Studies on the use of heat pipes in medium voltage switchgears

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The use of heat pipes in switchgears has been investigated in three steps:

1) along the conductor (to reduce temperature rise of hot spots):

- connected with cooler points on the conductor

2) transverse the conductor (to reduce temperature rise of hot spots):

- connected with enclosure or ambient temperature

3) heat exchanger (to reduce temperature rise of whole switchgear):

- connected with ambient temperature

Studies of applications have shown that various criteria must be observed. Cases 1) and 3) can be realized by commercially available heat pipes. For the other application (2)) heat pipes have been developed to ensure the heat transport to keep off the medium voltage and to minimize the contact resistances. All experimental results were also calculated by using the thermal network, thus conclusions on using heat pipes in other switchgears can be drawn easily. An adjustable reduction in the temperature rise up to 50 % is possible. This can be used to:

- **increase the current carrying capacity,**
- **prolong lifetime of switchgears,**
- **save copper by reducing the cross section of the conductors or**
- **provide a homogenization of the temperature distribution along the conductor.**

heat pipe; electrical contact; thermosyphon; thermal network; temperature rise; thermal resistance, medium voltage switchgear

I. INTRODUCTION

Medium voltage switchgears more and more often come to their current limits. Reasons are the population and economic growth and the demand of energy due to the rising prosperity and industrialization. Another reason is the distributed generation of energy, such as wind energy, which is produced mainly in the north because of geographical conditions and must be transported to the south. That energy has to be transported by overhead lines and distributed on nodes with switchgears. This distribution network is the medium voltage, with medium voltage switchgears at the nodes which have to ensure the transfer of electrical energy. The application for medium voltage switchgears is for a voltage range from 1 kV to 75 kV. This ever-increasing electrical energy needs increasingly powerful medium voltage switchgear, which can carry and distribute the necessary power.

The operational area of the switchgear has to be protected, to monitor and to lead the electrical energy [1]. Due to the high use area there are also many heat sources in the switchgear:

- Circuit breakers and fuses for protection and leading,
- assistive devices (e.g. current- and voltage transformers) for the monitoring and
- heat losses (e.g. the skin effect in the conductor or the eddy current losses) for the leading.

Nowadays the switchgears reach their thermal limits, which is a result of progressive development towards even more compact switchgears. Therefore, the existing systems or system components must be developed or optimized. The ohmic resistance of contacts or conductors and the current which flows through them generate internal heat losses (P_v). With these losses the equipment has a temperature rise according to IEC 62271-1 [2] each component has a temperature rise limit. After reaching the temperature rise limit on only one part of the switchgear, the whole switchgear is limited to this current, which is the current carrying capacity (CCC) [3].

There are two possibilities of reducing the temperature rise. This leads to an increase of the CCC:

1. reduction of heat losses, e.g. reduction of ohmic resistance at the contacts
2. improvement of heat transfer, e.g. to use an active cooling.

The aim of this study was to improve the heat transfer of a medium voltage switchgears with the use of heat pipes. It is not always possible to reduce the ohmic resistance. In the literature

[4, 5] is mentioned that especially the transitions of contacts between two different materials are striking. Due to higher temperatures, the process of aging of these contacts will be even more promoted. Thereby the ohmic resistance of the contact increases more and more.

Within the scope the experiments were calculated in a thermal network. Based on the thermal network it is possible to extrapolate the results into other switchgears. So the transferability to other switchgears is given.

II. Thermal Network

The second principle of thermodynamics postulates a heat transport from a body with high temperature to a lower temperature body. The generated loss of heat is provoked by four different heat transport mechanisms [6] [7]:

- thermal conduction
- thermal convection
- thermal radiation and
- phase transition.

The thermal conduction describes the energy transport of molecules and electrons. It is transported by diffusion and kinetic collision so it describes the heat transportation within a body. The convection is similar to the conduction. The energy is conducted to a fluid and as a result of a density change the fluid begins to flow. The thermal radiation is also known as electromagnetic radiation. This is the kinetic energy of atoms and molecules. Any body above 0 K provides this radiation. It describes the transport from one body to another and needs no heat transfer medium.

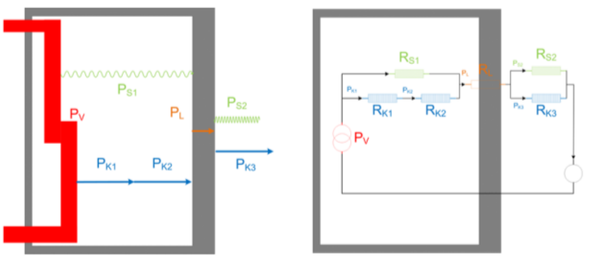


Fig. 1. Thermal processes and thermal network of an indoor switchgear

TABLE I. Analogy between the electrical and thermal Network

Elements	**Networks**			
	electrical		***thermal***	
Potential Difference	$\Delta\varphi$	[V]	$\Delta\vartheta$	[K]
Current	I	[A]	P	[W]
Resistance	R_{el}	[V/A]	R_{th}	[K/W]
Capacity	C_{el}	[As/V]	C_{th}	[Ws/K]

Finally the phase transition, which is the energy that is needed to energize from one physical state to another. The heat transport and the temperature rise can be calculated with the thermal network. Therefore the analogy of the electrical and thermal networks can be used (Table I and Fig. 1) [8] [9].

<u>Thermal Network of an indoor medium voltage switchgear:</u>

The investigated switchgear has an operating voltage from 6 kV, is air-insulated and has a low oil circuit breaker and a CCC of 1000 A. For calculating this switchgear in a thermal network the first three heat transport mechanisms must be involved (e.g. the thermal conduction for the heat connection between the different parts along the current path, the thermal radiation for the heat transport between the three phases and the enclosure and the thermal convection for the heat transport from a phase to the expansion space). So the thermal network of this switchgear is a very compact structure (Fig. 2). After heating the three phase conductors with the CCC of 1000 A a temperature rise along the current path was detected by thermocouples of type K. The resistance of the contacts were measured by a low-resistance-meter and integrated in the thermal network with a power loss source.

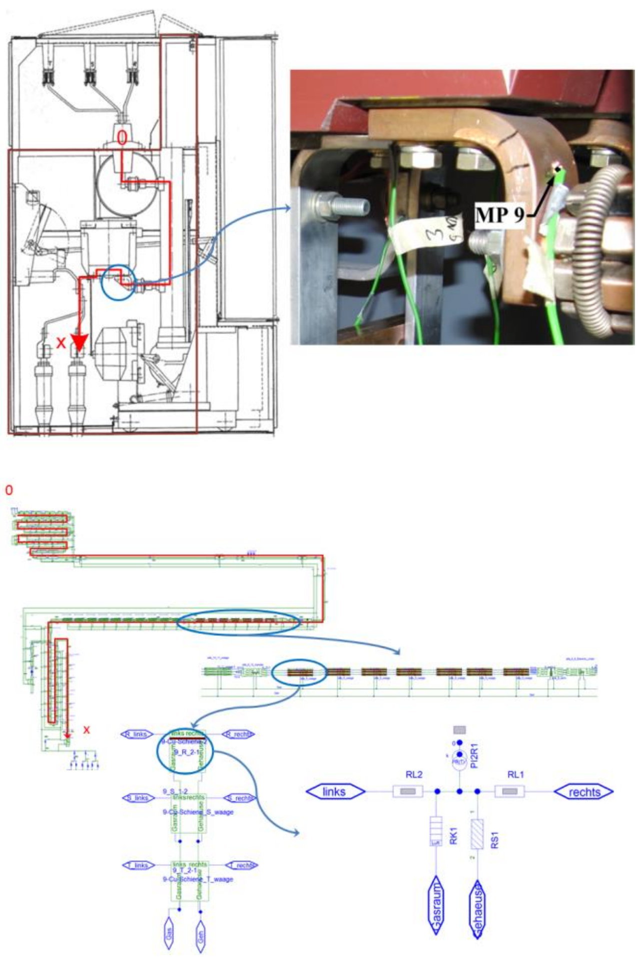


Fig. 2. Thermal network of an indoor switchgear, the red line is the same current path x (begin at 0)

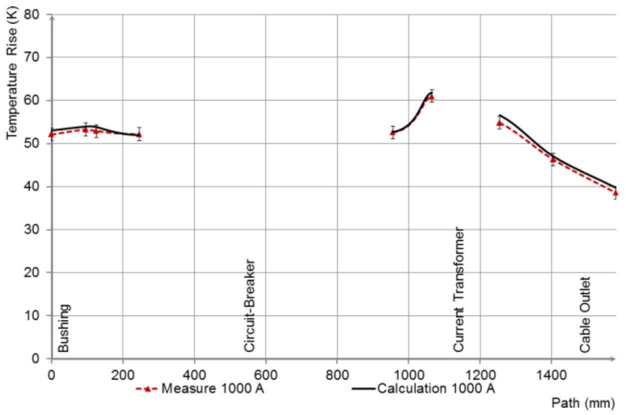


Fig. 3. Thermal processes and thermal network of an indoor switchgear on the current path x

The quantization of the thermal network has to be thusly designed to get a lower temperature difference between calculation and measurement of 1.5 K (Fig 3). All studies with the heat pipe were made on this switchgear and this thermal network researched, to reproduce the experiments.

III. Heat Pipe Principle

This part describes the basic working principle and the advantages of heat pipes. More details of the heat pipe theory can be found in [10] [11] [12]. The heat pipe is a component, which uses the phase transition very efficient.

Already in 1942 the principle of the heat pipe was invented by Mr. Gaugler, which was patented in the U.S. in 1944. By this invention, the refrigerant transport in refrigerators should be achieved by capillary force. This principle fell into oblivion and was rediscovered in 1963 by Grover, Cotter and Erickson, for the solution heat transfer problems in space. Since then the heat pipe has conquered more and more fields of application, e.g. the use in PCs or for the brakes in cars. The heat pipe is basically a gas-tight closed pipe, which contains a medium in the interior (Fig 4). The physical state of this medium is liquid. This pipe is dividable into at least two parts:

- the evaporator (Zone A),
- the condenser (Zone C) and
- perhaps an adiabatic transport zone (Zone B).

The evaporator of the heat pipe is connected with a heat source, e.g. the conductor of a switchgear and the condenser is connected with a heat sink, e.g. the ambient over a heat exchanger. The liquid medium gets a lot of energy at the evaporator and if this energy is higher than the enthalpy of vaporization the medium will vaporize. The vapor flows to the condenser (Zone C), the cooler part through the adiabatic transport zone (Zone B) where it condenses and emits the energy. Then the liquid condensate returns over gravity forces to the hot part (Zone A). There are also other ways for the condensate film to flow back to the evaporator e.g. the capillary forces. Heat Pipes which work with gravity forces have one significant point.

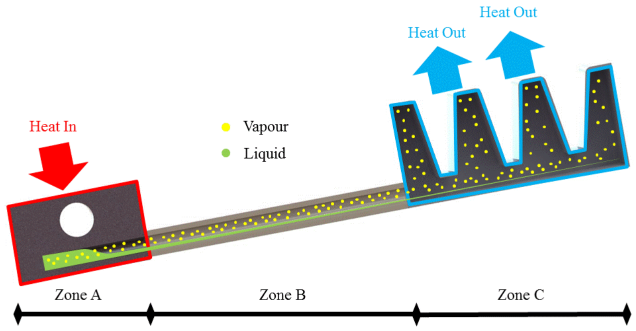


Fig. 4. Schematic of a heat pipe

TABLE II. Thermal Resistance of a Heat Pipe [13]

Thermal Resistance	Thermal Magnitude	Position
$R_{w,evap}$, $R_{w,cond}$	10^{-1} K/W	through the wall
$R_{c,evap}$, $R_{c,cond}$	10^{+1}K/W	through the capillary structure

The level of heat sink must be above the heat source so the fluid can return. They are also known as thermosyphons.

With this latent heat transport and the compact architecture the thermal resistance of the heat pipe is up to 400 times less than the thermal resistance of a copper rod (length of 400 mm and a diameter of 6 mm) in the same direction of heat transport. The heat pipe can also be called a thermal short-circuit between the connected points on it, because it connects two various points with a low thermal resistance (R_{HP}) (Figure 3 and Table II). If there is a high temperature difference between these two points, a very huge heat transport is possible and both points get nearly the same temperature. For this, the heat pipe needs no extra energy and no moving parts, so it has a low-maintenance and it works self-sufficiently.

$$R_{HP} \approx R_{w,evap} + R_{c,evap} + R_{w,cond} + R_{c,cond} \quad (1)$$

The two connecting thermal resistors from the heat source ($R_{e,evap}$) and the heat sink ($R_{e,cond}$) represent the radial resistance between the wall of the heat pipe and the heat (2).

$$R_{total,HP} = R_{e,evap} + R_{HP} + R_{e,cond} \quad (2)$$

IV. Applications

Resulting the conditions of the switchgear and the principles of the heat pipe the goal is to use this passive cooling system in this system. The heat loss is generated by the internal resistance of the conductor and the current which flows through it. With the equal resistance on the whole conductor the same heat losses are generated on every point of it, so that the temperature rise will be identical on each point of the conductor. With the conditions of a switchgear it can be possible that moving parts (e.g. a plug-in contact) or the connection of two components (e.g. a connection of two conductors) can cause an increased resistance. This increased

ISBN 978-3-8007-3624-9

resistance creates a hotspot. So the thermal conduction dissipates the resulting heat and so an uneven distribution of the temperature rise along the conductor is given.

There are four possibilities of using the heat pipe to decrease the temperature of the hotspot or the switchgear (Table III):

case 1) along the conductor,

case 2) like a heat exchanger,

case 3) transverse the conductor to the enclosure or

case 4) transverse the conductor to the ambient temperature.

The studies of the three applications have shown that various criteria must be considered.

Along the conductor (case 1)

The heat pipe along the current path can be used for cooling hotspots on the conductor. Through the targeted use of heat pipes and the ideal connectivity along the current path, it is possible to dissipate the heat loss to the outside along the conductor, where the temperature rise is lower than the hotspot. This increases the temperature at the condenser zone of the heat pipe and at the evaporator zone, where e.g. the plug-in contact is seated, there is a reduction of the temperature ($T_{Reduction,Hot}$). Because of the very low thermal resistance of the heat pipe it is possible to have nearly the same temperature on the hot point (T_{Hot}) and the cooler point (T_{Cool}) after connecting the heat pipe. For a low heat dissipation the temperature reduction ($T_{Reduction}$) from the hotspot is (3):

$$T_{Reduction,Hot} \approx (T_{Hot} - T_{Cool})/2 \qquad (3)$$

With this method the heat conductivity of the conductor is improved, without affecting the electrical properties. Thus, the heat loss remains in the busbar and results only in a better removal along the conductor. This possibility can be realized by commercially available heat pipes, which are today a bulk good, but the thermal resistance of the connectivity from the coupling element must be very low. So two points exist with different temperatures and normally on these points the couple elements are simple to connect. The voltage difference is very low, because both of the couple elements are on the same current path and the distance between them is short. By attaching the heat pipe to the hot spot, only this point or the connection surface of the coupling element can locally be cooled. Due to the compact design of switchgears and the short distances between the elements the existing temperature differences are low and so the heat transport is also relatively low. The current transport through the pipe has to be avoided, because the electrical resistance is very high, due to the fact that the area which can transport the current is very small. A positive side-effect of attaching the couple elements is that the radiation and convection surface increase with it and additional heat loss to the inner gas and the enclosure of the switchgear is released.

Heat exchanger (case 2)

The heat exchanger gives the possibility of transporting the heat energy from one gas to another e.g. the heat transport from the inner gas from a metal-enclosed switchgear to the ambient air without a gas exchange between the two. The inner gas is completely separated from the ambient air. So the heat pipe connects the fluids thermally.

Metal-enclosed switchgears are used for:

- filling in an gaseous dielectric medium e.g. the sulfur hexafluoride (SF_6),
- for the security of the live parts or the internal arc,
- for the electromagnetic compatibility and
- the standardization of the enclosure and their components for easy mounting.

This makes it possible to reduce the size of the switchgears significantly, but a reduction of the volume of the gas chamber results in an increase of the temperature rise. The studies have shown that it is possible to decrease the inner gas temperature ($T_{Reduction,Gas}$) and so nearly the same temperature reduction is reached on the conductor of the whole chamber in the switchgear ($T_{Reduction,Switchgear}$), which the heat exchanger is built in (4).

$$T_{Reduction,Switchgear} \approx T_{Reduction,Gas} \qquad (4)$$

There are two possibilities of decreasing the temperature rise of the gas:

a) convection area of the enclosure

This possibility has the advantage that only the convection area of the enclosure in- and outside the switchgear has to be increased by cooling fins. The installation increases the size and the weight of the switchgear and this means that more material has to be installed. But not at each switchgear can the convection area be increased on the enclosure. One example is that the hot chamber of the switchgear is at the bottom.

b) heat exchanger with heat pipes

The problem of the hot chamber at the bottom can be solved by heat pipes in a more elegant way. One convection area in this chamber, the other on the top of the switchgear and a heat pipe between these convection areas. It is possible, because the adiabatic transport zone (Zone B) can have a huge length. This method can be used for winding switchgears and chambers which are hard to reach.

In both methods the exchanger is only connected with the enclosure and no live parts, when the distance between it and the live parts is still given. With a huge convection area it is possible to transport a huge heat dissipation from the inner gas of a chamber in a switchgear to the ambient air or into the switchgear room. With the cooling of the inner gas of the switchgear chamber the whole components in this chamber area are cooled down with nearly the same temperature. It is possible that the parts of switchgear are cooling down with the connection of the other parts with the thermal conduction. If the heat exchanger must be installed afterwards, strong structural changes to the switchgear will have to be made. A better option is the new development of switchgears where such a heat exchanger and the components of the heat pipe, such as the adiabatic transport zone, can be considered. The heat exchanger is adaptable to other switchgears because of its simple and individual design and to use existing components to create a heat exchanger.

Transverse the Conductor (case 3 and 4)

Transverse the conductor is the most difficult way to use heat pipes in medium voltage switchgears. The evaporator (Zone A) of the heat pipe has to be connected to a live part with high voltage and the condenser (Zone C) is contacted with the grounded enclosure or is located outside it. So the pipe does not have only to transport the heat losses, it must also have an dielectric insulation for the permanently occurring voltages, the briefly occurring over voltages as well as the short circuit voltage, e.g. the voltage limits for a 36 kV medium voltage switchgear [14]:

- Is 70 kV for 1 minute the power frequency withstand voltage and
- 145 kV the lightening impulse withstand voltage.

This dielectric insulation for the heat pipe can be realized with:

- a whole insulation of the heat pipe or
- an insulation between the evaporator and the condenser (Zone B).

The studies have shown that a whole insulation of the heat pipe is not practicable. Nowadays there is no material which has a high thermal conductivity and an enormous dielectric insulation. The material aluminum nitride has a high dielectric strength (20 kV/mm) and a good thermal conductivity (130 W/(m·K)). With these properties and the insulating voltage the radial thermal resistance ($R_{c,evap}$) is up to 100 times higher than that of the heat pipe. The tiny thermal resistance of the whole pipe and the passive cool down process are destroyed.

The other possibility is the dielectric insulation of the adiabatic transport zone (Zone B) and also of the working fluid of the heat pipe, because this fluid can connect the evaporator and the condenser in the liquid state. The transport zone can be produced with any material, because it only has to transport the fluid from the evaporator to the condenser. The condition for this zone and its material is that the length of this zone must have the dielectric strength to separate the live parts. The working fluid must have a high dielectric strength and it shouldn´t react with other materials. Other important things for the heat pipes are a very low leak rate, the mechanical requirements and the different ambient conditions.

A new heat pipe must be developed to summarize the various specialized conditions. To minimize the contact resistance ($R_{e,evap}$) on the evaporator zone (Zone A) the heat pipe is integrated into a couple element (Fig. 3). So it is an add on module, which can directly be integrated in an existing switchgear and can use existing contact points. The adiabatic zone is a ceramic pipe, which only transports the fluid. The liquid with the combined conditions of no react and a high dielectric strength is hydro-flour-ether. Furthermore the installation of the constructed heat pipe must have a minimum angle of 15° so that the condensate can flow with the gravity forces back to the evaporator. There are two options in the switchgear to connect the condenser:

1) *couple element to the enclosure (case 3)*
   where the heat pipe distributes the heat losses from the live part to the enclosure. In this way the connected parts gets higher temperature rise, by cooling down the connected live part.

   So it is possible to cool down the hot spot without increasing the average enclosure temperature

   The limitation of the minimal temperature rise of the live part is the temperature of the enclosure ($T_x = T_{enclosure}$) or

2) *heat exchanger to the ambient temperature (case 4)*
   as a heat exchanger to the ambient air. The limitation of the minimal temperature rise of the live part is the temperature of the heat exchanger ($T_x = T_{Heat\ Exchanger}$).

Both options can be used for the reduction of the temperature rise of a hot spot. The temperature rise of the live part depends on the temperature of the connected point (5).

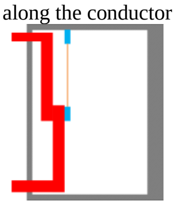
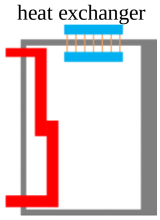
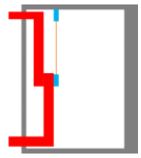
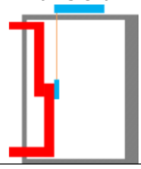
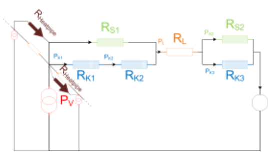
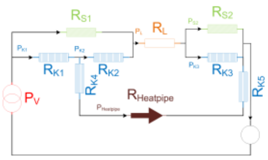
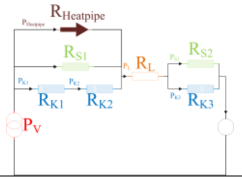
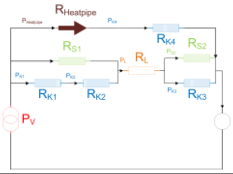
$$T_{hotspot} \approx T_x + P_v * R_{total,HP} \qquad (5)$$

By attaching the heat pipe to the hot spot this point or the connection surface of the coupling element can be locally cooled down. Furthermore there is heat conduction through the cooling of the adjacent part to be expected. And when the heat pipe is connected to the hot spot it has a high temperature difference between these points and so it can distribute a high heat loss. So to integrate this module have to be created significance changes in the structure of existing switchgears. So it is better to develop a new switchgear, where these parts are included. The dielectrically disconnection of the evaporator and the condenser must be considered with an insulated fluid and adiabatic transport zone.

V. SUMMARY

The various electrical resistances of a switchgear produce an uneven temperature rise due to the current of it. The low thermal resistance of heat pipes can be used to increase the heat dissipation of thermal conduction, radiation and convection of the switchgear. The points of possible installations are on the conductor to cool down a local hot spot, e.g. the electrical contacts or in metal-closed switchgears in the inner gas. So the heat pipe reduces the temperature rise of the connected element of the point of installation. Now it is possible after creating a thermal network of the switchgear to divide the different possibilities and appraisal the temperature reduction and the possible increase of the CCC. So a transfer to other medium voltage switchgears is given (Table III). The heat pipe can be used to increase the CCC, prolong lifetime of switchgears, save copper by reducing the cross section of the conductors or provide a homogenization of the temperature distribution along

TABLE III. COMPARISON OF THE APPLICATIONS FOR SWITCHGEARS

	application			
	case 1	***case 2***	***case 3***	***case 4***
installation	along the conductor 	heat exchanger 	transverse the conductor connected to the enclosure 	ambient 
thermal network				
advantages	• easy to use • low cost • no voltage	• very large heat dissipation • global significance • no voltage	• average heat dissipation • reduction of the temperature of hot spot	• very large heat dissipation
disadvantages	• local significance • low heat dissipation	• significant changes in structure of switchgear • average cost	• high costs • voltage-proof • significant changes in structure of switchgear	• higher costs
possible increase of CCC	up to 15 %	up to 40 %	up to 25 %	up to 75 % [15]

the conductor. All solutions have different advantages and disadvantages, so it is thinkable that more than one application is increased in the praxis.

potential applications in the future

During the investigations there were three ideas for more efficient uses of the heat pipe have been discovered, which have a high potential. The first idea is to integrate a heat pipe into a conductor during the production to distribute the heat losses more efficiently (e.g.: from a electrical contact). The second one is to use the heat exchanger for cooling down the rooms of the switchgear or to transport the heat from the inner gas directly to the ambient air. The last idea is to integrate a couple element in the production of switchgears into the side/ rear wall and connect it with a connection point of the heat pipe in the conductor.

Integrating these ideas into medium voltage switchgears will be the focus of the next developments.

ACKNOWLEDGMENT

Special thanks to the Federal Ministry of Education and Research for financing the research, the SZM Bad Muskau for providing the indoor switchgear, ILK and THETA Ingenieurbüro GmbH for her advice and assistance.

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