Characteristics of ventilation circuits applied to cylindrical rotor synchronous machines

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Abstract - The use of cylindrical rotor in synchronous machines offers excellent conditions for the heat dissipation from the stator and rotor windings. This paper describes the main ventilation arrangements for this type of construction as well as specifies the main factors that determine the choice of the most appropriate ventilation method for each application.

1 INTRODUCTION

Cylindrical rotor synchronous machines are characterized by their rugged pole design. The poles are built flush with the rotor surface and their windings lay in slots in the rotor periphery, thus also called as non-salient pole type rotor.
Similar to the stator core lamination, the cylindrical rotor consists of steel laminations provided with radial ventilation channels to improve heat dissipation from rotor lamination core and field windings.
These construction characteristics provide evenly distributed temperature along the core laminations and ensure a larger contact area of the core lamination faces with the air thus enlarging the heat transfer area between the field winding and the cooling air.
However, to ensure homogeneous cooling of the heat sources, the machine cooling system must be properly sized. This calculation must ensure proper airflow to dissipate the heat losses from the machine as well as provide proper airflow distribution through the machine aiming a balanced cooling of the heat generating sources.
The stator and rotor windings of cylindrical rotor synchronous machines can be cooled by two different ventilation systems: by single ended or by double ended ventilation circuit. These two methods are described in following items.

2 SINGLE ENDED VENTILATION CIRCUIT

The single ended ventilation system is characterized by having only one area for the air intake and one area for the air outtake.
The typical arrangement of synchronous machines with such type ventilation system comprises a centrifugal fan with straight radial blades or backward-curved blades in the region of the air outlet.
With this arrangement in the ventilation circuit, the centrifugal fan uses the low pressure area generated in the air inlet area to suck the air through the machine.

2.1 AIRFLOW PATHS

Figure 1 shows the desired airflow in a single ended ventilation system. As can be seen the airflow does not occur through a single path, but rather by means of parallel branches.

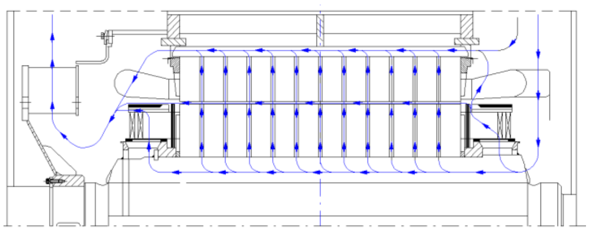

Figure 1: *Airflow path in single ended ventilation system of a cylindrical rotor machine*

The airflow adjustment in each branch of the ventilation circuit is given by weighting the areas of the airflow passage and pressure generated by the fan and radial ducts in the rotor lamination core and the airflow passing over the rotor end windings.
The main airflow branch corresponds to the air that path the passes through the radial ducts of the rotor, since these air channels generate more

pressure than the rotor end windings.
As this branch provides the largest percentage of the net airflow that flows through the machine, special care should be taken when designing the four air passage areas in the single ended ventilation circuit as shown in Figure 2:

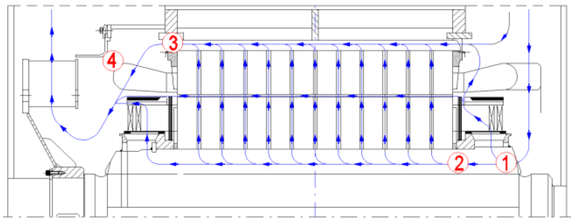

Figure 2: *Main areas of the air passage of the main branch in the single ended air circuit*

Description of the air passage areas:

1. Cross area for the air inlet into the rotor, comprising the areas between the ribs and the rotor pressing ring;
2. Cross area for the axial air inlet into the rotor lamination core, delimited by the area between the ribs below the inner diameter of the rotor lamination core;
3. Air outlet area of the stator lamination core, also known as bypass;
4. Air passage area between the fan cover and the winding head at the air outtake side.

The incorrect dimensioning of any of these air passage areas can seriously impair the effectiveness of cooling system resulting in reduction of the net airflow through the machine. Thus, care should be taken when dimensioning the ventilation circuit to ensure low air resistance and airflow losses in the main branch of the ventilation circuit, avoiding unwanted airflow reduction and ensuring lower pressure drop in the ventilation circuit, thus requiring lower air pressure generated by the fans. With a correct dimensioning of the ventilation system lower windage losses will be ensured and lower noise level will be generated by the machine.
The airflow lines in the air inlet area of the rotor indicate that the airflow rate passing through the area 1 is greater than the airflow rate passing through the area 2 due to the presence of a branch between these two areas that guide the air to the rotor end winding. In order to avoid air throttle in the rotor air circuit, it is recommended that the area 1 is always greater than the area 2, preferably having a relation with the ratio of the airflow rates in each excerpt, as shown in Eq. 1:

$$\frac{A_1}{A_2} \geq \frac{Q_1}{Q_2} \qquad \text{Eq. 1}$$

Where:
A: transversal areas for the air passage;
Q: airflow rates in each excerpt;
Indexes *1* and *2:* each excerpt as shown in Figure 2.

2.2 ANALYSIS OF THERMAL DISTRIBUTION

Cylindrical rotors are characterized by the fact that they concentrate the largest net airflow rate in the radial ducts. That can be evidenced analyzing the temperature distribution along the rotor.
Considering the Figure 3, obtained by means of thermal calculation software, it can be noted that the average temperature of the copper in the rotor lamination core is lower than the temperature of copper in the end windings, caused by the higher airflow rate directed to this area.

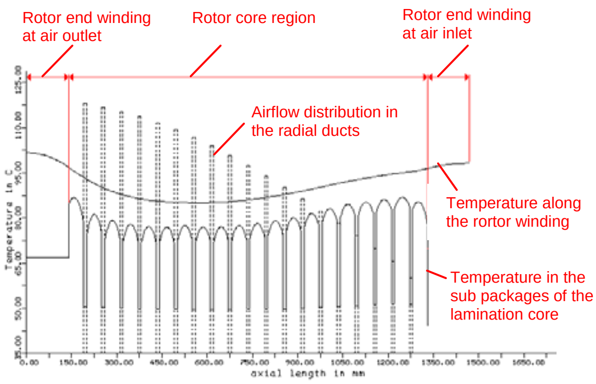

Figure 3: *Typical temperature distribution for the rotor with single ended ventilation circuits*

In the stator, on the other hand different cooling conditions are present. As commonly no air deflector is used near the air inlet of the winding, this end winding is cooled by a large airflow that has the temperature of inlet air. The cooling condition of the end winding changes at the air outlet. Although almost all the airflow inside the machine passes over the end winding at the air outlet, the temperature of this cooling air is approx. 15 to 20°C higher than the cold air inlet. Thus, the resulting temperature distribution will be similar to that shown in Figure 4, where the temperature of stator winding in the core region is higher than the temperature of the end windings at the air inlet side and slightly lower than the temperature of the end winding temperature at the air outlet.

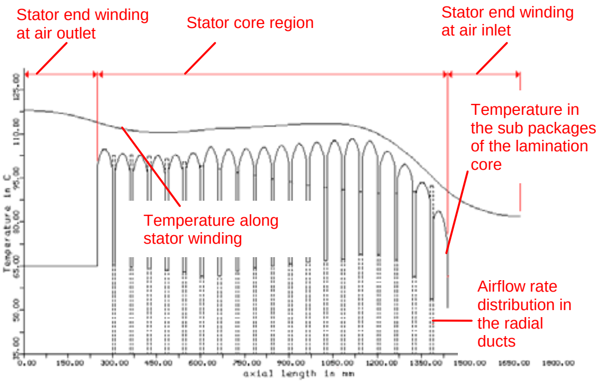

Figure 4: *Typical temperature distribution for the stator with single ended ventilation circuits*

3 DOUBLE ENDED VENTILATION CIRCUIT

This system is provided with two air inlet areas at the drive end and non-drive end of the machine and one air outlet area at the stator lamination core. Due to this air inlet/outlet disposition, one can say that there is symmetry in the ventilation circuit.

The typical arrangement of this ventilation system on cylindrical rotor synchronous machines is characterized by the use of radial fans fixed on the rotor pressing rings. In this assembly design, as shown

Figure **5**(a), the radial fans operate in parallel with the radial ducts of the rotor for the sole purpose to generate airflow for cooling the stator end windings. Another possible arrangement consists of the use of axial fans mounted on the shaft and serial coupled with the radial ducts of the rotor, as shown in

Figure **5**(b). This concept aims to generate an increased pressure at the air inlet over the rotor lamination core thus improving the airflow through the radial ducts. Although this design can be used in the same applications of radial fans, the use of axial fans is recommended for applications where the radial rotor ducts are not able to provide sufficient pressure to the required airflow for the machine cooling. As example for this application are the cases where the rotor laminations are integrated directly with the machine shaft without using ribs.

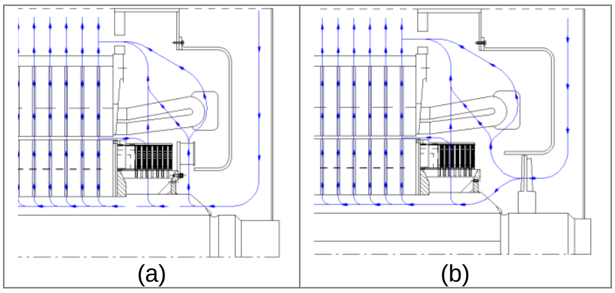

Figure 5: *Illustration of the airflow paths in a double ended circuit of cylindrical rotor machines. (a) with radial fans; (b) with axial fans*

3.1 AIRFLOW PATHS

The double ended ventilation circuit as well as the single ended ventilation circuit has parallel airflow paths. The difference lies in the fact that the double ended ventilation system presents a symmetric airflow circuit, given by the two air inlet areas. This advantage provides a better airflow distribution in the machine.

The proportions of the total airflow that passes through each air outlet branch are defined according to the cooling requirements for the heat sources and are regulated by the ratio between the airflow passage areas and the pressure generated by radial ducts and fans.

The critical areas for the air passage to the double ended ventilation circuit, as shown in Figure 6, correspond to areas that limit the air throughput in the two main flow paths, formed by the radial ducts in the rotor and stator lamination cores and the stator end winding.

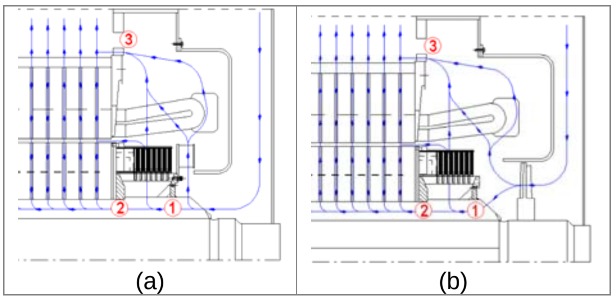

Figure 6: *Main areas of air passage in the main branches of a double ended ventilation circuit. (a) with radial fans; (b) with axial fans*

Description of the air passage areas:

1. Air passage area between the shaft ribs and the rotor pressing ring;
2. Transversal area for the air inlet to the rotor lamination core;
3. Air passage area over the stator lamination pressing ring (*by-pass*).

The air inlet area in the rotor with double ended ventilation circuit has the same feature as shown

in item 2.1 aiming to meet the relationship between the values of the areas 1 and 2 and the air flow passing through these areas, as shown in the Eq. 1.
As the air passage area through the by-pass (area 3) is part of an independent air path section of the radial ducts of the rotor, it is determined by calculating machine temperature and thus obtaining the minimum airflow required for cooling the stator end windings.

3.2 ANALYSIS OF THERMAL DISTRIBUTION

For the thermal analysis of double ended ventilation circuits a symmetry approach is adopted considering the center of the active part of the machine (ranging from the lamination core center up to the end of the end windings). Figure 7 shows typical thermal distribution in the rotor winding with a double ended ventilation circuit fitted with axial fans as well as radial fans.
This figure shows that the distribution of the rotor winding temperatures is similar to the unilateral ventilation circuit, where the end windings are hotter when compared with the temperature measured along the stator core. Although the rotor end windings, generate reasonable pressure they will become hotter since the pressure loss at the air outlet in the outer diameter is quite higher due to the use of a bandage or retaining ring to withstand the high centrifugal forces of the copper weight in these areas.

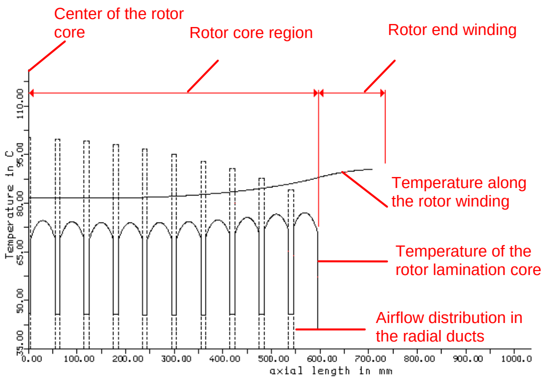

Figure 7: *Typical temperature distribution for the rotor with double ended ventilation circuit in half of machine winding*

The temperature distribution in the area of the stator windings is contrary to temperature distribution in the rotor. When radial fans are used, greater airflow is achieved in the area of the stator end windings. Consequently greater airflow speed is achieved in this section, which promotes the heat transfer. Thus, as shown in Figure 8, lower temperatures can be noted in the end winding when compared with the winding temperatures in lamination core.

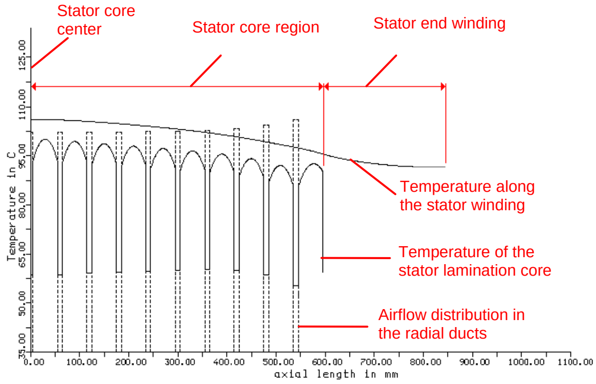

Figure 8: *Typical temperature distribution for the stator with double ended ventilation circuits in half of the machine winding, with radial fans*

As shown in Figure 9, when axial fans are applied, there is a tendency to achieve more homogeneous heat distribution along the stator winding. This fact is explained due to the lack of fans exclusively dedicated for cooling the end windings. Axial fans, as already mentioned, tend to optimize the ventilation in a balanced way between the main branches of airflow. Thus, when lower temperatures are required for the stator end windings, the by-pass area in the counter plates must be increased, as shown in the area 3 of Figure 6, in order to reduce the resistance to the airflow in this section.

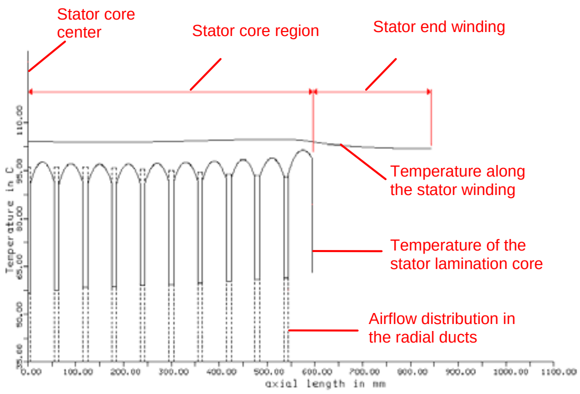

Figure 9: *Typical temperature distribution for the stator with double ended ventilation circuits in half of the machine winding, with axial fans*

4 COMPARATIVE ANALYSIS

Based on the above description about single and double ended ventilation methods, different performance characteristics and practical application can be achieved that allow you to perform a comparative analysis between them, explaining the strengths of each concept, as described in the following items.

4.1 ADVANTAGES OF USING SINGLE ENDED VENTILATION CIRCUIT:

- The application of this ventilation system allows the inclusion of flywheels or brake wheels inside the machine housing, coupled to the fan. This system provides great benefits, since the use of brake wheel inside the machine housing is only allowed when it is mounted at the air outlet area, thus avoiding that the dust generated during braking process damages the winding insulation.
- This ventilation system allows greater versatility in the heat design since it allows obtaining different values for the total airflow rate by changing only the fan geometry.
- When no requirements are stated in the purchase order for machines with low noise levels, also the use of the ventilation box is no longer needed since lateral openings can now be adopted at the drive end and non-drive end side for the air inlet and air outlet.

4.2 ADVANTAGES OF USING DOUBLE ENDED VENTILATION CIRCUIT:

- Lower pressure losses in the ventilation circuit, due to the air flow symmetry, which provides twice the area of air inlet over the rotor when compared with the single ended ventilation circuit.
- Lower windage losses. This advantage is because the fans used in bilateral ventilation systems have smaller diameters than the radial fans used in single ended ventilation systems.
- Rotor windings with more uniform temperature distribution caused by the symmetry of the ventilation circuit.
- In general, due to the use of smaller diameter fans this configuration results in lower noise levels when compared with the single ended ventilation circuits.

5 CONCLUSION

The conceptual analysis of the ventilation circuits in this paper describes the typical thermal behavior of cylindrical rotor synchronous machines with ventilation ducts. Also additional precautions are specified that need be considered when designing main air passage areas for each ventilation circuit system.

The definition of ventilation concepts to be used in each product line depends strongly on the application. Typical examples are machines with high inertia, which require the use of flywheels, typically found in hydrogenerators where the application of single ended ventilation system becomes quite favorable. The selection of this ventilation system allows the flywheel assembly inside the machine, coupled to the blower at the air outlet area. This arrangement enables a better rotor dynamic machine behavior, since a large solid component, a flywheel, is assembled between the bearings. However in general one can say that where no specific technical requirements are made for any application, the double ended ventilation system provides a better thermal performance than the single ended ventilation system, since it ensures a more homogeneous heat distribution along the rotor and stator windings and provides higher ventilation efficiency, resulting in lower windage losses. The choice between the use of radial or axial fans in the double ended ventilation system depends on the pressure-generating capacity by the rotor. Where the radial ducts and the rotor end windings are able to generate sufficient pressure to the airflow provision required in the design, the use of radial fans is recommended. As already mentioned above, the use of these fans is not intended to benefit the rotor ventilation, but the cooling of the stator winding heads.
In situations where the rotor is not able to generate the required air pressure, the use of axial fans is advantageous, since they are serial coupled serial with the rotor. This fan types will add pressure to the system, achieving the required airflow in the radial channels and to the rotor end windings.

6 REFERENCES

[1] WEG Technology Papers related to Heat Transfer and Fluid Dynamics analysis for Rotating Electric Machines.
[2] Results of experimental analysis at Thermal Tests Laboratory.
[3] Consulting notes regarding Heat Transfer na Fluid Dynamics applied to Rotating Electric Machines.