Heat Pipes – A Novel Cooling Principle for Generator Circuit-breakers

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Kurzfassung

Heat Pipes – Ein innovatives Kühlsystem für Generatorschalter

Bedingt durch ihren Einbauort werden an Generatorschalter sowohl bezüglich des Stromtragvermögens, als auch bezüglich des Ausschaltvermögens, sehr hohe Anforderungen gestellt. Ein wichtiger Gesichtspunkt bei der Auslegung eines Generatorschalters ist daher sein Stromtragvermögen. Bei einem gegebenen Schalter ist eine Erhöhung des Stromtragvermögens nur durch eine verbesserte Wärmeabfuhr an die Umgebung zu erreichen.

In der Vergangenheit wurden aktive Kühlsysteme (z. B. forcierte Luftkühlung) benutzt, um den Nennstrom eines Schalters über den Nennstrom bei natürlicher Kühlung hinaus zu erhöhen. Solche Kühlsysteme weisen aber verschiedene grundsätzliche Nachteile auf.

Mit einer neuen Entwicklung, welche auf der Anwendung von „Heat Pipes“ in Generatorschaltern beruht, können diese Nachteile überwunden werden. Dank dieses innovativen Ansatzes wird es möglich, mit einem völlig passiven Kühlsystem sehr wirksam Wärme über eine grosse Potentialdifferenz abzuführen. Die Nachteile eines aktiven Kühlsystems können somit vollständig ausgeschaltet werden. Die Wirksamkeit dieser Lösung wurde durch Erwärmungsversuche bestätigt. Als Konsequenz steht nun eine Typenreihe von Generatorschaltern zur Verfügung, bei welcher das aktive Kühlsystem durch ein passives „Heat Pipe“-Kühlsystem ersetzt wurde.

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Introduction

Generator circuit-breakers are widely used in power plants nowadays because they offer many advantages when compared to the unit connection [1]. Due to their place of installation on the other side, stringent requirements are imposed on generator circuit-breakers both with respect to the current carrying and short-circuit current interrupting capability.

An important issue for a generator circuit-breaker is its current carrying capability. The rated currents of generators range typically between 3`000 A (for 50 MVA units) and 5`0000 A (for 2`000 MVA units). As a consequence of these currents, heat is generated in the circuit-breaker. An increase of the rated current of a given circuit-breaker can only be achieved by improving the heat transfer to the environment ensuring that the temperatures of all components stay within admissible limits. The ensuing challenge is therefore to remove this heat from the conductor. This task is made even more taxing since the heat source is on a high electrical potential. Active cooling (e.g. forced air cooling) has been widely used in the past to increase the current carrying capability of generator circuit-breakers above their naturally cooled rating. Active cooling, however, has several undesirable side effects, e.g. power consumption, reliability, maintenance requirements, noise, size of equipment. A recent development to overcome these disadvantages has been the design of a heat pipe cooling system for generator circuit-breakers. Using this innovative approach, it is possible to achieve an efficient heat transfer across a large electrical potential difference with an entirely passive device. The drawbacks of an active cooling system can thus be fully avoided.

Heat Pipe Principle

It is not within the scope of the article to go into details of heat pipe theory. These can be found in standard textbooks [2]. An excellent overview can also be found in [3]. In this section we will briefly describe the basic working principle and the performance limits of heat pipes.

Heat pipes are highly efficient heat transport elements and consist of a hermetically sealed enclosure containing a small amount of working fluid. They make use of the evaporation of a suitable working fluid, transport of the latent heat of vaporisation to the condenser, condensation of the vapour, and back flow of the condensate to the evaporator.

The means how the condensate is being transferred back from the condenser to the evaporator is the major distinction between different heat pipe designs. Different forces can be utilised, e.g. capillary forces (surface tension), gravitation, acceleration (centrifugal) forces, thermally induced pressure differences or some combinations thereof.

The classical heat pipe utilises capillary forces and was originally developed for space applications. The internal surface of the enclosure is providing a capillary structure that is saturated with the working fluid. Usually there is no excess fluid, i.e. no part of the heat pipe is flooded with liquid. To some extent the capillary forces allow such heat pipes to work against gravitational forces, i.e. the evaporator may be “above” the condensing zone.

The classical two-phase thermosiphon or gravity heat pipe is without a capillary structure and requires gravitational forces for the return of the condensate to the evaporator (this implies of course that the condenser is above the evaporator). There is a certain amount of liquid in the device forming a pool (Figure 1). In operation the liquid is evaporated from the pool at the bottom, the vapour condenses in the condenser and a condensate film flows back at the heat pipe wall.

In principle a heat pipe is operational for all temperatures between the melting point and the critical temperature of the working fluid. The maximum amount of heat that can be transferred in a gravity heat pipe is limited by several effects.

– Vapour pressure (or viscous) limit
For very low operating temperatures close to the melting point, the maximum vapour pressure drop and thus the vapour flow is limited by the low vapour pressure at the exit of the evaporator. However, this limit causes no constraint in the design of a heat pipe for the application in generator circuit-breakers. The only possibility the vapour

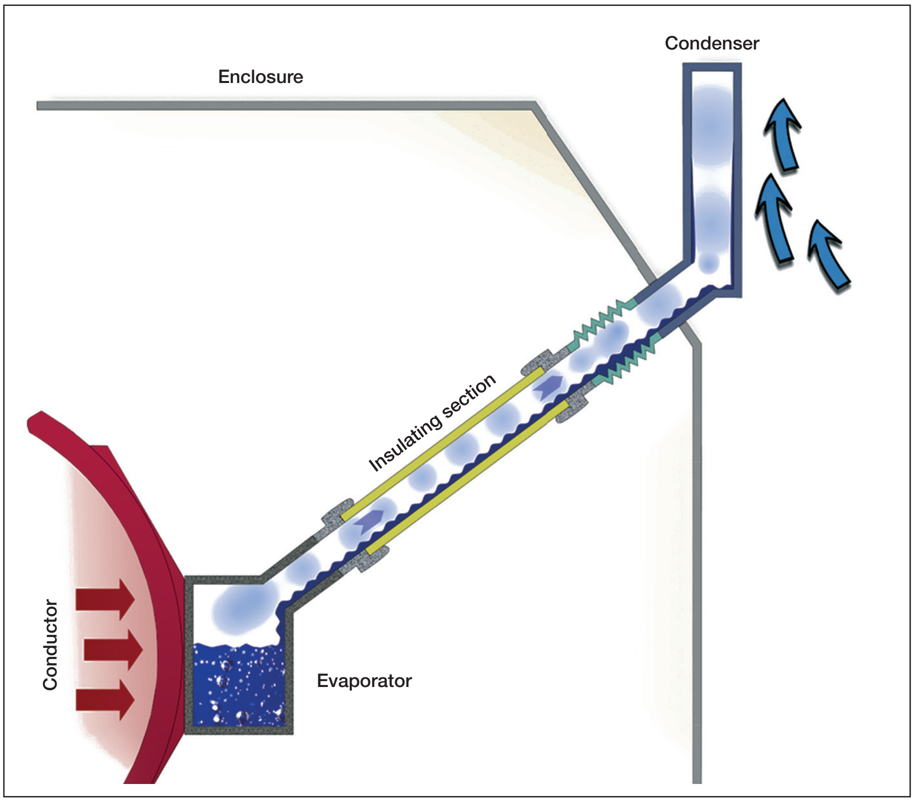

Figure 1. Schematic of a heat pipe. The heat source in case of an application in a generator circuit-breaker (conductor) and the enclosure of the circuit-breaker are also indicated.

pressure limit might become relevant is during the start-up of a cold circuit-breaker (e.g. from –40 °C). But the large thermal mass of the circuit-breaker and correspondingly large thermal time constant (typically 2 hours) allow for a smooth start up of the heat pipe without the vapour pressure limit becoming relevant.

- Sonic limit
  This performance limit is also observed at relatively low operating temperatures. It corresponds to the point when the vapour reaches sonic velocity at the end (exit) of the evaporator. Similar to the vapour pressure limit this effect needs not be considered any further for generator circuit-breaker applications.
- Boiling limit
  This limit occurs under high heat fluxes in the evaporator section. It corresponds to the transition from nucleate boiling to film boiling. In the latter region a more or less stable vapour film between the evaporator surface and the liquid drastically reduces the evaporation heat transfer coefficient. For the application considered here the transition to film boiling does not pose a serious limitation since the maximum heat flux is limited by the thermal conductivity of the conductor of the circuit-breaker to values far below the nucleate boiling limit.
- Dryout limit
  For two-phase thermosiphons at comparably low filling ratios (ratio of working fluid volume to evaporator volume) a dryout limitation can occur. The liquid film returning from the condenser to the evaporator is completely vaporized before it reaches the liquid pool. Thus dry patches are formed in the evaporator. Again this limit poses no design constraint for the generator circuit-breaker application since the working fluid also serves as insulating medium which implies that the heat pipes is designed with rather high filling ratios.
- Counter-current flow limit
  This limitation can occur under high axial heat fluxes when the high velocity vapour flow from the evaporator to the condenser intensively interacts with the counter-current condensate flow. In this case the flow rate of the condensate returning to the evaporator section is reduced and the maximum heat transfer limited. This limit can of course be shifted to higher values by increasing the heat pipe cross section, which lowers the vapour velocity and thus the vapour-liquid interaction.

Application of Heat Pipes to Generator Circuit-breakers

The main goal of the adaptation of passive cooling systems like heat pipes to a generator circuit-breaker is both to replace active cooling systems (like forced ventilation or heat exchangers employing motor driven fans) and to further enhance its rated current carrying capability. The term passive means that no mechanically moving parts like motors or fans are applied in the cooling system. Thus, a high reliability and long lifetime of the system can be achieved.

In the application considered here it is feasible to use gravity instead of capillary forces for the liquid return since from a thermal point of view it is more efficient to transport the circuit-breaker heat losses to the upper part of the circuit-breaker (instead of transporting the heat losses to a condenser below the circuit-breaker and releasing heat there to the ambient and thus heating up the circuit-breaker enclosure). A greater rate of flow of liquid is thus possible (no flow impedance of the capillary structure). Furthermore two-phase thermosiphons are more robust devices than capillary heat pipes (no danger that the capillary structure deteriorates). This design therefore results in the most simple and robust construction and the smallest number of parts.

General Requirements

Since the prime task of the cooling system is the transportation of heat from its origin (mainly the contact regions as major source of ohmic losses) to the ambient, the most obvious requirements are related to thermal issues. Of course, the cooling system also has to comply with all other requirements applicable to a generator circuit-breaker like the ambient conditions or the dielectric stresses. Furthermore, other functionalities of the circuit-breaker like the current interruption capability must not be influenced by the cooling system. It is self-evident that the cooling system has to be highly reliable for the total service life of the circuit-breaker.

- Thermal Conductivity of the Heat Pipe
  According to the circuit-breaker standards the maximum acceptable temperature rise at the main contacts is 65 K. For a generator circuit-breaker with a rated current of 23`000 A and six heat pipe modules this limit leads to the requirement that each of the heat pipe modules is required to have a thermal resistance less than 70 mK/W. This is approximately 5`000 times less than a copper rod with the same diameter and length as the corresponding transport section of the heat pipe!
- Dielectric Insulation
  Due to the very high required thermal conductance of the cooling system the heat pipe system has to transfer the heat losses from the conductor to the ambient outside the enclosure. Therefore, the cooling system bridges the insulation distance and has to comply with the respective insulation level under all possible operating conditions (e.g. lightning impulse withstand voltage 150 kV, power frequency withstand voltage 80 kV, 1 min.)

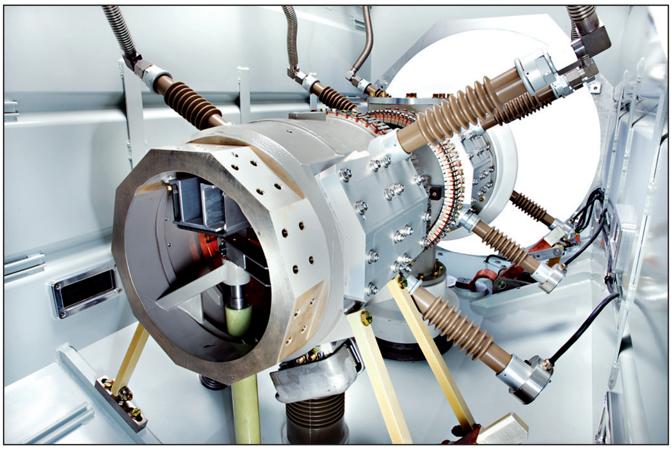

Figure 2. Heat pipes attached to a generator circuit-breaker type HECS-130XXLp. The transport sections are connected to the condensers that are incorporated into the enclosure of the circuit-breaker.

Figure 3. Generator circuit-breaker type HECS-130XXLp.

- Mechanical Requirements
  Mechanical loads on the heat pipe system arise from switching operations that cause relative vibrations between the conductor and the enclosure, earthquake, transport, and thermal contraction/expansion due to changes in temperature caused e.g. by changing ambient temperatures, load currents, or day-night cycles. In order to comply with the circuit-breaker specification this implies a specified number of mechanical operations of 2`0000 CO.
- Ambient Conditions
  The operating temperature is from –40 °C to +50 °C, and the systems are suitable for indoor as well as for outdoor installation.
- Lifetime, Maintenance
  The heat pipe system should have a lifetime of 20 years in order not to interfere with the regular generator circuit-breaker service interval. For the leak tightness of the heat pipe system this means a maximum leak rate of 10^{-6} mbar l/s. In the acceptance test all heat pipe components are checked to have leak rates less than 10^{-8} mbar l/s!

Heat Pipe Working Fluid

The working fluid used in the heat pipe modules is a hydro-fluor-ether. Beside their thermal properties this class of materials qualifies for an application in a circuit-breaker due to the following properties [4]:

- They have excellent dielectric properties with a breakdown strength around 15 kV/mm.
- The toxicity is low; therefore, fluid handling poses no problems.
- They are compatible with a wide range of materials.
- They are non-flammable.
- The global warming potential is low and they have zero ozone depletion potential.

Heat Pipe Set-up in a Generator Circuit-breaker Type HECS-130XXLp (Figure 2)

In order to comply with the above-mentioned requirements the cooling system for the generator circuit-breaker type HECS-130XXLp consists of six heat pipe systems per pole. The transport section of each heat pipe consists of two parts, an insulating section and a flexible tube to mechanically decouple the circuit-breaker conductor from its enclosure. The heat pipe condensers are integrated into the generator circuit-breaker enclosure.

Testing of Generator Circuit-breakers with Heat Pipes

Temperature Rise Tests

A temperature rise test in accordance with IEEE Std C37.013 [5] and IEC 62271-1 [6] has been successfully performed on a generator circuit-breaker type HECS-130XXLp (Figure 3) with a rated current of 23`000 A (50 Hz).

For the test the middle phase was equipped with bus-ducts (isolated phase bus duct (IPB)) of about 2 m length on each side of the generator circuit-breaker to represent the site conditions which can be expected in a power plant. The temperature of the bus-ducts was adjusted according to the ambient temperature, so that the maximum permitted temperature rise of the bus ducts were not exceeded. That means that the temperature rise of the active part of the bus duct was set to 50 K and the temperature rise of the enclosure of the bus duct was set to 30 K. The middle phase was completely equipped with a circuit-breaker, a disconnector, current transformers, voltage transformers, a surge arrester and surge capacitors. At one end of the IPB the active part was connected by copper bars with the enclosure so that the current through the con-

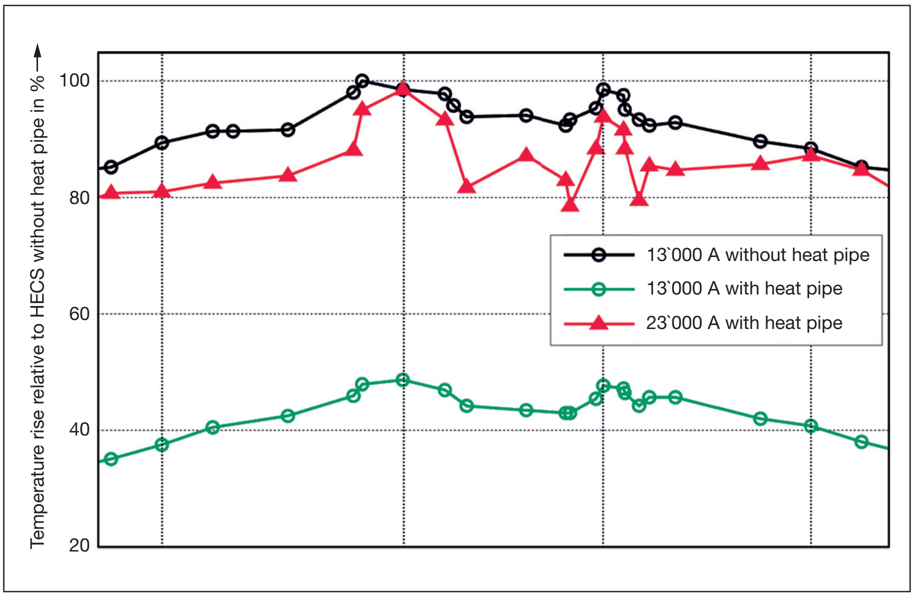

Figure 4. Temperature rise along the conductor, relative to the maximum temperature rise of a generator circuit-breaker type HECS-130L (13'000 A, without heat pipe) which is well below the limit of 65 K.

ductor and the enclosure was identical. The outer phases of the circuit-breaker were heated by electrical heaters inside the enclosure to simulate the heat dissipation of these phases during operation.

The resulting temperature rise along the conductor is shown in Figure 4. The effectiveness of the heat pipes is clearly visible since the hot-spot of the generator circuit-breaker type HECS-130XXLp at 23`000 A is even somewhat lower than the corresponding temperature rise of a the same circuit-breaker without heat pipes at 13`000 A (HECS-130L). The two local maxima in the temperature profile correspond to the position of the disconnector and circuit-breaker contacts.

Mechanical Tests

Several heat pipe modules have been subjected to mechanical shock tests on a vibrating table. The acceleration of the vibrating table was controlled to represent the stress of a heat pipe attached to an arcing chamber during a close-open operation of the circuit-breaker. The shock test was exerted 2`0000 times for each direction (x, y, and z). All tested modules withstood this stress without any measurable deterioration.

Furthermore, a type HECS generator circuit-breaker equipped with heat pipes successfully passed a mechanical type test in accordance with IEEE Std C37.013. Again, the test was conducted for 2`0000 close-open operations.

In order to verify that the heat pipes are able to cope with the mechanical stress arising from thermal contraction and expansion due to temperature changes, heat pipe modules and components were subjected up to seven temperature cycles between -50 °C and 120 °C without failure.

Dielectric Tests

A generator circuit-breaker type HECS-130XXLp equipped with six heat pipe modules successfully passed a dielectric type test according to IEEE Std C37.013 and IEC 62271-1. In addition an individual heat pipe was also subjected to a power frequency withstand test at –40 °C in a climate chamber, since at low temperatures the vapour pressure of the working fluid is reduced. Thus, this condition is dielectrically more critical than a test at room temperature. The heat pipe withstood an applied voltage of 90 kV for more than a minute.

Table 1. Range of generator circuit-breakers based on heat pipe cooling principle.

Type	Rated Maximum Voltage	Rated Current	Rated Short-circuit Breaking Current
HECS-100/130XLp	25.3 kV	18,000 A/50 Hz	100/130 kA
		17,400 A/60 Hz	
HECPS-5Sp*	25.3 kV	17,500 A/50 Hz	130 kA
		17,000 A/60 Hz	
HECS-130XXLp	25.3 kV	23,000 A/50 Hz	130 kA
		22,000 A/60 Hz	

*Version for pumped storage power plants

Conclusions

An important issue for a generator circuit-breaker is its current carrying capability. An increase of the rated current of a given circuit-breaker can only be achieved by improving the heat transfer to the environment. Active cooling (e.g. forced air cooling) has been widely used in the past to increase the current carrying capability of generator circuit-breakers above their naturally cooled rating. Active cooling, however, has several undesirable side effects (e.g. power consumption, reliability, maintenance requirements, noise, size of equipment). A recent development to overcome these disadvantages has been the design of a heat pipe cooling system for generator circuit-breakers. Using this innovative approach, it is possible to achieve an efficient heat transfer across a large electrical potential difference with an entirely passive device. The drawbacks of an active cooling system can thus be fully avoided. The effectiveness of this solution has been verified by temperature rise and other pertinent tests.

As a consequence of this achievement a new range of generator circuit-breakers is now available where the active cooling system has been replaced by a passive cooling system based on heat pipes (Table 1).

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