INTRODUCING THE NEW PRODUCT LINE OF REGULATED DISTRIBUTION TRANSFORMER COOPERATION OF SIEMENS AG AND A. EBERLE GMBH & CO. KG.

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ABSTRACT

As the Distribution System Operator(s) (DSOs) are facing greater and greater challenges to maintain the voltage fluctuations of the network, caused generally by the addition of renewable power plants, the transformer manufacturers try to aid the DSOs and hence offer different regulated distribution transformer solutions. When attempting to solve the fluctuation problems, these are based on different regulation principles. In this paper we are introducing an innovative regulated distribution transformer, developed jointly by A. Eberle GmbH and Siemens AG. A. Eberle (AEB) has developed their own, standalone, low voltage regulation system (LVRSys™), which can regulate the voltage of a Low Voltage Grid, and provide at same time a great Smart Grid experience via monitoring, SCADA communication and PQ analysis. At same time Siemens AG is one of the market leaders in the distribution transformer segment, and has a great knowledge in transformer optimization and manufacturing. The two companies united their knowledge base and developed a top of the line, flexible, technology built into a regulated distribution transformer. This paper addresses the system concept, the implementation results, and introduces the newly designed product.

GENERAL CONCEPT

The general idea was the implementation of AEB's LVRsys™ solution into a Siemens distribution transformer to achieve a compact regulation distribution transformer. The first goal was to build a first goal was to have a working functional model to investigate the practicability of the concept. A 160 kVA distribution transformer with integrated boosters and control electronic has been built, tested and installed on the real network for one year. Since the solution was very promising – especially at the lower rated powers – we've started to work on a design solution which is more optimized and sophisticated.

These transformers usually replace standard distribution transformers in a substation, which means the layout of the new concept should be the same or at least almost the same as a standard transformer. This fact leads us to a design challenge especially if we consider that the booster transformers and the control unit could cause major dimension increment.

In this paper we would like to introduce our solution and describe the challenges we faced during the development. The paper will focus on the following:

- Electrical optimization of the booster transformers and the active part
- Layout optimization of the transformer tank, mechanical implementation of the booster transformers
- Control unit optimization, and integration onto the transformer tank
- Tests and field test results

Figure 1. Functional model of the new regulated distribution transformer (160 kVA)

OPTIMIZATION OF BOOSTER TRANSFORMERS AND THE ACTIVE PART

Integration of booster transformers into the tank of distribution transformer (DT) involves the following issues: the increment of the tank volume and the whole transformer weight, moreover the additional losses of boosters which are added to the basic losses of DT. To handle this situation we optimized the DT's active part and the booster transformers together.

The basis of the optimization process was the fact that we have to keep the losses under the allowable limits without a significant increment of transformer weight and volume. Specifications of customers and the relevant regulation, Ecodesign Directive describe the permitted no-load loss (P0) and load loss (Pk) of transformers at the nominal voltage position. By our solution at the nominal tapping of DT all boosters operate in short-circuit, therefore the additional no-load losses of them are irrelevant, so we focused only on the additional load losses of boosters. The other optimization condition was the maximal area of booster package, which parameter could not exceed the area of DT's active part.

We executed a pre-optimization on the rated power series of DT from 100 to 630 kVA with the relevant regulation ranges from ±4×1.75% to ±4×2.5%. Results showed that we could find the optimum when the sum Pk of boosters is set between 10 and 15% of DT's allowable load loss.

Using standardized, single phase, SU type iron cores and coil formers, the size of booster package remains under the maximal area limit by lower regulation steps and booster ratings. But in case of higher regulation ranges and booster ratings, we did not find any results with the prescribed boundary conditions. To solve this situation, we investigated the possibilities of a unique booster construction.

The so-called free-tape (FT) booster is manufactured with a free configurable iron core, a special wound core technology. By the optimization with FT boosters we could handle the cross-section of the iron core and the dimensions of the core window as free parameters therefore we extended the set of possible solutions.

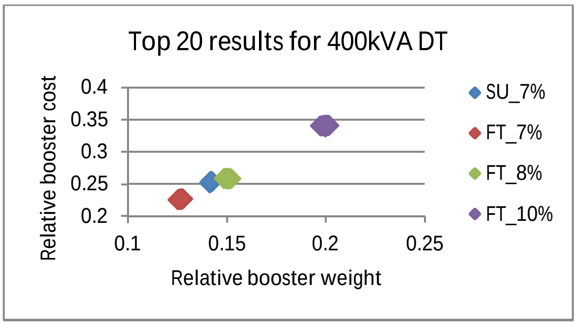

Figure 2. Pre-optimization results of booster transformer for 400 kVA

Figure 2 shows the pre-optimization results of boosters for a 400kVA transformer, where top results mean the lowest material cost of boosters. Relative booster cost and weight are defined as the ratio of whole booster package and distribution transformer (basic DT without boosters) cost and weight.

We can see that SU type boosters fulfil the given boundary conditions only by 7% maximal regulation range. In this case the FT solution possesses better attributions, lower material cost and weight, therefore the introduction of FT type boosters seemed unequivocally profitable.

DESIGN OPTIMIZATION OF THE TRANSFORMER TANK

In case of the 160 kVA functional model the only goal was to be ensured about the possibility of the implementation of the booster transformer into the oil tank. This means that the transformer tank was far from the most optimized solution. The dimensions had plenty of reserves, and since off the shelve connection boxes were used the cabling of the secondary side of the boosters and the connection between the transformer and the control unit were not optimal and sophisticated – as it can be seen on Figure 1. However this solution already had the benefit of flexibility, which means that the placement of the control unit could be varied between the long or short side of the transformer according to the customer's request.

During the development of the first 100 kVA prototype transformer we've investigated plenty of transformer tank design solution where we taken into account the optimal cable layout inside the transformer tank and between the transformer and the control unit, the flexibility of the control unit placement and most of all the dimensions of the transformer itself. The final concept of the design – active part only – can be seen on Figure 3. It can be seen that the boosters are placed below the active part and fixed into a so called booster frame. The booster frame is connected to the frame of the iron core so the transformer and the boosters can be moved together during manufacturing.

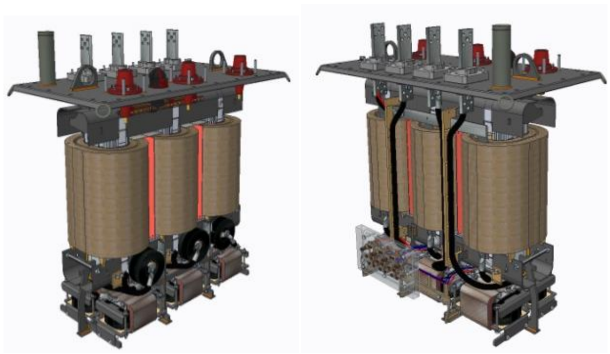

Figure 3. The active part with the booster transformers and the current transformers.

In the functional model the connection of the secondary side of the booster transformer and the power supply of the booster transformers were lead out at the top of the transformer tank which caused long wires. To reduce the material cost and try to minimize the additional copper losses in case of the prototype transformer the connection terminal of the booster transformers is placed on the lower part of the transformer tank. With this solution we could reduced the cable length. Above that this so called cast resin bushing is our own design based on the solution which was used in case of the FITformer REG 2.0. This cast resin bushing gives us a high degree of freedom regarding the numbers of terminals. For example it is possible to place current transformer inside the oil space and wire them out to the control unit – or to the higher level control system.

Figure 3. Cast resin bushings right after the casting process (inside its casting form)

The control unit itself is placed on the side of the distribution transformer. The solution is flexible the electronics can be placed on the short side or on the long side of the transformer tank. Since the control unit is replacing some of the corrugated wall, handling the pressure inside the transformer tank was a challenge, but the tank passed the pressure test without any issue.

CONTROL UNIT

The control unit of the regulated distribution transformer is based on A-eberle's LVRSys™ standalone low voltage regulator system. The switching elements of the regulator are thyristors and the booster transformers are connected into the electronics in an H-bridge topology. The six booster transformers have independent control circuit which means that a phase independent regulation can be achieved. In case of any failure of the control unit electromechanical bypass contactors short circuit the booster transformers and the transformer can be operated as a standard distribution transformer at its nominal tapping position. The system has a sophisticated control algorithm which can take into account the actual current flow on the grid and if the impedance of the distribution system is set up the control unit calculate the voltage drop on the network and adapts the voltage setpoint according that. Above that since the regulation electronics is semiconductor based, rapid switch over procedure can be achieved and with the latest optimized firmware we could reach the milliseconds range for a switch over.

Not just the transformer was optimized after the functional prototype model but the control system also. The new optimized design lead us to massive size reduction, reduced and more optimal wiring, easier service concept, user friendly interface and not least it became more cost effective. The old and the optimized control unit can be seen on the picture below.

Figure 4. The old (on the left) and the optimized (on the right) control electronics

One of the optimization results was that the power stage and the driver stage were integrated into one unit. The thyristors were implemented directly on the driver board. The 120 signal lines from the driver boards to the thyristors were eliminated which gave better noise immunity easier assembly and clean design. If any hardware error occurs the control unit display shows the user where the error happened and which board has to be replaced. The control unit integrated with the power stage is a plug and play solution. The power stage can be bypassed from the transformer which means that the maintenance of the control system is done without the disconnection of the transformer from the network.

The new concept require less hardware components the costs thus be reduced. There is only an USB interface, a RJ45 interface and a temperature signal available. The generation before had also RS232, RS485 and 3 temperature inputs.

TEST AND FIELD TEST RESULTS

In this chapter we would like to present some interesting test result of the transformer. As it was mentioned above, the most challenging part of the design was to keep the loss levels as low as possible. Therefore the loss measurement of the transformer gave us a validation about the design. The no load loss measurements were performed three times. We measured the no load losses of the booster transformers, the active part and the losses of the complete system. The results can be seen in Table 1.

	No load loss P_0
Small booster	9.99 W
Big booster	14.16 W
Transformer active part	193.95 W

Table 1. No-load loss measurements of the transformer active part and the booster transformers

The no load losses were measured in every position with and without the control unit. The results can be seen in Figure 5.

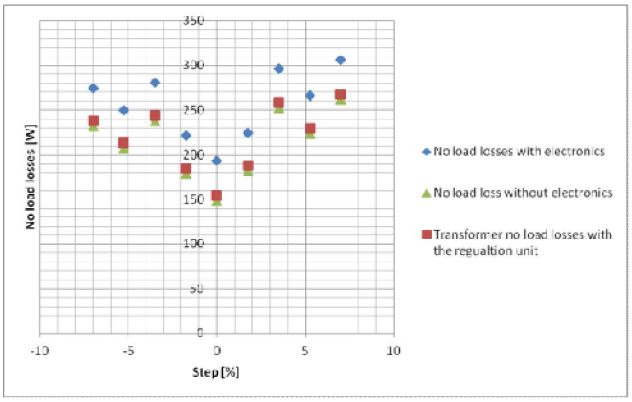

Figure 5. No load loss measurement of the transformer with and without the control electronics

The measurements results shows as the boosters are turned on and off in each phases. Obviously the losses are the highest where both booster transformers are turned on. A small asymmetry in the losses can be seen in the opposite steps (e.g -3.5% and 3.5%) which is caused by the different excitation direction. From the no load loss measurement we defined the losses of the system. Since according the Voltage regulated distribution draft in the loss measurements the transformer and the regulation unit losses has to be taken into account, we separated the losses of the control unit (which contains the logic) and the regulation unit.

On the 100 kVA prototype two different short circuit tests were performed according to the IEC 60076 standards. First test was done to ensure about the mechanical strength of the system, so it was performed without the control unit. And the second test was done including the control unit. The test was performed at the worst case, namely at the outermost position where the currents are the highest. The tests were performed according the above mentioned standard and after every short circuit the control unit functionality was tested. The transformer passed the test without any issue.

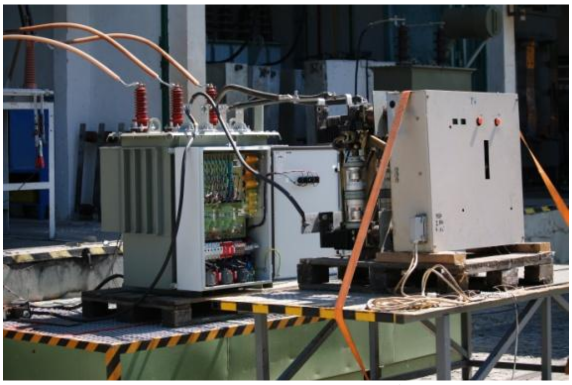

Figure 6. The 100 kVA prototype transformer at the short circuit tests

The 160 kVA functional model was installed on a distribution network and was field tested for one year. During the field test period there weren't any issue with the regulation unit. The partner DSO has no issue with the parameterization of the control unit and was satisfied with the overall product.
The control unit has a large buffer memory where it can store the measured values, error logs, and actual taping position. These log file were analyzed after the field test period. The following chart shows the phase voltage and the actual taping position for one day period. It can be seen that when the voltage drops (or rises) the regulator switch over to adjust the voltage to the desired value.

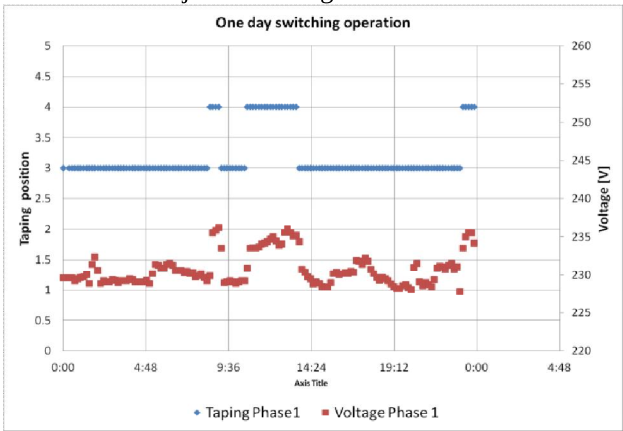

Figure 7. One day switching operation and voltages of the field test transformer

SUMMARY

In this paper we introduced a new regulation distribution transformer which was a result of collaboration of two companies with two different expertises. A 160 kVA functional model was built tested, and field tested and taken into account the experiences from the design and manufacturing a concept for a new product line was developed. Based on this a 100 kVA and 400 kVA transformer was built and the possibilities of 630 kVA regulated distribution transformer were investigated. The results show that this product could have a lot of potential relative to the competitor's solution. Such as state of the art semiconductor based regulation which allows independent phase control, sophisticated control algorithm which taken into account the exact impedance of the network, modular design with ease of maintenance, and safe fault mode which switch back to the nominal position of the transformer. Above that the solution can keep the off load tap changer at the medium voltage side and dual medium voltage windings design can be realized with this solution. However to be open and honest it has its disadvantages such higher loss levels, dimensions and weight but these can be handled during the optimization phase of the transformer.