which are characterized by especially high reliability, operating safety and compact design. Voltage regulation is implemented in two stages. Voltage limits for slow and fast switching, as well as the desired rated voltage can be entered in the form of parameters. The control system can be individually adjusted to various grid conditions by entering delay times.

2.2. Controllable transformers in the distribution grid of the future

Future distribution grids need more than just controllable transformers. Therefore, a modular 3-stage concept based on monitoring, telecontrol and load flow control has been developed. This permits grid operators to gradually expand their conventional distribution stations and adapt them to the changing grid conditions and requirements. In the complete configuration (including all three stages), the intelligent distribution stations (iSub) are equipped with Remote Terminal Units (telecontrol and regulating devices), smart short-circuit indicators, current/voltage sensors, motor-driven medium-voltage switching devices and a controllable distribution transformer. The modular structure of the iSub also allows the operator to install only individual components in existing stations.

The actual distribution station is capable of directly controlling the locally installed controllable distribution transformer, but also to send commands to various other grid components with the existing measured values, such as to inverters in power generation systems. This enables a very rapid response to extreme high and low load periods in combination with highly fluctuating infeeds from wind and solar

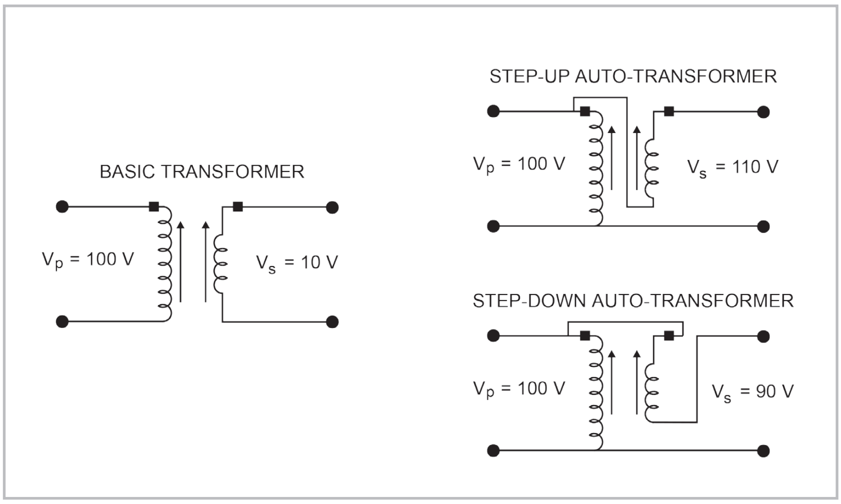

Figure 2. Comparison of the two-winding transformer and the voltage regulator - autotransformer

Figure 3. Medium voltage in phase control station

power. For the grid operator, this represents an option to optimize future investments.

3. Integration of renewable power sources using voltage regulators in the MV grid (e.g. voltage level 10 kV or 20 kV)

In some applications, it may be expedient to combine intelligent power stations or controllable distribution transformers with voltage regulators. This is particularly the case in areas where high levels of power generation from wind and photovoltaic systems are paired with high power consumption in industrial grids.

The current distribution grids in rural areas are often characterized by long transmission lines and low cross-sections – a reliable design for the drop in voltage resulting from the relatively low loads. However, multiples of the load peaks can result in medium voltage systems to which many distributed feeders are connected.

In this combination, fluctuating load and infeed conditions can give rise to significant changes in the operating voltage at individual distribution stations. This makes compliance with the voltage limits of +/-10 % in the distribution grid levels an ever-increasing challenge. Voltage adjustments in the medium-voltage grid are currently frequently made only with tap changers in the substation transformers. As a result, voltage changes cannot be corrected; instead, the voltage change affects the entire medium-voltage grid, thus necessitating expansion of the grid.

> **In areas where high power generation from alternative sources is paired with high industrial loads, it is expedient to combine intelligent power stations with voltage regulators**

The more intelligent option is using regulators to equilibrate the various load conditions with fine-tuned control, maintaining a constant output voltage.

These voltage regulators are independently installed transformers which can substitute an additional substation in the MV grid. This particular voltage regulator is, in principle, an autotransformer (Figure 2). A special feature of autotransformers is that the primary and secondary windings are connected both magnetically and electrically. The step-up autotransformer can increase the input voltage from 100 V to 110 V with a series connection of the secondary winding to the upper end of the primary winding. This procedure is reversed in the step-down transformer to lower the voltage to 90 V. The integrated mechanical switch enables both functions to be combined, achieving a control range of 20 % (+/-10 %).

These parts are mounted in one tank and filled with oil for cooling and insulation purposes. One voltage regulator is connected to one phase of the grid. In the medium voltage substation, there are three voltage regulators installed. The voltage regulator serving as medium voltage substation will be installed in an existing grid.

> An economically optimal grid solution should also account for the existing voltage control equipment

Figure 4 presents a comparison between the voltage levels over a period of 24 hours in a summer time with and without using a medium voltage regulator. The graphs clearly indicate that the range of the voltage deviation will be minimized due to the direct voltage adjustment in the medium voltage grid.

4. Which solution for which grid situation?

As both controllable distribution transformers and voltage regulators essentially address the same grid planning issue, the optimum solution for the grid operator must be determined using a planning process. The necessary workflow is described in the next section.

The first step in the planning horizon is to determine the critical points in the grid where voltage issues can be anticipated. This can be achieved with long-term measurements for the current situation. However, future scenarios require the performance of corresponding grid calculations based on the load and utility forecast.

An economically optimal solution should also account for the existing voltage control equipment. This includes the currently existing distribution transformers with their off-load tap changers that can only be switched when the transformer is de-energized, and of course the primary substation with its medium power transformer with the on-load tap changer, which can contribute significantly to improving the voltage based on its large control range. This makes it clear that not only should independent voltage control equipment be planned in the grid, but also that the existing and future control equipment requirements must be coordinated.

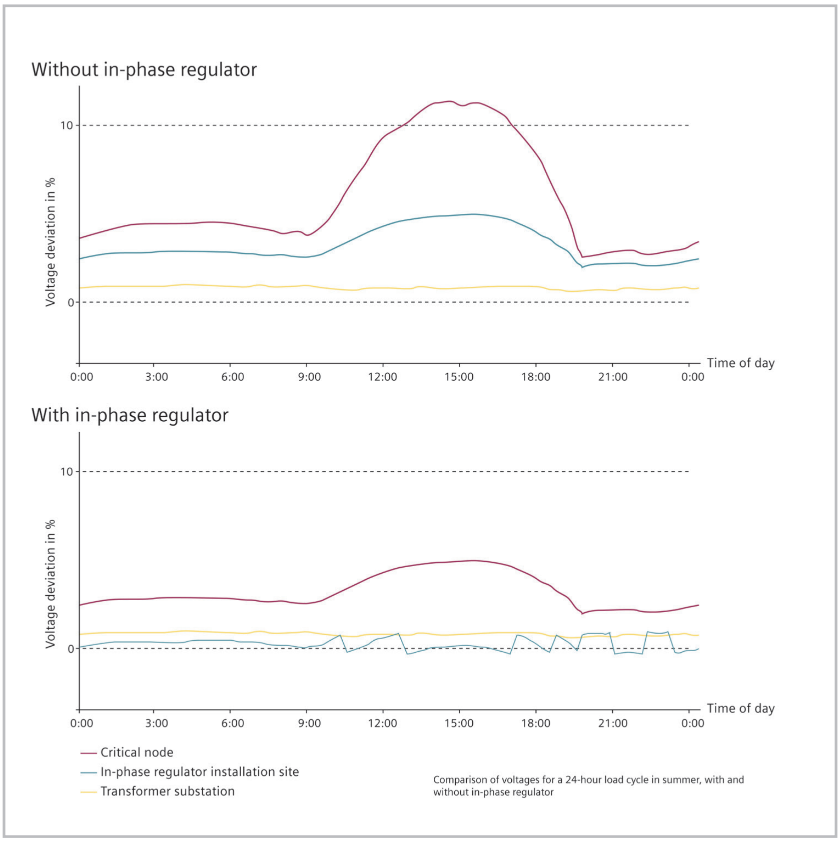

Figure 4. Comparison of voltages for a 24-hour load cycle in summer, with and without the in-phase regulator

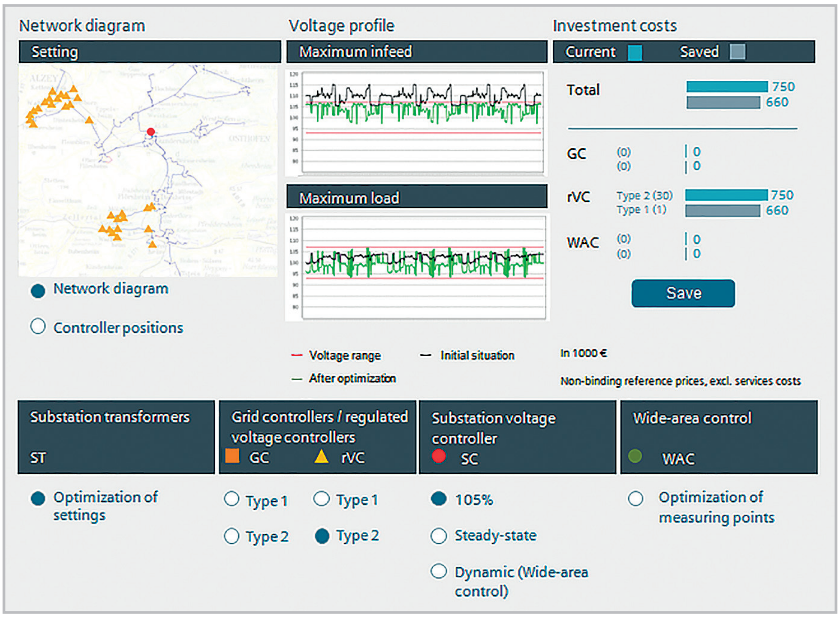

Figure 5. Overview of the optimization environment

> **Not only should independent voltage control equipment be planned in the grid, but also the existing and future control equipment requirements must be coordinated**

The planning workflow consists of the following individual steps [3]:

- Load/generation forecast with determination of the resulting extreme operating cases
- Determination of the requisite voltage regulating elements
- Determination of installation locations
- Coordination of control settings with existing grid elements
- Equipment configuration

The grid nodes to be monitored need not generally be at the end of the supply line. It is therefore especially important to determine the required measuring points - of course these can be determined in the context of field testing for an existing grid. Despite this, analytical support would be helpful in simplifying field testing or even rendering it superfluous.

Therefore, a corresponding procedure has been developed to determine the minimum required set of measured data based on optimization calculations. The grid calculation program PSS SINCAL [3] is first used to generate a grid model using all necessary information on the grid topology as well as the load and generating units. The starting point for the optimization is then the case in which all grid nodes are explicitly monitored with voltage measurement. Next, the mixed-integer optimization is used to determine the subset of grid nodes to be explicitly monitored, which is absolutely necessary for complete observability regarding permissible voltage limits. The voltage conditions are then implicitly observable for all other grid nodes where the voltage measurement can be eliminated. A grid node is implicitly observable if there is no load or generation condition in which a voltage range is violated at any node under consideration of the explicit measuring points.

The results are calculated in a graphical optimization environment with the network editor, parameter configuration unit, visualization of voltage bands and variant analysis components (Figure 5). The central area presents the voltage profile of the network across all network nodes and demonstrates that the voltages are within the permitted range in both extreme cases after optimization (green colour). The black lines indicate the resulting voltages at the neutral positions of the regulating equipment as the starting point of optimization.

Conclusion

Although the shift in energy policy ("energy turnaround") poses a significant challenge for grid operators, solutions are available. The use of intelligent technology enables the elimination of expensive and comprehensive grid expansion. This can be applied both to the low voltage grid where regulated distribution transformers can be used for the infeed of energy from distributed producers, and in the medium voltage grid where voltage regulators can compensate for the fluctuating infeed and load. However, the grid situation must first be analyzed. The use of voltage regulators and controllable distribution transformers must be carefully configured if the most cost-effective possible implementation of new resources is to be achieved. The presented controllers and the corresponding innovative planning solutions provide an important contribution and support to the grid operators when confronting the technical and economic challenges posed by the energy turnaround.

Bibliography

[1] DIN EN 50160, Merkmale der Spannung in öffentlichen Energieversorgungsnetzen

[2] Eco directive 2009/125/EG

[3] Ohl, Betz, Wagner, Blug, Mladenovic, Optimierte Koordination von Spannungsregeleinrichtungen. EW 12/2015

[4] Website PSS®SINCAL: http://www.siemens.de/pss-sincal

Author

Saskia Baumann holds a B.A. in mechanical engineering and an MBA. She joined Siemens in 2011 and has been working in various positions within the distribution transformers segment of Siemens Transformers. Currently she is the responsible product manager for regulated distribution transformer products.