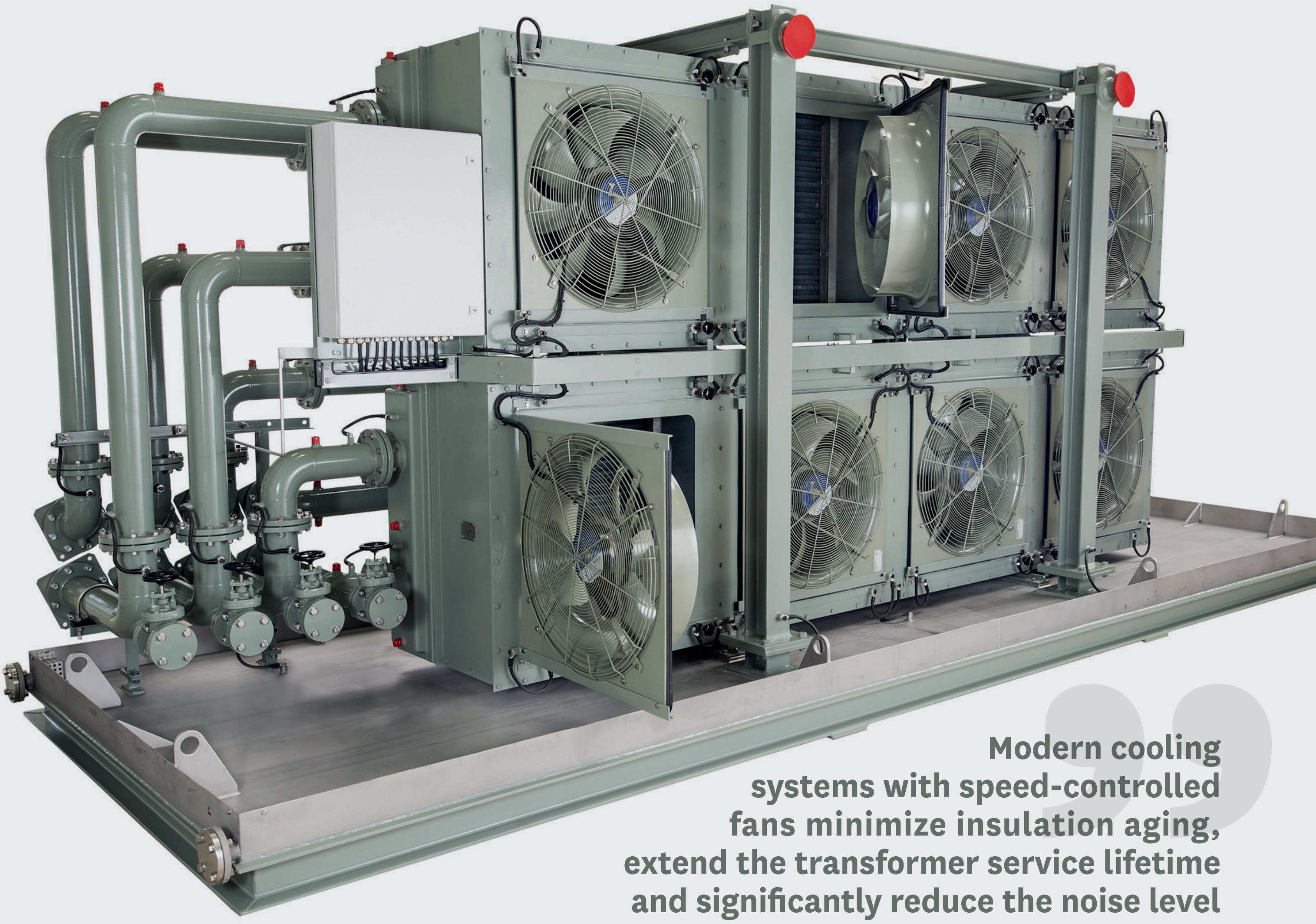


> **Modern cooling systems with speed-controlled fans minimize insulation aging, extend the transformer service lifetime and significantly reduce the noise level**

Variable-speed air-forced cooler technology

Solutions for upgrading or expansion of transformer oil cooling systems

ABSTRACT

Advanced air coolers are able to cool transformer oil more efficiently than older systems. Replacement or expansion of cooling plants by a new solution can lead to reduction of oil temperatures by several degrees and have a positive influence on the service lifetimes of oil and therefore transformers. Or, conversely, better coolers can – at the same oil temperatures – enhance the maximum performance of a transformer or allow it to operate at a higher average load. The upgrade or expansion of a cooling system in some cases can eliminate the need for immediate investment in a new transformer, or extend the life cycle of existing transformers.

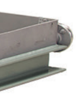
KEYWORDS

component, cooling, upgrade, lifetime, performance

Introduction

Today, many relatively old transformers are being operated at, or beyond, the expected rated performance limits at the time of their design. This is associated with higher load and hence higher average temperature of the transformer oil, which leads to faster deterioration of the oil and solid insulation, meaning the transformer itself. The Montsinger Rule [1] illustrates the key role played by oil cooling in the service life of a transformer: a rise of approximately 8-10 K in oil temperature results in halving the transformer life cycle.

To extend the service life of a transformer, or to upgrade it for higher output require-



ments, modernization and/or expansion of the oil cooling system has proved effective. Today, forced air oil coolers (AF) offer more cooling capacity on a certain footprint than was the case, for example, 20 years ago. According to comparing calculations of existing old units with the implementation of new, modern fans, an improvement of cooling capacity based on same footprint and noise level of 10 – 15 % could be realized. As a result, the replacement or the expansion of an oil-cooling system can lead to more output, less wear, and/or longer system lifetime cycles.

The use of new cooling systems is not only recommended when the existing cooling technology is at the end of its life cycle or defect; the upgrade of cooling systems may also serve for performance enhancement and, in certain cases, can eliminate the immediate need for investments in new and larger transformers. Relevant applications, for example, include power grid sections that – as a result of supply from renewable energy sources – are subject to higher loads than when the transformers were originally planned and designed. Another example is grid sections for which upgrading of turbines and/or generators has led to output increases.

Determination of remaining service lifetime

It is advised to examine a number of criteria before investing in more powerful cooling systems.

1. The first question is whether the transformer, and especially all its insulation materials, are still serviceable for a sufficiently long period of time, and if there are any other current carrying components (bushings, tap changers, leads, etc.) that may limit the increased loading levels.

2. The second question is whether it is necessary to implement a greater oil flow in order to achieve a better cooling performance and, if so, to realize this without damage to the system (e.g. creating hot spots via dead zones in the oil flow or abrasion of solid insulation material), considering the basic transformer design (Oil Natural – ON, Oil Forced – OF, or Oil Directed – OD) made by the OEM requires a certain flow rate and associated oil velocity through the active part.

> **The upgrade of cooling systems may enhance performance and, in certain cases, postpone investments in new and larger transformers**

Arriving at answers to these questions involves two aspects: engineering evaluation, on the one hand, and risk analysis, on the other. These answers, from a cost-effectiveness point of view, will help to reach the optimal decision between upgrading the cooling system and replacement of the complete transformer.

Benefits of active cooling systems with variable-speed control of drive systems

Various systems have proved effective for cooling transformer oil.

Cooling by air, supported by fans (Air Forced – AF), is one of the most widely used solutions. Advances made in heat exchanger design, in fan construction, and above all in the variable speed control of drive systems have significantly improved cooling effects and the efficiency of the systems.

These systems allow the construction of higher-performance solutions without having to enlarge their dimensions. These advanced heat exchanger and fan technologies offer benefits for transformers from various standpoints:

- Cooling effects can be controlled as a function of winding temperatures to assure limitation of the upper average temperature limit as specified by the OEM or the operator of the transformer.
- The fan drives can be controlled on the basis of the momentary load, and can even counter, in anticipation, the effects of an increase in oil temperatures by revving up to faster speeds before the temperature increase takes place. This enables higher output peaks and reduces thermal load.
- Variable-speed control can be used to keep the oil temperature constant.
- It is possible to match the speed of a fan to outdoor air temperature (or incident solar radiation) and to compensate

> **The progress in heat exchanger design, in fan construction, and in the variable-speed control of drive systems has significantly improved the efficiency of the cooling systems**

poor heat dissipation with the aid of higher speeds. This reduces mechanical wear and acts to extend the service life of the system.

- Permanent operation of the fans, even at low speed, eliminates the formation of condensation inside the fan motors. This prevents premature failure by corrosion in case of fan shutdown.
- Noise control of the cooling fans
- Less pollution of cooling core by environmental dust due to lower air flow in partly loaded transformer conditions

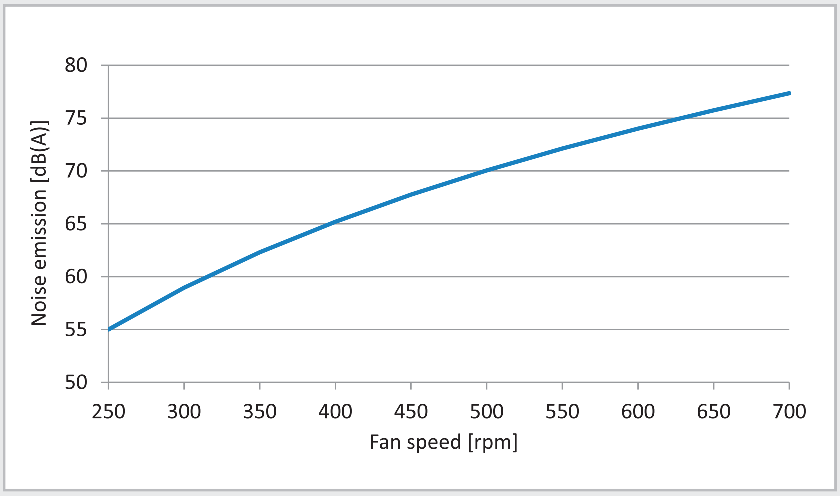


Figure 1. Example of the operating noise of a fan as a function of its speed (values according to datasheet of fan manufacturer)

A major benefit of variable-speed control in such systems is exact matching of fan speed to requirements. With motors that are switched on and off, it is always necessary to use the highest speed stage, which leads to higher power consumption and louder operation. Accordingly, variable-speed fan drives also offer benefits in areas where minimization of operation noise is necessary.

Figure 1 shows an example of the operating noise of a fan as a function of fan speed. An increase of 10 dB (A) produces a doubling of the perceived sound volume.

Reduction of operating noise

A comparison of variable-speed fans with fans having fixed speed at half-load operation can show how much quieter a system can operate with speed-controlled fans. The overall air flow is linearly changing with the fan speed, according to the following principle:

$$Flow_1 / Flow_2 = RPM_1 / RPM_2 \qquad (1)$$

where RPM_1 and RPM_2 stand for the speed of the fans at operating points 1 and 2. The following equation shows the relationship between the reduction of speed and the lowering of sound level. All sound levels are expressed in dB (A), which means A-weighting of the sound level according to the perception of the human ear.

$$\Delta Noise = 50 \cdot \log (RPM_2 / RPM_1) \qquad (2)$$

Under the assumption that, at operating point 2, two fans operate at a speed 50 % lower than at operating point 1 – i.e., at 300 instead of 600 rpm – and assuming that 74 dB (A) was measured at 600 rpm, this would result in the following noise reduction:

$$\Delta Noise = 50 \cdot \log (300/600) = -15 \text{ dB (A)} \qquad (3)$$

Instead of a level of 74 dB (A), the two variable-speed fans would accordingly produce only 59 dB (A) at 300 rpm. In the case of two fans with an ON/OFF operation only, halving the air flow would be possible by switching off one of the fans. However, halving the number of identical noise sources, meaning using one fan instead of two, produces noise reduction of only 3 dB (A). Operation of only one fan at 600 rpm would produce a level of 71 dB (A). As cooling power linearly depends on fan speed, the operation of two fans at half speed enables half load operation as well. But two fans working at half speed are 12 dB (A) quieter than one fan at full speed. A system with variable-speed fan motors is therefore considered at half load to be less than half as loud as a conventional system at the same performance. In other words, for part load conditions, one full speed

> **At half load, a system with variable-speed fan motors is considered to be less than half as loud as a conventional system at the same performance**

Table 1. Comparison of audible noise of coolers in an ON/OFF operation and with variable-speed fan control

	ON/OFF operation		Variable-speed control	
Operation Point 1 at 100 % load	Fan 1: 600 rpm	Fan 2: 600 rpm	Fan 1: 600 rpm	Fan 2: 600 rpm
	71 dB (A)	71 dB (A)	71 dB (A)	71 dB (A)
	Σ= 74 dB (A)		Σ= 74 dB (A)	
Operation Point 2 at 50 % load	Fan 1: 600 rpm	Fan 2: 0 rpm	Fan 1: 300 rpm	Fan 2: 300 rpm
	71 dB (A)	0 dB (A)	56 dB (A)	56 dB (A)
	Σ= 71 dB (A)		Σ= 59 dB (A)	

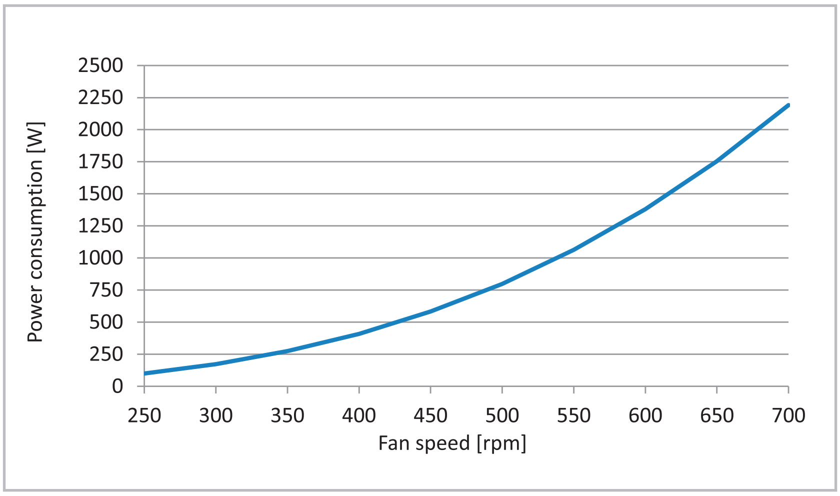


Figure 2. Example of power consumption of a fan as a function of its speed (values according to datasheet of fan manufacturer)

Operation of variable-speed motors at half load requires, approximately, only one-fourth of the electrical energy used by fixed-speed fans at half-load operation

Variable-speed motors are more economical with energy use since power consumption increases by a power of three as motor speed increases

running conventional fan is much louder at the same output than two slow running EC fans.

Energy saving by variable-speed motors

Variable-speed motors are also more economical with energy use since power consumption increases by a power of three as motor speed increases. Fig. 2 demonstrates the relationship between power consumption and speed.

The example illustrated in Fig. 2. shows the savings potential with variable-speed drives: it can be assumed that, for operation of two fans at 600 rpm (at full load), the power consumption for both fans operating simultaneously would amount to 1380 W. At half-load operation, it would be possible to switch one fan off, which would reduce the consumed power to 690 W. With variable-speed drives, halving the fan speed would enable the desired air flow. Power would then be calculated by the following equation:

$$P_2 / P_1 = (RPM_2 / RPM_1)^3 \qquad (4)$$

where:

P_1 and P_2 stand for electrical power at operating points 1 and 2;

RPM_1 and RPM_2 stand for the speed of the fans at operating points 1 and 2. Upon operation of the two variable-speed fans at half speed, the following would result for the above-stated example:

$$P_2 = 1380\ \text{W}\cdot(300 / 600)^3 = 172.5\ \text{W} \qquad (5)$$

As a result, operation of variable-speed motors at half load requires, approximately, only one-fourth of the electrical energy used for half-load operation with fixed-speed fans. Table 2 summarizes the equations (4) and (5) .

Selection of drive variants

A variety of fan sizes, geometrical characteristics and drive systems are available for selection (Fig. 3). In addition to the AC (Alternating Current) motors widespread for many years, AC motors with frequency converters are also available. Although they enable infinitely variable matching of fan speed, they also generate additional hardware costs and are more susceptible to breakdown – which means that they have not been successful on the market. Speed matching, on the other hand, enables systems with frequency converters to use considerably less average annual power than do conventional AC motors without this type of control.

Table 2. Comparison of power consumption of fans at 50-percent and 100-percent load

	ON/OFF operation		Variable-speed control	
Operation Point 1 at 100 % load	Fan 1: 600 rpm	Fan 2: 600 rpm	Fan 1: 600 rpm	Fan 2: 600 rpm
	690 W	690 W	690 W	690 W
	Σ= 1380 W		Σ= 1380 W	
Operation Point 2 at 50 % load	Fan 1: 600 rpm	Fan 2: 0 rpm	Fan 1: 300 rpm	Fan 2: 300 rpm
	690 W	0 dB (A)	86,25 W	86,25 W
	Σ= 690 W		Σ= 172.5 W	

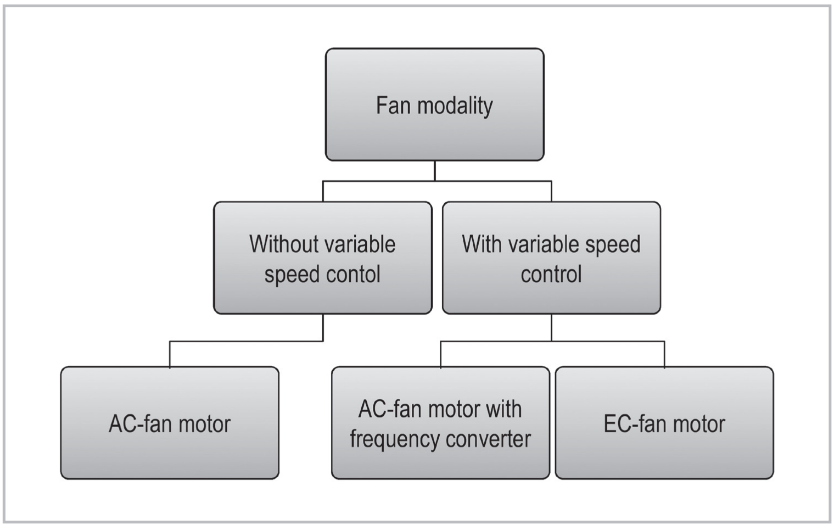


Figure 3. Possible drive modalities for the fans used by air-cooled transformer-oil coolers

Figure 4. Measurement of noise emitted by the transformer oil cooler at a distance of 2 m. Replacement of these old fans by new fans with EC drive and advanced fan blade geometry lowered the sound level by 16 dB (A) and reduced power consumption.

> **With new variable-speed fan motors, in some cases it was possible to reduce energy costs by even 95 % and the sound level by 16 dB (A)**

A more cost-effective alternative to AC motors with frequency converters are brushless EC (Electronically Commutated) motors. They can also adapt fan speed with infinitely variable control, but they do not require additional power electronics – and they achieve greater efficiency than does an AC motor with or without frequency converter.

Providing redundancy

In dimensioning of a cooling system, cooling capacity can be provided for less than maximum fan speed to create redundancy. A system with four coolers, for example, can be designed so that the fans operate at rated cooling capacity below their maximum speeds, with resulting power savings. If one fan fails, the rest can operate at higher speeds, thus exploiting the redundancy provided.

Noise reduction and energy savings examples

The example of noise reduction for a 160 MVA transformer in Germany, built in 1975, demonstrates engineering progress in drives and cooling technologies. In this example, the customer requested noise reduction for his fan-equipped, forced-air oil cooling system. Initial measurements at the beginning of the project detected a sound level of 103 dB (A) at a distance of 2 m from the fans (Fig. 4). The eight 400 V fans (two per cooler section) operated at a fixed speed of 1430 rpm and were dimensioned so that each of the cooling units could dissipate 33 % of the cooling capacity. The power consumption of each of the fans was approximately 2800 W.

Eight new fans with improved engineering design and EC drives were installed in the same casings, as replacements for the old fans. The speed is now infinitely variable between 0 and 1700 rpm. At maximum speed, the new fans enable 60 % greater air flow than did their predecessors, with the sound level reduction by 7 dB (A) and with maximum power consumption of 1800 W per fan at top fan speed. At nominal output, the EC fans even operate at 16 dB (A) lower than the old systems. Thanks to the improved fan drive efficiency, more efficient fan blades, and speed control systems, the EC fans furthermore require less power than fans with fixed speed.

The savings in power costs are so high that investments in variable-speed fan motors are amortized very quickly – as the following approximate calculation shows.

For simplicity purposes, it may be assumed that the oil cooler of a 160 MVA transformer must, on average, provide a yearly average of 50 % of its rated cooling duty. Operating with the old fixed-speed fans, three fans would be necessary to provide the required 50 % cooling duty. Annual power consumption would accordingly result as follows:

$$W_{\text{total (100\%)}} = 6 \cdot 2800\ \text{W} \cdot 8760\ \text{h} = 147{,}168\ \text{kWh} \quad (6)$$

$$W_{\text{total (50\%)}} = 3 \cdot 2800\ \text{W} \cdot 8760\ \text{h} = 73{,}584\ \text{kWh} \quad (7)$$

At an easy-to-calculate electricity price of €0.1/kWh, operation of the fans would accumulate power costs of €7,358.

The speed-controlled EC fans are able to operate up to 1700 rpm at 1800 W. But to provide 100 % of the cooling capacity only 850 rpm is required.

$$W_{\text{total (100\%)}} = 8 \cdot 1800\ \text{W} \cdot (850\ \text{rpm}/1700\ \text{rpm})^3 \cdot 8760\ \text{h} = 15{,}768\ \text{kWh} \quad (8)$$

At 50-percent load, as in the example above, for the AC fans the required rpm is 425 only. Therefore:

$$W_{\text{total (50\%)}} = 8 \cdot 1800\ \text{W} \cdot (425\ \text{rpm}/1700\ \text{rpm})^3 \cdot 8760\ \text{h} = 1{,}971\ \text{kWh} \quad (9)$$

The new versus old installation differs in electricity costs of €7,358 - €197 = €7,161. With the upgrading costs, including installation, of approx. €12,000 for replacing the old AC fans with new EC units, the return on investment (ROI) would be achieved in fewer than two years. If a fan replacement is necessary in any case for maintenance reasons, only the additional costs of approximately €500 per EC fan would have to be considered in ROI calculations. With eight fans, this would result in an additional investment of €4,000, which would be amortized after around 7 months.

> **The payback period of an investment in variable-speed fan motors can be between several months and two years**

In addition, the new system offers customers the possibility of adapting the cooling output to the cooling demand and a tremendous reduction of the average sound level. This effect is even of greater value taking into account the megatrend of urbanization, in which residential areas are getting closer to local transformer substations. Table 3 summarizes these information.

Example of individual output enhancement

It is also feasible to use additional compact cooling to match the oil temperature requirements toward the objective of enabling transformers to supply more output, but keeping the same temperature level as before. Such a solution was realized during a project in Malaysia. In this case, the requirement was to raise the output of a 185 MVA transformer by approximately 10 % to 204 MVA. Since

Table 3. Comparison of energy consumption of the old and new cooling solution

	Old installation		**New installation**	
Operation at 100 % load	No. of fans	6	No. of fans	8
	Fan speed	1430 rpm	Fan speed	850 rpm
	Sound (total)	103 dB (A)	Sound (total)	87 dB (A)
	Power consumption of each fan	2800 W	Power consumption of each fan	$1800\ \text{W} \cdot (850/1700)^3 = 225\ \text{W}$
	$\Sigma = 6 \cdot 2800\ \text{W} \cdot 8760\ \text{h} = 147{,}168\ \text{kWh}$		$\Sigma = 8 \cdot 225\ \text{W} \cdot 8760\ \text{h} = 15{,}768\ \text{kWh}$	
	14,717 € p.a. (at 0.1 €/kWh)		1,577 € p.a. (at 0.1 €/kWh)	
Operation at 50 % load	No. of fans	3	No. of fans	8
	Fan speed	1430 rpm	Fan speed	425 rpm
	Sound (total)	100 dB (A)	Sound (total)	72 dB (A)
	Power consumption of each fan	2800 W	Power consumption of each fan	$1800\ \text{W} \cdot (425/1700)^3 = 28.1\ \text{W}$
	$\Sigma = 3 \cdot 2800\ \text{W} \cdot 8760\ \text{h} = 73{,}584\ \text{kWh}$		$\Sigma = 8 \cdot 28.1\ \text{W} \cdot 8760\ \text{h} = 1{,}969\ \text{kWh}$	
	7,358 € p.a. (at 0.1 €/kWh)		197 € p.a. (at 0.1 €/kWh)	

Figure 5. Standardized cooling module for thermal dissipation rating of approximately 130 kW

In one case it was possible to increase the power transformer capacity by 10 % only by adding an auxiliary cooler

no modifications were performed to the transformer itself, performance enhancement resulted in additional heat production of 290 kW – which the existing cooling plant, a radiator system, was not capable of dissipating. As a result, a fan-equipped, air-cooled system was installed in parallel to the radiator system. The new system was designed for oil temperatures at the input and output that were identical to the existing cooling system. In this way, the additional cooling had no influence on the thermal behavior of the radiators.

The new air cooler was installed at the small existing space, providing approximately 46 % more cooling duty. Despite the output increase, the maximum oil temperature was lower than prior to the upgrade: after installation of the new cooler – and under otherwise identical operating conditions – the oil temperature at the cooler inlet was 72.9 °C (before: 78.4 °C). After the upgrade, the oil temperature at the cooler outlet was 51 °C (before: 55 °C). Reduction of the maximum oil temperature acts to extend the system lifetime cycle.

Modules for enhancement of the cooling output

In addition to individually designed coolers, standardized, ready-to-use cooling modules are also available. They can be set up and installed locally without major assembly effort, as either replacements or additional systems. Ex works, they are equipped with a heat exchanger, a fan, a

Attenuation of the noise production has become increasingly important today due to urbanization

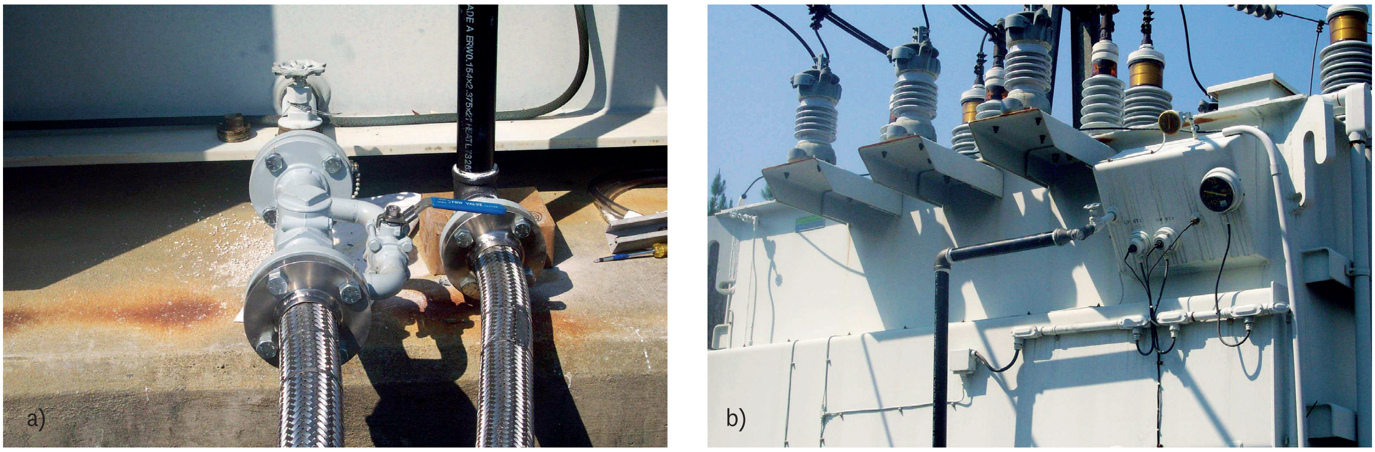


Figure 6. Oil-side connection of the cooling modules at the oil drain tap of the transformer (a), and at the oil filler fitting (b).

pump, and a frame – which enables transport of the entire module by a forklift, for example. Alternatively, they are available with a control system that allows speed matching of the fan to the oil temperature, as for individual cooling systems. The modules offer a cooling capacity of approximately 130 kW each, at a top oil rise of 45 K, for example. For higher output requirements, it is possible to install several of these compact modules in parallel.

Applications of these modules include temporary oil cooling during repairs or retrofitting and replacement of equipment. They are easy to connect to the oil input and output fittings of the transformer.

Summary

Today, the application of new, speed-controlled fans – by now successfully field-tested – makes it possible to positively influence the temperature and the noise emission of large-scale transformers. Attenuation of the noise production of existing installations has become especially important today within the context of the large-scale trend toward urbanization of residential areas. This trend means that populated areas are being increasingly developed in the vicinity of power distribution stations. The examples shown in this paper clearly demonstrate that appreciable reduction of an installation's own power consumption – and consequently of noise emission – can be achieved, especially under part-load operation of transformers. Investments necessary for these benefits are amortized extremely quickly and result in extraordinarily positive benefits in lengthening the life cycle of transformers and fans.

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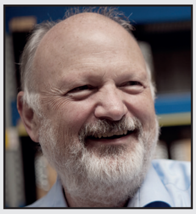

Wolfgang Siffring was born in 1956 in Eppingen, Germany. After completing his master's degree (Dipl.-Ing.) in Mechanical Engineering in Darmstadt, Germany he began his career at an engineering office planning piping networks for nuclear power plants. Three years later he changed to an international company for industrial furnaces. There he worked for 16 years, first as a Design Engineer and then as Design Department Manager before he went into sales in 1995 as Sales Manager. In 2001 he joined GEA Renzmann & Gruenewald GmbH (today Kelvion Safety Heat Exchangers GmbH), an international company engaged in design and production of heat exchangers for transformer oil cooling. At Kelvion Safety Heat Exchangers he holds the position of Vice President Sales. He is the author and presenter of several technical papers at international conferences throughout the world and is committed to support and develop the Transform Group network in order to help the industry improve.