DISTRIBUTION TRANSFORMERS - READY FOR THE SMART GRID

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ABSTRACT

For the past hundred years the definition of the term distribution transformer has been closely connected to its function: to transform and distribute electric power to end users. The direction of energy flow was clearly defined: from medium voltage network to low voltage network. All controls, protective measures and other considerations were based on this fact.
Today, all players in the energy sector who sense a responsibility for our common future are taking steps to reduce CO_2 emissions.

• Utilities attempt to reduce losses in their distribution network, consequently impelling leading transformer producers to reduce the losses inherent in their products.

• Energy producers develop and introduce green, renewable energy sources, convert this energy into electric power and offer it to utilities. In several countries such as Germany, the state subsidizes this activity starting with the smallest solar panels, though biogas and geothermic energy, all the way up to wind generators. This activity has spawned a new trend: the diversification of power generation.

• This diversity in power sources has created a challenging task for utilities. They must monitor, evaluate and control the medium- / low-voltage network by implementing new solutions, tools and devices – the Smart Grid.

Siemens is prepared to answer these challenges. Technology and Innovation management of the Transformer Business Unit within Siemens, in cooperation with Siemens Corporate Technology, have defined and supported several projects dealing with these issues. The results of these projects are now ready for implementation and installation.

This paper summarizes the status and results of these projects in three main fields:
• Distribution transformers with reduced losses – amorphous core and other considerations
• A new control element for the Smart Grid: the regulated distribution transformer
• Upgraded monitoring and overload management of distribution transformers.

DISTRIBUTION TRANSFORMERS WITH REDUCED LOSSES – AMORPHOUS CORE AND OTHER CONSIDERATIONS

Siemens is committed to the development and production of environmentally friendly products. Although reduction of CO_2 emission is not a direct goal of the Smart Grid concept, we are convinced of the necessity to introduce low-loss distribution transformers as an integrated part of forthcoming Smart Grid solutions.

Loss reduction concept in general

Although load conditions for distribution transformers are well-known to most readers, Figure 1 can act as an illustrative aid in our discussion.

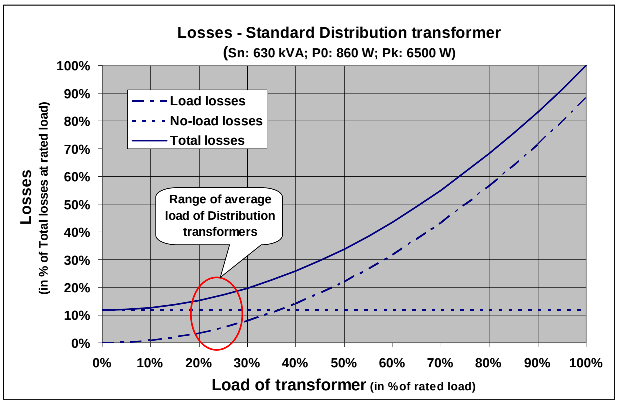

Figure 1: Transformer losses as a function of load

Since the average operating load range for distribution transformers is 20-25%, it is obvious that the focus of development is on the reduction of no-load losses.
In Europe the average CO_2 emission factor for electrical energy production is about 0.3 kg/kWh. Using this it is easy to calculate that each watt reduction in no-load loss is equivalent to a 2.6 kg annual reduction in CO_2 emission.
There are two main developmental directions under consideration: the application of amorphous core material and further development of grain-oriented electrical steels.

Amorphous Steel vs. GOES

Table 1 compares various physical and design characteristics of the GOES- and amorphous-steel-based designs.

It is important to point out that the use of an amorphous steel core in single-phase transformers in the power range from 10 to 200 kVA shows a clear-cut advantage, while larger 3-phase units for Europe prove challenging in terms of meeting requirements on noise and short circuit prevention. Therefore, new trends in GOES development (thin-gauge technology, "one grade up" solutions) can serve as a competitive alternative solution to amorphous steel cores in the European market.

Core raw material	GOES	Amorphous
Specific losses at 1.3 T, 50 Hz	0.4 … 0.7 W/kg	0.2 W/kg
Saturation	> 2.0 T	~1.6 T
Thickness	0.2 …0.35 mm	0.02 …0.025 mm
Machinability	easy	complicated
Brittleness	no	yes
Dynamic stress-proofness	unproblematic	critical
Core execution availability		
Stacked	yes	no
Wound	yes	yes
Core cross-section availability		
Round / oval	yes	no
Rectangular	yes	yes

Table 1: Comparison of GOES and Amorphous material

Development of amorphous transformers

Siemens has extended its portfolio of single-phase and three-phase liquid-immersed distribution transformers designed with amorphous steel cores.
Our Canadian factory is already set to produce single-phase amorphous steel core transformers in the 10 to 100 kVA power range.
Our European factories have developed and successfully tested three-phase units in the 100 to 630 kVA range. Table 2 shows typical comparative data for 250 and 400 kVA transformers (Ck/A0 category according to EN 50464-1).

	Rating [kVA]	No-load loss [W]	Load-loss [W]	LwA [dB(A)]	Length [mm]	Width [mm]	Height [mm]	Weight [kg]
GOES-based Ck/A0	250	300	3250	47	1170	735	1270	930
Amorphous-based	250	100	3250	56	1200	800	1170	1350
GOES-based Ck/A0	400	430	4600	50	1120	850	1300	1340
Amorphous-based	400	140	4600	60	1400	900	1240	1800

Table 2: Typical comparative data

A NEW CONTROL ELEMENT FOR SMART GRID: REGULATED DISTRIBUTION TRANSFORMER

Decentralized generation of electric power by means of photovoltaic elements, wind energy etc. reduces the distances over which it must be transmitted. This, in turn, results in a reduction in transmission and upstream grid losses. Problems are encountered with decentralized electric power generation if – as is particularly the case in rural areas – there is no adequate power consumption. In such cases, grid voltage increases to its upper limit, triggering a shutdown of the power generation process. This will not occur if the excess energy is transmitted to the medium-voltage grid and then dissipated to high-consumption areas.

In order to control the energy flux from low to medium voltage, it is necessary to have a transformer with a variable voltage ratio which allows switching without an interruption in the flow of energy. Conventional technology employs a traditional on-load tap changer on the medium-voltage side of the transformer (Figure 2).

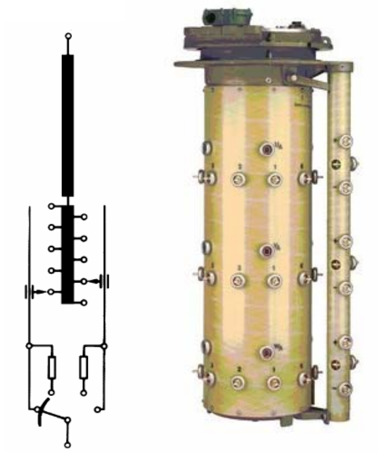

Figure 2: Conventional tap changer

New concept

The new approach uses a distribution transformer with taps on the low-voltage side of the transformer and a combination of low-voltage switchgear with contactors, breakers, solid-state relays (thyristor-based) and an appropriate control unit (Figure 3). The solid-state relay acts to ensure continuous current flow by conducting the current during the mechanical switching operations. This principal solution is under legal protection (Patent No. WO/2010/072622).

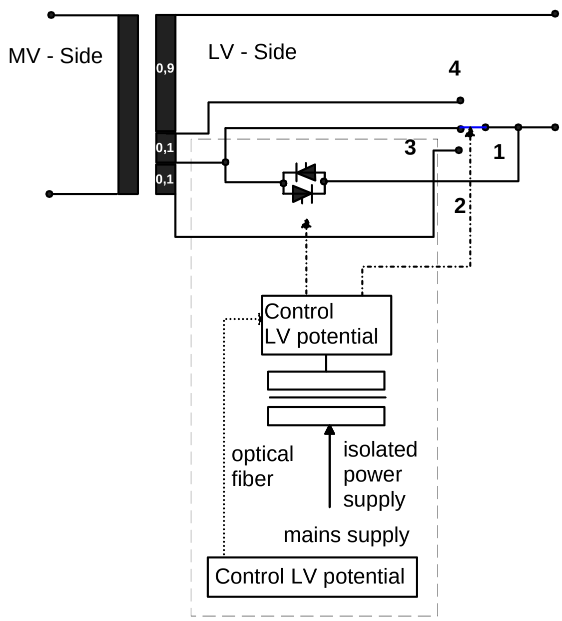

Figure 3: Principle of on-load tap changer

Tappings in LV windings

It is obvious that tappings can be created by whole turns. The number of turns in LV windings ranges from 25 to 80, so the theoretically possible "voltage step" is between 1.25 and 4 %. The patented concept makes it technically possible to create two additional tappings in any LV winding. To provide a wider range of control over the voltage ratio of the transformer it is necessary to create tappings after 2, 3 or 4 turns. As a final result, the voltage step at transformer LV terminals will range from 5 to 8 %.

Control unit

The switchgear 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 4).

Logical condition to fire thyristors:

|voltage across contact 1| - |voltage across contact 4| > 0

Logical condition to extinguish thyristors:

|voltage across contact 1| – |voltage across contact 3| = 0

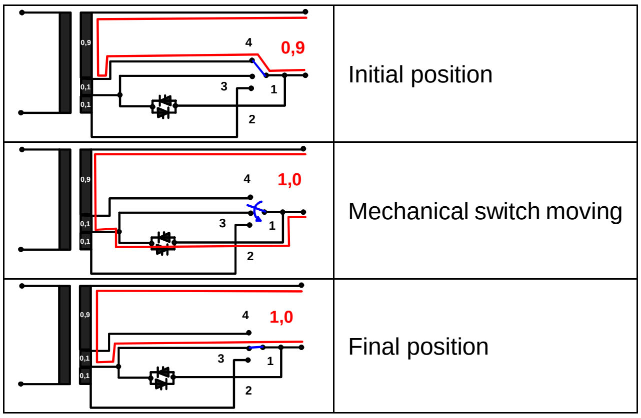

Figure 4: Commutation process

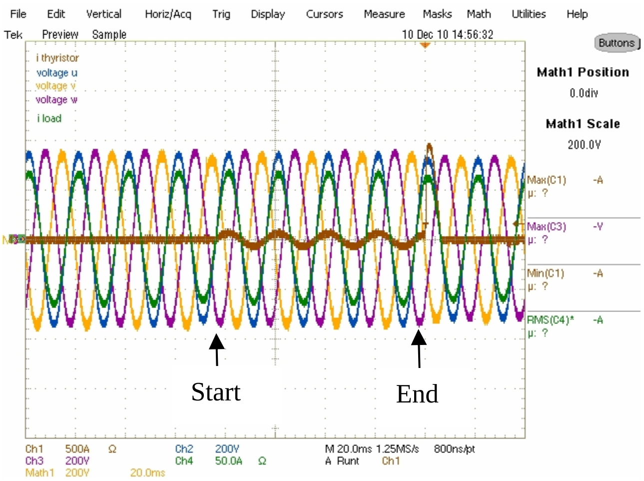

Figure 5: Measured data from "working model"

During tap changes an inter-turn short circuit is possible. In order to limit the current flowing through the solid-state relay, a reactor or resistor is wired in series.

Figure 5 depicts a switchover from tap 2 to tap 1 triggered by decreasing the voltage. An inter-turn short circuit of 10ms duration occurs. Current flow is limited to 500A by a resistor.

The results of laboratory tests performed on a "working model" are promising. Flickers caused by switching operations remain within standard limits.

Integration issues

There are two integration processes in progress:

1.) The solution has to be integrated into the MV/LV Smart Substation. This goal necessitates a standard interface for the control unit. With this interface, any type of control unit implemented on the low-voltage grid will be able to give a command for the transformer's control unit to alter the voltage ratio.

2.) The transformer's control and switching unit has to be integrated into the transformer itself. The goal of this integration is to keep its outside dimensions and the positions of transformer connections very close to those of existing conventional transformers.

UPGRADED MONITORING AND OVERLOAD MANAGEMENT OF DISTRIBUTION TRANSFORMERS

Condition monitoring (CM) is the process of monitoring a machinery condition parameter such that a significant change is indicative of a developing failure.

During the last decade CM has become a standard requirement in large power transformer (LPT) specifications. Using sensors such as on-line dissolved gas analysis (DGA), changes inside the transformer could be monitored on-line and in real time. Other measurement devices could be used to track the condition of the on-load tap changer or the bushings to obtain all necessary monitoring parameters for a transformer.

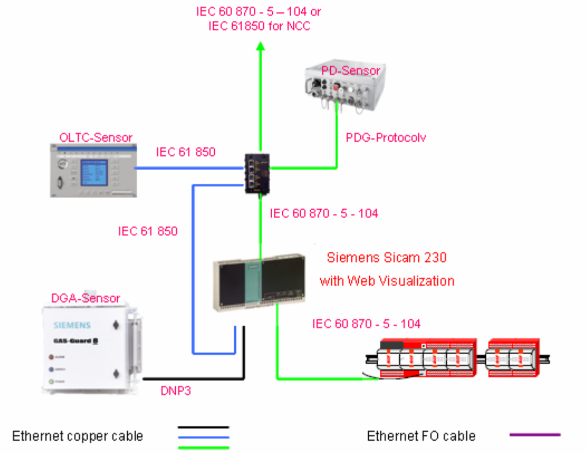

Figure 6: LPT CM Sensor overview

As a general guideline, the cost of a CM system ranges between 5 and 10% of the cost of a transformer. Applying the same concept to a distribution transformer (DT), the CM system price will exceed this ratio by far.
In addition to measurable variables, non-measurable condition parameters such as relative aging or overload capability are highly valuable monitoring indicators.

Such computation models can be run using only existing operational parameters. Using the existing sensing equipment at the distribution substation and implementing the calculation algorithm into the existing substation control hardware offers a very cost-effective method of attaining high-value information on the status of the transformer.

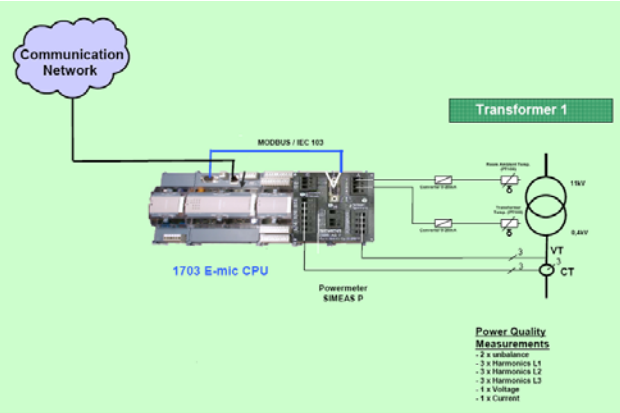

Figure 7: DT CM sensor overview

The loss of life (LoL) of a transformer is defined by the degradation of the paper insulation on the winding.
According to IEC 354 aging (A) as a function of temperature is calculated using the formula:

$$A = 2^{\frac{T_{HS} - 98°C}{6°C}}$$

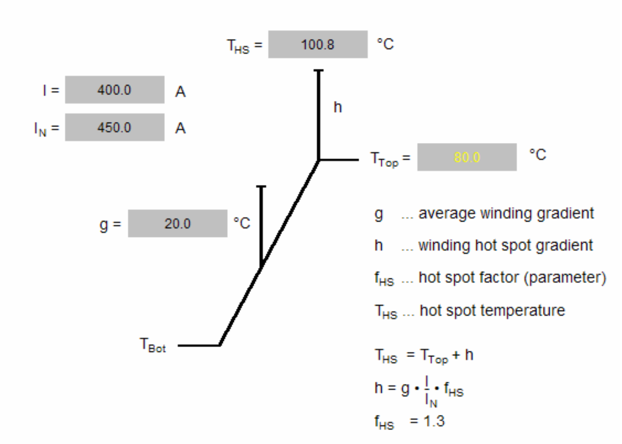

Figure 8: Hot spot calculation

Based on the measured maximum oil temperature and the load current of the transformer, the hot spot in the winding is calculated using the formulas given in Figure 8.

This hot spot temperature is then used in calculating a relative value for loss of life:

$$LoL = \frac{\sum_{n=1}^{N} A_n * t_n}{N * t_n}$$

Here, A_n denotes the relative aging rate during interval n, t_n is the n^{th} time interval, n is the number of each time interval and N denotes the total number of intervals during the service period under consideration.
From the hot spot temperature we can also calculate the load factor. The load factor is the ratio between the actual load on the transformer and the maximum load possible for a defined time period without the maximum hot spot temperature T_{HS} being exceeded.

Although special sensing equipment is not cost effective when used in conjunction with distribution transformers, the Smart Grid opens up the possibility of implementing condition monitoring functions such as loss of life and load factor, thereby maximizing transformer utilization without increasing the risk of failure.

SUMMARY

Power supply in the future will present our infrastructure with major challenges. Demographic dynamics, resource scarcity and a strong environmental focus will keep the power industry busy. Intelligent energy management within the grid will allow more efficient use of the power produced by integrating and bundling small power generation plants. In the future, power generation surpluses will have to be stored in bulk, in such stores as heat pumps or e-cars.

All parties involved will need to follow this trend and think of intelligent solutions tailored to the so-called Smart Grid.

For distribution transformers, the challenges in the areas of increased energy efficiency, on-load voltage regulation and higher utilization must be taken on.

Siemens is well prepared to face these challenges, and has provided here an overview of one possible future concept for distribution transformers used in the Smart Grid.