NEW TRENDS IN NOISE REDUCTION OF POWER TRANSFORMERS

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ABSTRACT

In the electrical network power transformers play a key role in transmission and distribution of electrical energy. Noise emissions on power transformers will be supervised in Germany strictly according to the German Federal Immission Control Act (Bundes-Immissionsschutzgesetz) [1] and are a challenge for the utilities to fulfill the therein stated requirements.

When in operation power transformers make noise, produced by an overlapping of different sources. On the one hand, no-load noises are produced by vibrations caused by the magnetostrictive deformation of the core. On the other hand, electromagnetic forces in the windings, tank walls and magnetic shielding predominantly influence the load noise. In addition, cooling systems using fans have a large influence on sound emissions. The determination of sound levels of transformers is regulated in the standard DIN EN 60076-10 "power transformers - part 10: determination of sound levels" [2]. This standard describes sound pressure and sound intensity measurement methods by which sound power levels of transformers, reactors and their associated cooling auxiliaries may be determined. It aims to apply to measurements made at the factory. Besides this measurements can also be performed at site.

In this article the reasons of noise of transformers will be investigated. Various activities to reduce noise will be described. Optimization of the cooling system, particularly for large power transformers, is necessary due to high customer expectations and holds an ever increasing status. This development can also be observed in the relevant standards. As an example the maximum permissible value for sound emissions of 91 dB(A) of a 40 MVA transformer had been indicated in the issue of May 1983 of standard DIN 42508 [3]. In the revision of August 2009 this value was lowered to 83 dB(A). A difference of 10 dB(A) is considered as twice as loud by human beings. Thus, the sounds of power transformers have almost halved in value during the last 20 years.

Furthermore new trends for controlling the fans using EC-technology and the results of preliminary investigations will be presented. Primary focus of these studies is the optimization of losses and noises as well as achieving a reduction in wiring expenditures.

INTRODUCTION

The German Federal Immission Control Act [1] is a law which provides protection against damaging environmental influences by way of air pollution, noise, vibrations and similar processes. The purpose of this law is to protect humans, animals, plants, ground, water, the atmosphere as well as cultural and any other assets from damaging environmental effects, and to prevent the emergence of damaging environmental effects. The provisions of this law also apply to the erection and operation of high voltage substations. In the 16th, 18th and 22nd Federal Immission Protection Directives on the German Federal Immission Control Act, threshold values for sound emissions of different sources of sound are prescribed. The sound emissions of power transformers are strictly monitored according to the German Federal Immission Control Act. An overview of everyday sounds is depicted in Fig. 1.

Ever greater demands are placed on the noise levels of power transformers by standards and consequently by the utilities. The factors which lead to the production of noise as well as new trends to optimize noise emissions will be explained in more detail in the following section.

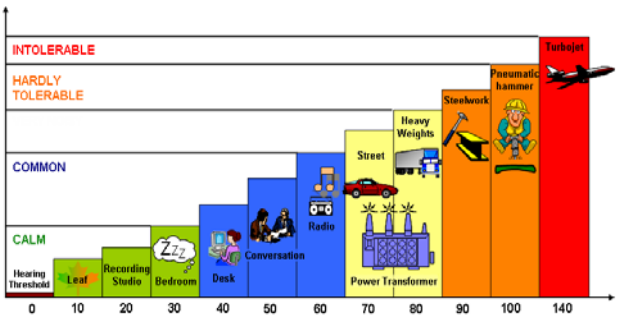


Fig 1: Everyday sounds in dB(A)

TRANSFORMER NOISE EMISSIONS

No-load and load noise

The creation of no-load noise is dependent on the existing magnetic flux density and is influenced considerably by the operating voltage and induction with which the transformer is operated. Frequencies caused by a multiplication of the power line frequency, in particular the 200 Hz and 300 Hz components of the sound spectrum cause the core to vibrate considerably where the induction is increasing. This effect predominates under no-load conditions.

Electromagnetic forces cause vibrations in the windings, tank walls and magnetic shielding. The deciding factors for this are the load current and the resulting stray field of the windings. The forces arising are quadratic proportional to the current. The sound power emitted is proportional to the square of the oscillation amplitude. Consequently, the vibrations produced are strongly dependent on the load of the transformer. The fundamental oscillation of 100 Hz (at a power line frequency of 50 Hz) produces a particularly distinctive sound which is dominant amongst the sounds produced when under load.

The transference of vibrations though the oil occurs almost undamped and is emitted as an airborne sound across the transformer's tank. The mechanical connection between the active part and the tank also forms a link for the transference of vibrations.

Examples of known and applied measures to reduce sound inside transformers include a vibration-damped set-up of the active part in the tank or avoidance of mechanic core resonances by way of a suitable design of the core. Using FEM calculations, further statements can be made about the mechanical strength of the design chosen, as a result of which an optimisation of e.g. type and location of stiffeners can be derived. Lowering the induction in the design of transformers is also possible. This leads to a reduction in noise.

The reduction of sounds emitted from the tank of a transformer by installing it on vibration dampers, installation of sound-insulating walls or complete encasement of the transformer, feature amongst the external measures which can be taken to reduce noise. The measures can also be taken at a later stage. Noise reduction of up to e.g. 20 dB(A) can be achieved by way of external measures.

It is also known that if the sound intensity doubles, the noise level increases by around 3 dB(A); if it triples, by around 4.8 dB(A). The same noise level change can be expected if, in addition to the first source of sound, a second with the same sound intensity is set up. To consider the practical implications of a transformer installed in open space, a reduction of the noise level by 4 to 5 dB(A) can generally be expected where the distance to the transformer is doubled.

Noise caused by cooling systems

Every cooling device used with a transformer produces noise in operation. Fans and pumps produce mainly broadband sounds coming from the forced flow of air or oil. In order to describe the transformer's cooling mechanism clearly, shorthand using a key with four letters is pre-determined by the standard DIN EN 60076-2 [4]. The most common types of cooling are as follows:

ONAN Oil transformer with external air cooling system and natural movement of both cooling mediums

ONAF As for ONAN, though the movement of the cooling air is forced

OFAF Oil transformer with external air cooling system and forced movement of both cooling mediums. At ODAF "direct" recirculation of the oil to the windings

OFWF Oil transformer with external water cooling system and forced movement of both cooling mediums. At ODWF "direct" recirculation of the oil to the windings

All circulations powered by pumps and fans have a big influence on the sounds coming from the cooling systems listed above. They convey fluids, the friction from which produces sound emissions which cannot be ignored.

Sound produced by fans is extremely dependent upon the peripheral speed of the fan blades. This questions the use of faster fans. Instead, if a fan which runs slowly is used, the number of fans must be increased as a consequence, or a difference size must be chosen, in order to obtain a corresponding air flow and in this way to produce the cooling effect required. There are also possibilities of providing the fans with expensive measures which absorb the sound. In contrast to this, this article describes a new method based on the use of continuously variable speed-controllable fans and shows how noise optimisation can be achieved.

INTELLIGENT FAN CONTROL WITH SPEED-CONTROLLABLE FANS

Control of fans in accordance with current technological practice

When considering the thermal design of a transformer, the goal is not to exceed specified threshold values for the average temperature of the windings, the maximum oil temperature and the hot spot temperature of the transformer. An example of how this is achieved is by using fans, which are attached to radiators (ONAF cooling).

Current technology allows the fans to be turned on after a temperature threshold has been exceeded. To avoid starting currents from being too high, one group of fans is normally turned on first and a second group is automatically switched on after a time delay of a few seconds. When the temperature falls below a preset value, all fans are switched off (hysteresis).

Another common control method is to turn on two groups of fans in stages. Either all the fans are switched off (ONAN operation), one fan group is switched on (ONAF 1 level) or both fan groups (all fans) are switched on (ONAF 2 level). A disadvantage of fans used in the conventional way is that they are equipped with asynchronous motors and are run at nominal speed. If a preset oil temperature is exceeded, the first fan group is switched on. After another predefined temperature threshold is exceeded, the second fan group is switched on.

The oil temperature is normally registered by a PT100 temperature sensor on the cover of the transformer and wired to a corresponding display device, which is in the electrical cabinet, with switching contacts to activate the contactor for the fan groups.

A disadvantage of current technological practice for the control system is that the cooling performance cannot be varied with sufficient flexibility. A correspondingly better flexibility for the cooling performance can be achieved by turning on fans individually. However, this has a very high control and wiring expenditure in the electrical cabinet as its consequence and in practice is rarely used. For special applications there is the possibility of achieving a somewhat improved flexibility for the control system, by way of pole-changing or use of a frequency converter. However, these methods have just as high control and wiring expenditure as a consequence, and in practice have rarely been used.

The cooling system can, however, be controlled in an improved method by continually variable speed-controllable fans which are now available [5]. These make it possible to control speed with respect to temperature and optimally will keep the temperature of the transformer relatively constant over a broad range of load conditions. In this way the breathing of the transformer can be reduced considerably. The water content of the oil/paper insulation system is an important indicator for the operational reliability of a transformer [6, 7]. Alongside the degradation of the oil/paper insulation, the occurrence of water caused by the breathing of the transformer is a further reason for moisture. The influence of water has the additional effect of acting as a catalyser for the continued ageing process. Accordingly, a reduction of the breathing of the transformer leads to a reduction in the absorption of moisture and to the cellulose ageing more slowly and to the ageing more slowly through oil oxidisation. Due to reduced breathing, a distinct lengthening of the life can consequently be achieved. Or alternatively the transformer can be subjected to higher loads (with higher over temperatures).

Speed-controllable fans with EC technology

The speed-controllable fans which recently came onto the market are electronically commutated DC motors (EC fans) [5]. The typical size of a transformer fan is an outer diameter of 500 mm or 800 mm. The fans consist of the components (Fig. 2.a): motor rotor, motor supporting structure and fan blades. Typically the fan is in a pipe duct which could also have a protective grid. The motor rotor consists of an EC external-rotor motor with die-cast aluminium or plastic/aluminium hybrid rotor blades. Transformer fans for the forced cooling of oil radiators are normally used to drive the air in a horizontal or vertical (from bottom to top) direction. The motors used for transformer fans are protected in accordance with the corresponding regulations [8]. In the case of EC fans, the motor is protected by way of temperature monitors with an electronic evaluation module, and the electronics by way of current limiters. These numerous, integrated protective functions monitored by microprocessors can turn off the motor automatically if the electronics or the motor overheats, in the case of phase failure, blocking, power supply under voltage and short circuiting. Operation of the fan is possible worldwide at 50 Hz and 60 Hz power supplies with a wide voltage input, 1-phase, of 200 ... 277 V AC, or 3-phase, of 380 ... 480 V AC.

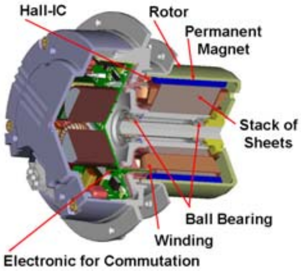
The EC fan has a brushless DC motor which is powered in blocks. In the external-rotor construction, it has a permanent magnet as a rotor and is driven by a control unit. The motor is controlled by way of an integrated PID controller. High starting currents are avoided by way of a soft start. In addition, continual operation of this wear-resistant technology is conducive to high life expectancy.

The life of EC fans is dependent on two main factors:

- the life of the insulation system of the fan
- the life of the ball bearing

The life of the insulation system is largely dependent on the voltage, the temperature and the environmental conditions such as moisture and dew. The life of the ball bearing is determined predominantly by the temperature. Current technological practice is to use ball bearings which are used in every assembling position. As an approximate value (dependent on the general conditions), the expected life of the ball bearings at an ambient temperature of 40 °C is > 40,000 operating hours. In order to take into consideration special conditions of use, individual life expectancy calculations can also be produced. For the reasons given, EC fans are favoured over conventional standard AC fans with respect to life expectancy, and are particularly well suited for use with power transformers.

a)



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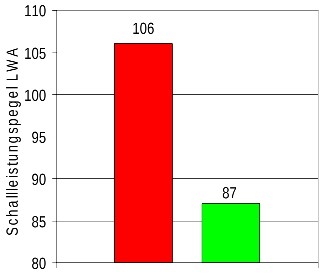

Fig 2: New speed controllable fan (EC technology)
a) Fan motor with components
b) Reduced noise emissions, comparison of 8 standard fans with 6 poles (left bar) with 16 EC fans, half speed (right bar)

The performance characteristics of different 8, 10 and 12 pole standard fans and a modern EC fan were compared with one another. The investigations [9] have shown, alongside obvious advantages regarding noise reduction (Fig. 2.b), an increased overloading is possible and reduced losses when using modern EC fan technology is obtainable. To sum up, all advantages of the speed-controllable fans available today compared to the use of conventional asynchronous motors are listed:

- Continuously variable speed-control is possible
- Optimised cooling performance
- Reduced sound emissions
- Increase in overload capacity
- Less breathing of the transformer
- Less ageing of the oil/paper-insulation system
- Increased life expectancy of the transformer
- Limiting of inrush current by way of soft starting
- Soft starting and continual operation support a long life of the fans
- Higher motor efficiency at up to 90 %
- Reduction of the power input (losses)
- Reduction of operating costs
- Fan standardisation: 1 fan can be used for all speeds and sound requirements

Architecture of the new concept with speed-controllable fans

Current technological practice is to wire each individual fan of an ONAF-cooled transformer from the electrical cabinet, typically, to a separate power supply. Excessive cabling at the transformer (Fig. 3.a) from the electrical cabinet to each individual fan is the result, which means the use of a large electrical cabinet. In addition, there is a motor circuit breaker in the electrical cabinet for each individual fan. The result is that the cabinet has to be equipped with a multitude of terminal blocks, safety devices and control and operating elements.

In contrast, the new concept intends to use speed-controllable fans and to greatly simplify the effort and expenditure involved in installation by way of a new layout. This is achieved by having a common power supply for all fans (Fig. 3.b, Fig. 4). Consequently the effort and expenditure involved in installation is reduced considerably, as only one cable has to go from the electrical cabinet to the power supply. In addition a common control cable can be used for all fans. Alternatively, the joint control cable and power supply can also be put into use as loop in order to achieve an increase in protection against failure.

a) b)

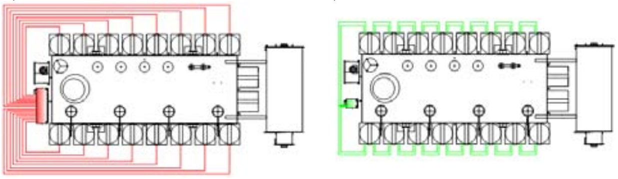

Fig 3: Schematic top view of a transformer with wiring of the new speed controllable fans
a) Conventional extensive wiring with large electrical cabinet
b) New reduced wiring with minimized electrical cabinet

Each individual EC fan is equipped with an integrated motor protection device. Accordingly the motor protection devices required for asynchronous motors do not feature in the electrical cabinet. Numerous terminal blocks are also left out as the concept only requires one cable from the cabinet to the power supply. The size of the cabinet can be reduced to approximately a quarter using the new concept.

The concept also plans for every fan to automatically run at a pre-defined emergency speed if the control signal fails. This could be necessary due to cable damage or a defective control unit. It is therefore precluded that the fans completely fail due to there being no control signal. In this way the failure of one fan would be compensated by the remaining fans running slightly faster. If the control signal or the power supply fails, a change-over contact in the fan reacts and a message is transmitted. In this way the operator can be informed of the failure so that he may take corrective actions.

To sum up, all the advantages of the new concept are listed in this overview:

- Integrated motor protection (motor blocking, over current, under voltage), therefore no extra motor protection switches in the electrical cabinet required
- New concept for emergency operation of fans
- Reduced wiring expenditure and less installation material
- Much less space and consequently a smaller electrical cabinet required

Intelligent fan control system with different control options

The new concept provides for various control options for EC fans. Various connection possibilities form the basis for this. The fans have signal inputs to control their speed as well as a signal output in order to be able to report faults. In addition, the fans are equipped with a RS485 interface. This leads to several control options:

- Manual speed presetting using potentiometer
- Automatic control by way of PT100 temperature sensor
- Automatic and manual control by way of software via RS485 interface
- Automatic and manual control by means of an online monitoring system

With the aid of a monitoring system the fans of a cooling system can be controlled dependent on the load and the oil temperature. Use of an intelligent cooling apparatus monitoring and control system has the following advantages: detection of irregularities such as e.g. defective fans, pumps, optimisation of the hot spot temperature, reduction of the transformer breathing, reduction of sound emissions, cost optimisation by managing losses or increasing the overloading condition by way of pre-cooling the oil.

The concept introduced in this article, to produce a cooling device control system with speed-controllable fans, can be linked intelligently to an online monitoring system. In this way the advantages of the concept introduced can be joined with those of the online management system. The monitoring system can preset the cooling performance required and control the fans intelligently.

Fig 4: First 40/50 MVA, ONAN/ONAF grid coupling transformer with new speed controllable fans with EC technology manufactured in Germany in 2009

SUMMARY

This article explained which physical processes cause sound emissions in transformers. Vibration of the core and the windings cause oscillations which are transferred across various links to the surroundings. Every cooling device used with a transformer produces sound when in operation. A combined sound is produced from the noises of the transformer and its cooling equipment. Various already-known measures to reduce sounds were touched upon in the article.

In addition, the article described a new intelligent concept to control fans with the objective of optimising noise and losses. First of all current technological practice, with which typical fans - divided into two fan groups - are driven, was described. A disadvantage of this method is that only a relatively inflexible system for varying the cooling performance can be achieved.

The cooling system can, however, be controlled in a much improved way by continuously variable speed-controllable fans which are now available. The article described the technology behind these fans. Using a number of examples the resulting multifarious advantages were illustrated. By using brushless DC motors the fans have a high expected life. Alongside the advantages of limiting the starting current through soft starting, the motor efficiency is 90 %. This leads to a significant reduction in the power input. In this way the transformer's operating costs can be reduced.

The investigations have shown that, as well as achieving a cooling performance which is optimised according to the load which the transformer is subjected to; significant reductions in sound emissions can be achieved. The advantages become even more significant as the fan speed slows. An increase of the overload capacity of the transformer can also be achieved. To do this the cooling performance of the fans has to be designed so that when the nominal load of the transformer is reached the fan speed is reduced. Consequently it is also guaranteed that when the transformer is overloaded, it can also be sufficiently cooled, as the fans can still be increased to the nominal speed.

A temperature-dependent, continuously variable speed control system will optimally keep the temperature of the transformer relatively constant over a wide load range. The consequence is reduced breathing and a resulting higher life expectancy for the transformer.

The layout for the wiring according to a new concept was presented. A considerable advantage is the reduction in wiring expenditure caused by a joint cable from all fans to the power supply. In addition, the motor protection device in the new fans is integrated i.e. less space is required and consequently a much smaller electrical cabinet can be used.

Moreover, the new fan control system allows for various control options. Alongside manual speed presetting, all fans can be controlled continuously, dependent on the oil temperature. An existing interface makes it possible to control the fans using software and to record current operating data. In addition, the concept is suitable for linking the cooling equipment control system with an online monitoring system. As well as managing losses, an increase in the overload capacity by pre-cooling the oil can also be achieved in this way, and rounds off the overall concept.

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