OPTIMIZATION OF ELECTRICAL PARAMETERS OF WINDINGS USED IN AXIAL FLUX ELECTRICAL MACHINES

Uhrík, M.
Department of Heavy Current Electrotechnics, Institute of Power and Applied Electrical Engineering,
FEI STU, Ilkovičova 3, Bratislava, 812 19, Slovak Republic
milan.uhrik@stuba.sk

Abstract
This paper deals with shape optimization of windings used in electrical machines with disc type construction. These machines have short axial length what makes them suitable for use in small wind-power turbines or in-wheel traction drives. Disc type construction of stator offers more possibilities for winding arrangements than are available in classical machines with cylindrical construction. To find out the best winding arrangement for the novel disc type machine construction a series of analytical calculations, simulations and experimental measurements were performed.

Keywords
electrical machines, axial-flux machines, windings, parameters, optimization

1 AXIAL FLUX ELECTRICAL MACHINES

Disc type electrical machines pose relatively new design approach in electrical machinery. They come out of the concept of axial flux machines, where the magnetic flux flows axially through the air gap. Magnetic field is usually excited by permanent magnets built in the rotor or glued on the rotor ferromagnetic core. Stator can be made from axially layered laminations (Fig. 1) or cast from SMC (*Soft Magnetic Composite*) materials. This paper deals with the comparison of parameters of windings which are most commonly used in axial-flux electrical machines and presents possible ways of their optimization.

2 TYPES OF WINDINGS USED IN AXIAL FLUX MACHINES

In comparison with classical cylindrical machines it is possible to use more winding configurations in axial-flux machines. When the machine is designed, it is assumed that in terms of induced back electro-motive force (EMF) all winding types are equivalent, since the back EMF is only a function of length of conductors placed in the stator slots regardless of the way how the end-windings are shaped and placed outside of the stator [1]. Nevertheless, there are differences among the winding types which are not considered in the law of induced EMF (so called *BLi* law). The coils can be arranged in single or more layers and connected either in series or in parallel. However, parallel connection of coils is not recommended in practical applications, since the back EMF can be different in each coil what can lead to occurrence of circulating currents between coils. In case that the coils are placed in different slots under the same magnetic pole their induced voltages can have different phase. If they would be placed in the same slots under different poles, the amplitude of induced voltage can be different. In this paper the most commonly used winding arrangements are considered. Special types of windings, like printed windings or coreless windings are not considered, since they are used only in very special types of electrical machines.

The most commonly used types of windings are illustrated in Fig. 1.

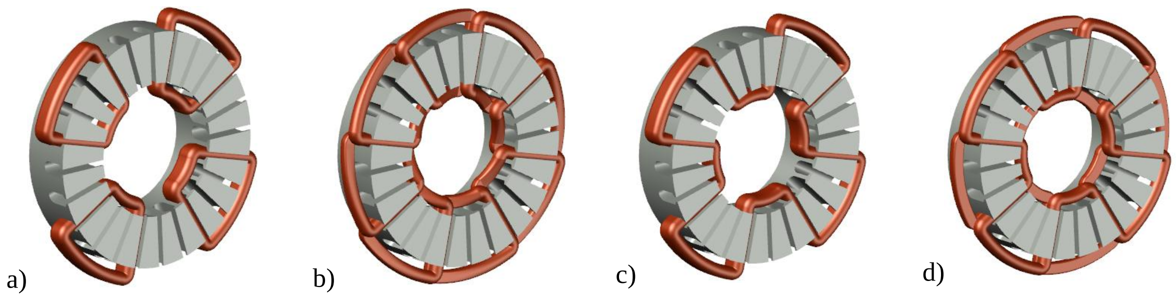

Fig. 1. Most common types of lap and wave windings.
a) 1-layer lap winding, b) 2-layer lap winding, c) 1-layer wave winding, d) 2-layer wave winding

3 ANALYTICAL CALCULATION OF WINDING RESISTANCE AND INDUCTANCE

To assess the properties of 4 basic winding arrangements mentioned in Fig. 1 a series of analytical calculations and practical experiments were performed. The considered stator (Fig. 1) was taken out of an axial-flux machine with the following nominal values: $P_n = 300\,W$, $V_n = 180\,V$, $n_n = 3000\,rpm$, $2p = 8$. The stator has been rewound four times, each time with different winding arrangement. After that, the winding parameters has been measured and recalculated. Comparison of calculated and measured values of phase resistance for each winding type are listed in Tab. 1.

Tab.1 Comparison of calculated and measured phase resistances at $t = 20$ °C for different stator windings

	Lap winding 1-layer	Lap winding 2-layer	Wave winding 1-layer	Wave winding 2-layer
Measured value $R_{f20°C}$ *V-A method*	4,90 Ω	4,70 Ω	5,60 Ω	5,00 Ω
Analytical calculation	4,89 Ω	4,66 Ω	5,64 Ω	5,02 Ω

Analytical calculation of leakage inductances is one of the most difficult part when designing an electrical machine. Therefore three different analytical approaches has been used for calculations. The first one has been taken out from [1]. The second one comes out of equations published in [2]. The last, most complex approach was taken from [3]. Resulting leakage inductances for each winding arrangement can be found in Tab. 2. There are also listed the values measured on real models of windings for comparison.

Tab.2 Comparison of calculated and measured leakage inductances for different stator windings

	Lap winding 1- layer	Lap winding 2- layer	Wave winding 1- layer	Wave winding 2- layer
Measured value L_σ	5,4 mH	4,0 mH	5,9 mH	4,8 mH
Analytical calculation 1 [1]	5,76 mH	5,52 mH	6,47 mH	5,86 mH
Analytical calculation 2 [2]	6,02 mH	4,86 mH	6,73 mH	5,19 mH
Analytical calculation 3 [3]	4,13 mH	4,15 mH	4,23 mH	4,18 mH
3D FEM analysis	5,29 mH	4,71 mH	5,16 mH	4,59 mH

4 CONCLUSION

Choosing the right winding arrangement is an essential question of correct and effective motor functionality. Too high inductance can have negative impact on motor power factor. On the other hand, too low inductance can cause higher current consumption and low dumping of current peaks in case of motors fed from electronic inverters.

The results of analytical calculations and practical experiments have shown that by using of double layer windings it is possible to use more compact coils with lower resistance and inductance. It has to be noted that the decrease in inductance is caused by decreasing the leakage fluxes of coils, not by decreasing the effective part of inductance and lowering effective magnetic flux. Single-layer windings can be manufactured more quickly and with lower labour costs, but their electrical properties are generally worse comparing to double-layer windings.

5 REFERENCES

[1] Hanselman, D.C. (1994). Brushless Permanent-Magnet Motor Design. New York: McGraw-Hill, Inc.

[2] Magureanu, R.; Vasile, N. (1990). Servomotoare fara perii tip sincron. Bucurest : Editura Tehnica. ISBN 973-31-0162-1.

[3] Gieras, J.F., R.J., Wang. a M.J., Kamper. (2004). Axial Flux Permanent Magnet Brushless Machines. Dordrecht : Springer Science. ISBN 1-4020-2661-7.

[4] Gieras, F. a Wing, M. (1998). Permanent Magnet Motor Technology. Design and Applications. New York: Marcel Dekker Inc. ISBN 0-8247-9794-9.

[5] Chiver, O., et al. (2010). Study regarding end winding inductance of three phase A.C. winding in a single layer. Proceedings of the International Conference on ENERGY and ENVIRONMENT TECHNOLOGIES and EQUIPMENT.