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Transformer monitoring according to IEC 60354

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High and middle voltage transformers are particularly important components in electrical energy supply networks. This statement is true even without considering network breakdown situations (blackouts). Electricity is required to sustain our comfortable standard of living, and without electricity it would not be possible to remain competitive. As a result, transformers deserve special attention.

■ General information

The following document describes a method for optimising the load on a transformer and calculating its lifetime consumption. The calculation procedures comply with international regulation CEI/IEC 60354: 1991 (Loading guide) or VDE 0536/3.77.

Particularly attention is paid to implementations using a REG-D or REG-DA voltage regulator from A. Eberle GmbH & Co. KG.

The "transformer monitoring" function can also be implemented on every voltage regulator in this series. This results in large additional operating benefits for very low investment costs.

The failure rate of a transformer increases exponentially with increasing service life, but the transformer‘s service life decreases exponentially with increasing load. In the past, these observations (confirmed in practice as well) would lead to differing standards and solutions although they all had the same goal of reliably measuring the "fever curve" or "health" of the transformer.

The hot spot temperature is the most important parameter; it not only indicates the load margin but also the transformer‘s lifetime consumption. Statistics reveal that approximately 30% of all transformer faults can be identified as coil faults [Cigre SC 12 WG 12.05].

■ Hot spot temperature

The highest temperature in a transformer coil is on the inside of the coil. On the coil surface, the insulation oil can absorb the heat and transfer it to the radiators. On the inside of the coil, however, relatively little oil is available for heat transfer. Furthermore, due to the geometric relationships, heat radiates from one wire bundle to another.

Measuring the temperature directly inside the coil is expensive and complicated. Generally, only optical sensor systems can be used because of the high voltages and strong electromagnetic fields. However, in order to obtain information on the hot spot without a direct measurement, indirect measurements based on the oil temperature and current have proven useful.

The temperatures in the transformer behave as shown in Figure 1. The simplified illustration shows that the oil temperature increases from the base of the transformer to the lid (left upright). In principle, the same behaviour is valid for the temperature on the inside of the coil. However, this is shifted towards higher temperatures by the value of the transition temperature g_r (right upright). The value of this temperature difference is a transformer constant that can be found in the technical specifications of the transformer or obtained from the manufacturer.

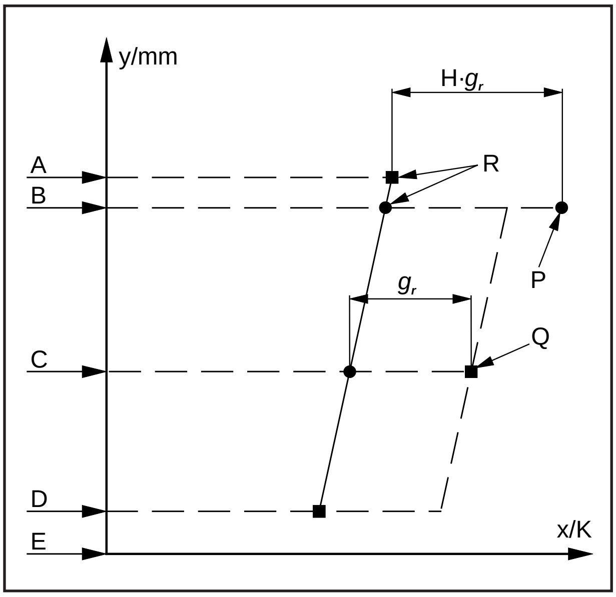

Figure 1. *Temperature model of a transformer according to 1EC 60354.*

Note: *The ordinate (y-axis) is given in mm and shows the position of a coil‘s measuring point; the abscissa (x-axis) is given in K because it primarily deals with temperature differences between the coil exterior and the coil interior.*

- A *Temperature of the uppermost oil layer*
- B *Temperature in the transformer tank on the upper end of the coil*
- C *Temperature of the tank‘s oil filling in the centre of the coil*
- D *Temperature on the underside end of the coil*
- E *represents the ground of the tank*
- P *Hot spot or hot spot temperature*
- Q *average coil temperature*
- R *Points that can be assumed to have equal temperature*

However, the deciding factor for the quality of the insulation - and thereby for the transformer's service life - is the hot spot or the hot spot temperature (P). The hot spot is determined by the parameter $H \cdot g_r$ ($H \cdot g_r$ = hot spot to top oil temperature difference). This is also a transformer constant and can be determined from the temperature difference between the oil (measured in the upper oil layer (A)) and the hottest spot of the transformer (P).

This temperature occurs on the inside of the coil and can also be considered to be the sum of the oil temperature and a temperature component generated by the current.

A function that recreates the coil's thermal behaviour over time and that is valid for nearly all transformers must be taken into consideration because a brief raise in the current does not immediately lead to an increase in the current-dependent temperature component.

The control circuit for calculating the hot spot temperature is shown in Figure 2.

The oil temperature, current measurement and several transformer parameters ($H \cdot g_r$ and y) are required to calculate the hot spot temperature (and thus determine the thermal properties of the transformer).

The hot spot temperature obtained from the addition of both temperatures is, as already described, a further operational measurement quantity that plays an important role in determining the optimal load profile as well as in calculating the lifetime consumption.

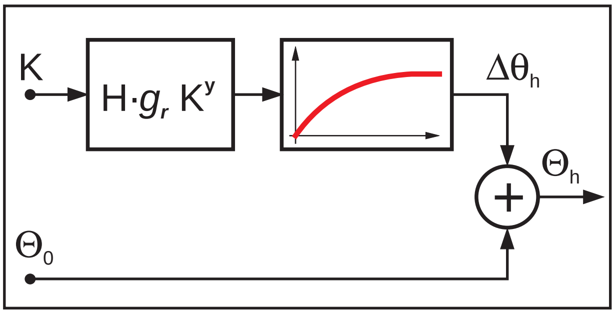

Figure 2. *Control circuit for calculating the hot spot temperature according to IEC 60354*

K	*Load factor I/In*
Θ_0	*Measured oil temperature*
$H \cdot g_r$	*Hot spot to top oil temperature difference*
$\Delta\Theta_h$	*Hot spot temperature increase*
y	*Coil exponent*
Θ_h	*Hot spot or hot spot temperature*

■ Lifetime consumption

A transformer's lifetime consumption is primarily dependent on the thermal load on the coil insulation throughout its operation. The crucial question is: how much does the transformer age compared to the operating time?

Detailed considerations of the relative thermal change of the insulation were employed by *Arrhenius*. The physical foundations were confirmed by *Montsinger* for the temperature range 80 °C to 140 °C and were summarised in a simple formula. This says that a temperature increase of 6 K results in the doubling of the lifetime consumption of a device.

The relative lifetime consumption V is then calculated as follows:

$$V = \frac{\text{lifetime consumption at } \Theta_h}{\text{lifetime consumption at } \Theta_{hr}} \qquad (1)$$

Θ_h hot spot temperature

Θ_{hr} nominal hot spot temperature.

From which, according to *Montsinger*:

$$V = 2^{(\Theta h - \Theta hr)/6} = e^{0.693\,(\Theta h - \Theta hr)/6} = 10^{(\Theta h - \Theta hr)/19.93}. \qquad (2)$$

The nominal hot spot temperature Θ_{hr} is 98 °C for a transformer according to IEC 60354 (VDE 0536). This temperature occurs when the transformer operates at nominal power with a coolant temperature of 20 °C. The increase in hot spot temperature is thus 78 K, 13 K higher than the average coil over-temperature g_r of 65 K. The nominal hot spot temperature Θ_{hr} represents the normal ageing of the insulation corresponding to the operating time and thus results in a relative change of V=1 (according to equation (2).

If, for example, in eq. (2) Θ_h = 104 °C and Θ_{hr} = 98 °C, a relative change of V=2 will result. This means that for a given operating period, the lifetime consumption doubles if the temperature increases by 6 K.

Values for the relative lifetime consumption, dependent on the temperature, are shown in Table 1.

Under these conditions, the IEC 60354 (VDE 0536) standard assumes the following:

- At normal load, the current is limited to 1.5 x I_N,
- The hot spot temperature of the coil is limited to 140 °C, because the laws stipulated by *Arrhenius* do not apply to anything above this temperature (due to the accelerated ageing processes).
- In emergency operation, nominal currents >1.5 x I_N are permissible, but the hot spot temperature must not exceed 140 °C and the oil temperature must not exceed 115 °C. There is danger of leakage if higher oil temperatures occur.

Table 1 *Relative lifetime consumption according to IEC 60354*

Θ_h	80 °C	86 °C	92 °C	98 °C	104 °C	110 °C	116 °C	122 °C	128 °C	134 °C	140 °C
V	0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	64.0	128.0

■ Determining the absolute lifetime consumption

The relationships are very straightforward for a constant hot spot temperature. The absolute lifetime consumption L is the product of the relative lifetime consumption V and the operating time T.

$$L = V \cdot T. \quad (3)$$

If a transformer operates for one day with a hot spot temperature of 116 °C, it ages by 8 days (V= 8, Table 1) during this time.

However, in practice, eq. (3) cannot be used, since the surrounding temperature and the load level of the transformer change continuously. Therefore, the following integration should be used for a given operating time T.

$$L = \frac{1}{T} \int_{t1}^{t2} V \cdot dt \quad (4)$$

with

T t_1- t_2
t_1 Start time
t_2 End time.

■ Cooling of the transformers

It is recommended to control the hot spot temperature using appropriate cooling measures because this has the largest influence on the service life of the transformer. The following cooling forms are defined in VDE 0532/T. 1 (Table 2):

ONAN	Oil Natural, Air Natural (no additional cooling measures)
ONAF	Oil Natural, Air Forced (with fan)
OFAF	Oil Forced, Air Forced (with oil pump and fan)
OFWF	Oil Forced, Water Forced (with oil and water pump)
ODAF	Oil Directed, Air Forced (with oil channels and fan)
ODWF	Oil Directed, Water Forced (with oil channels and water pump)

Table 2: *Cooling forms*

The various cooling methods influence the thermal behaviour of the transformer. The value of the parameter H·g_r and the coil exponent y depend on the cooling method. These transformer-specific measurements can either be found in the transformer's data sheet or obtained from the manufacturer. If no data are available, the standard provides appropriate reference values for medium and large power transformers. Recommended values according to IEC 60354/VDE 0532/T. 1 are:

Type of cooling	$H \cdot g_r$	y
ONAN/ONAF	23 K	1.6
OFAF/OFWF	22 K	1.6
ODAF/ODWF	29 K	2.0

26 K and 1.6 are recommended for distribution transformers with ONAN cooling.

It is particularly important to note that when the cooling method is changed the parameters in the monitoring device also change automatically. When commissioning the device, it is important to ensure that the appropriate values are entered for each type of cooling.

■ Voltage regulator and transformer monitoring

The REGSys™ voltage regulator system is used worldwide in over 12,000 medium and high voltage transformers, carrying out functions such as regulation, monitoring, recording and statistics calculations. In addition to these, the regulator can also take over the transformer monitoring function with fan or pump control (Figure 3).

Thus traditional functions of a voltage regulator such as measurement transducer, recorder, statistical unit, ParaGramer or logging can be combined with increasingly important functions. In the future, knowledge of both the hot spot (and thereby of the current load margin) and the remaining service life will take on increasing importance, because the transformers are under heavier loads than ever before due to economic reasons.

The running times of the oil pumps, fans or fan groups are calculated in addition to an IEC compliant measurement. The operating hours of the transformer, tap-changer and the oil pump are also calculated in the same way as the estimation of the contact load in the tap-changer using the I^2t equation.

If required, additional measurement quantities such as the oil level in the transformer or tap-changer can be shown on the display of the regulator.

If a real-time monitoring system is used to calculate the amount of gas in the oil (DGA = Dissolved Gas Analysis), the regulator offers several possibilities for recording and displaying the measurements and, when necessary, to transfer them to the control system via a protocol interface. Archiving in the voltage regulator and backing-up data using the WinREG Windows software are naturally available.

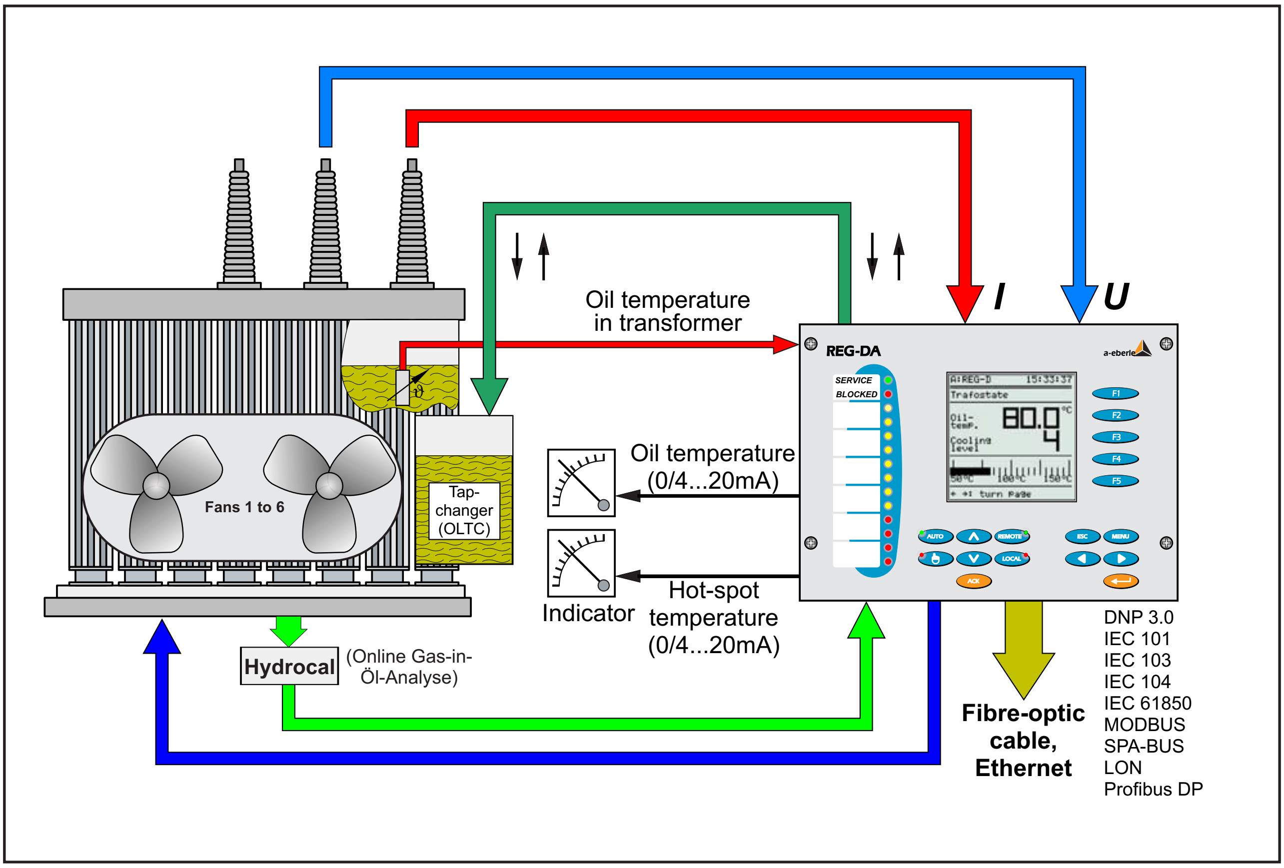

Figure 3. *Basic functional schematic of transformer monitoring module TMM*

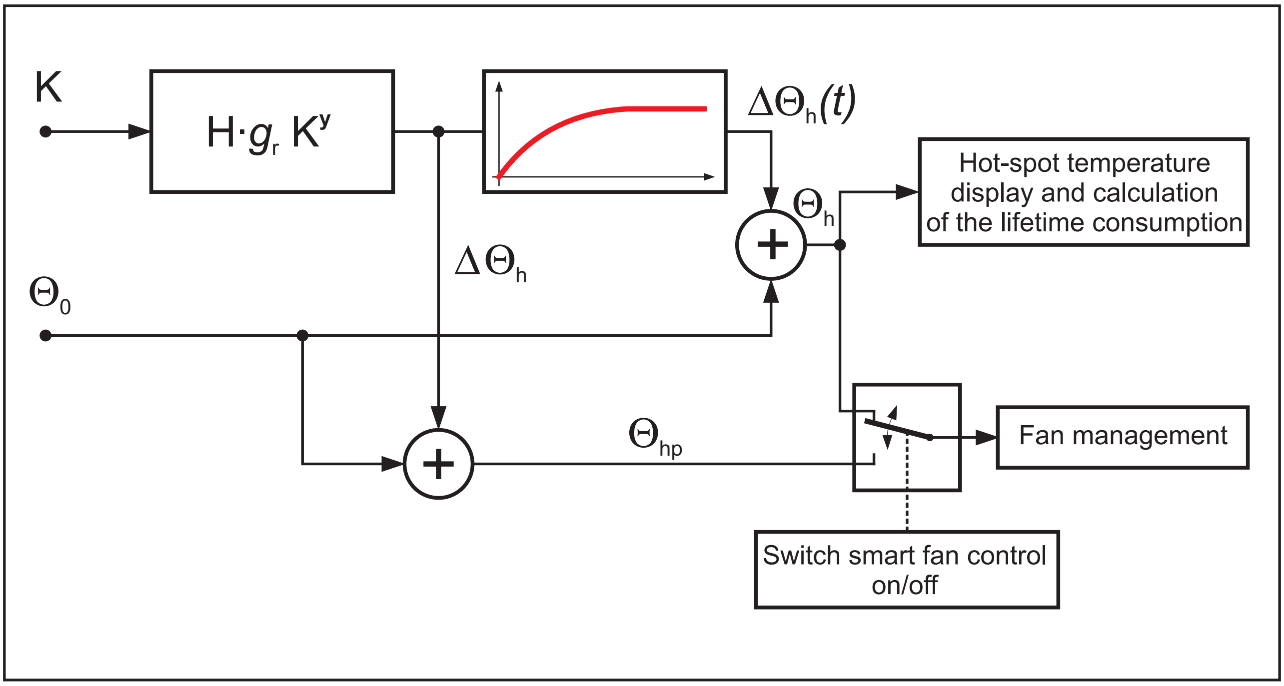

Figure 4. *Advanced control circuit for calculating the hot spot temperature according to IEC 60354 with intelligent ("smart") fan control*

K	Load factor I / I_n	Θ_0	Measured oil temperature
$H \cdot g_r$	Hot spot to top oil temperature difference	$\Delta\Theta_h$	Hot spot temperature increase
Θ_h	Hot spot temperature	Θ_{hp}	Expected hot spot temperature
y	Coil exponent		

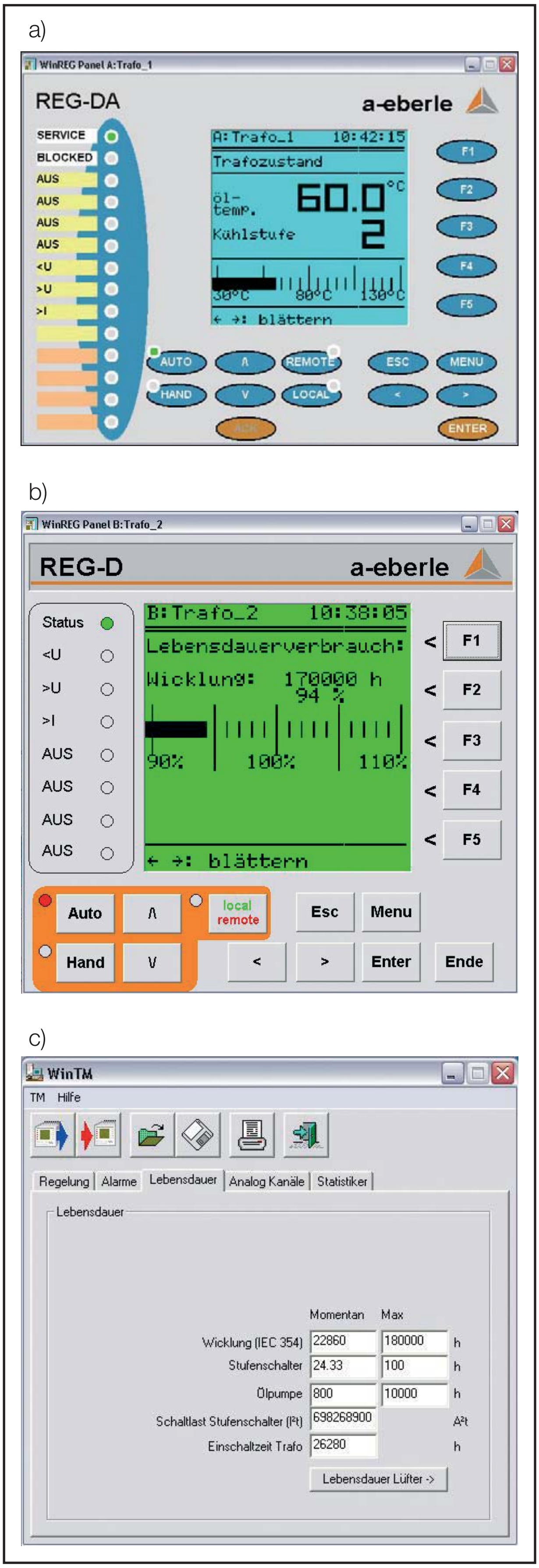

Figure 5:
Real-time display of the transformer monitoring module TMM on the regulator display with the WinREG operating software (a, b), as well as WinTM (c) as parameterisation

■ Intelligent fan control

Intelligent or "smart" fan control refers to pre-emptive control of the fan. The time delay component in Figure 4 is switched off to allow the hot spot temperature control to be determined. Using this process, the hot spot temperature immediately stops increasing when the load current increases and the fans are activated without delay. This results in a lower hot spot temperature and thereby a lower lifetime consumption.

However, the time component remains active when calculating the lifetime consumption, since the hot spot can only be modelled realistically when the coil's behaviour over time is taken into consideration.

■ Operation and display

Transformer monitoring is controlled by menus on the display of the REG-D (REG-DA) voltage regulator or via the WinREG software (Figure 5).

■ Updating the transformer monitoring function

Each REG-D or REG-DA voltage regulator – regardless of the year of manufacture and firmware version – can be upgraded to include the TMM transformer monitoring function. The update item consists of both a hardware and software component. The software module is loaded via the PC using the regulator's COM1.

A corresponding analogue module must be added for the regulator to be able to output the temperature as a mA signal or directly as a PT-100 signal. Each regulator has at least one or more empty connection point that can be equipped at a later point in time and which can accommodate the selected module. A 3-conductor connection is required for a direct PT-100 connection. This enables distances of up to 200 m between the transformer and the regulator to be connected without significant measurement errors occurring caused by the influence of the feeder cables.

Furthermore, the oil level of the transformer and/or of the tap-changer can be measured and supplied to the regulator. The information can be shown on the regulator display and, if necessary, output via the serial interface (Figure 6).

■ Perspective and future

The addition of the TMM transformer monitoring functionality to the REG-D / REG-DA voltage regulator (according to IEC 60354) is an innovation that is certain

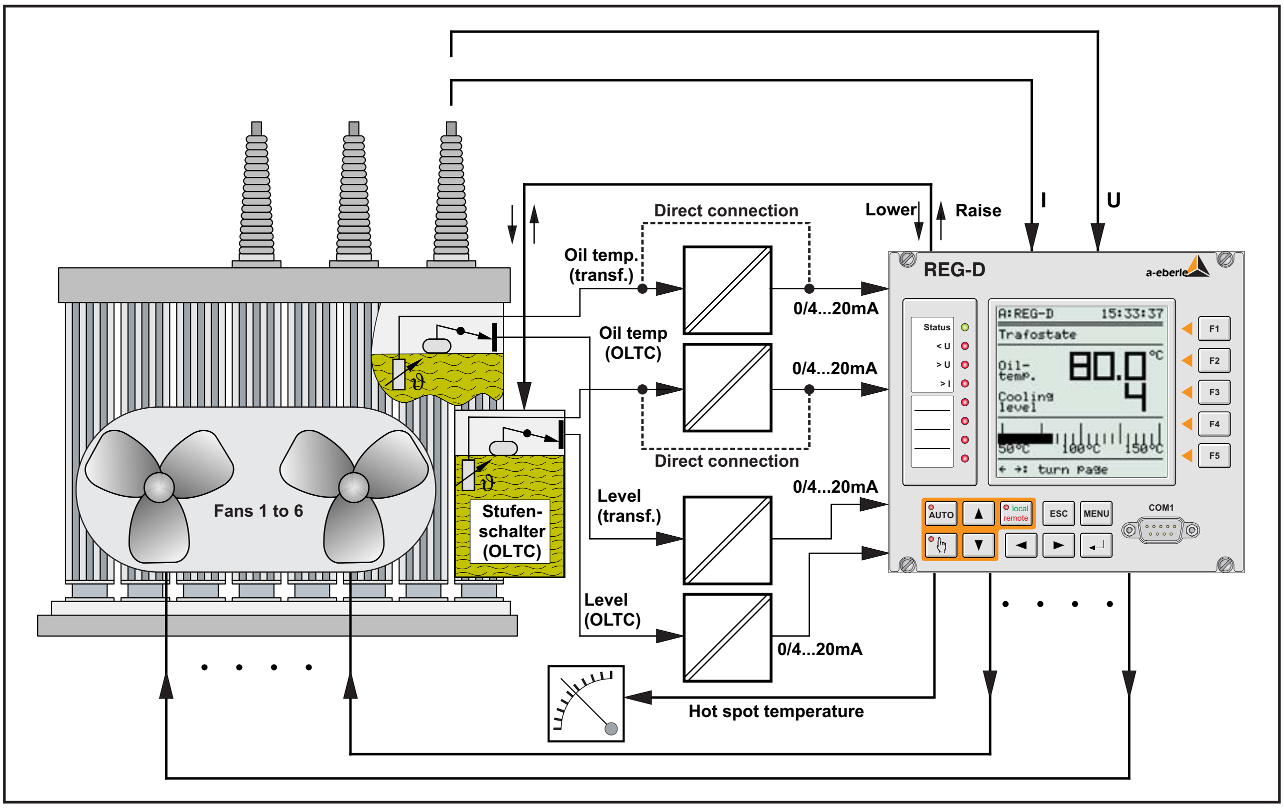

Figure 6. *Extended basic functional schematic of transformer monitoring module TMM*

to play an important role in future concepts for medium and high voltage transformers. For the first time it is possible to input an important variable - the hot spot temperature - into the voltage regulator to enable optimal transformer operation.

Additionally, an independent field unit with extended functions (REG-DM) is available.

All relevant measurement values can also be transferred to the control system, i.e. the implementation successfully complies with IEC 61850.

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