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Application of magnetic wedges for stator slots of hydrogenerators

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SUMMARY

The utilization of slot wedges made of magnetic material in a synchronous and induction motor or generator makes possibility to increase the efficiency of the machine. In this paper, the experiences acquired in design, installation, testing and exploitation of the magnetic slot wedges on two relatively large hydrogenerators of rated output 34 MVA, 10.5 kV, 50 Hz, 187.5 min^{-1}, cos $\varphi = 0,8$, vertical form, are presented. The magnetic slot wedges with high mechanical strength and low average permeability of $\mu_r = 2,8$ are embedded into open stator slots of the two hydrogenerators. The fixation of magnetic wedges in the stator winding slots is described in detail. The data referring to magnetic and mechanical properties of the installed magnetic wedges are presented.
With magnetic slot wedges the magnetizing current in excitation winding required to generate the air-gap flux is lower than with non-magnetic slot wedges.
The results obtained in the design stage and the comparison of on-site testing results of the generator with non-magnetic wedges and the same generator with magnetic wedges show an increase in efficiency. By installing the described magnetic wedges the surface losses in the generator rotor pole shoe iron were reduced by app. 20%, whereas the losses in the excitation winding were reduced by app. 8% due to the reduced air gap magnetizing current.
In addition, the results obtained by analytical calculation and by measurement of the magnetic wedge influence on generator's reactances are provided. Due to reduction of excitation current in no-load operation, synchronous reactances in direct and quadrature axis increase by app. 5% in the case of magnetic wedges. If an increase of reactances due to leakage reactance is taken into consideration, the total increase of synchronous reactances is app. 8%.

KEYWORDS

Magnetic Slot Wedge, Magnetic Permeability, Synchronous Hydrogenerator, Iron Surface Losses, Generator Reactances

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1. INTRODUCTION

Windings of asynchronous and synchronous motors, as well of synchronous generator which power exceeds 1 MVA are usually made from rectangular conductors in the form of coils or bars and are placed into the open stator slots. Due to the open stator slots, slot ripple in the air gap flux density caused by changing reluctance due to the slots occur in air gap. Fig. 1 shows air gap flux density distribution along the air gap periphery of a salient pole hydrogenerator, calculated by means of finite elements method for the no-load condition [1] for two different stator voltage in no load operation. The generator has 32 poles and a total of 264 stator slots.

Pulsation frequency of the magnetic flux density in the air gap is determined by number of stator slots Q and by synchronous speed of rotation of the magnetic field fundamental wave n_s in accordance with the equation

$$f_p = \frac{Q\,n_s}{60} \quad Hz \tag{1}$$

This is the pulsation frequency due to fundamental induction slot harmonic. Fig. 1 shows air gap flux density distribution whereas Fig. 2 presents analysis of higher harmonics. Only the harmonics up to No. 19 were considered.

Due to the above mentioned magnetic induction pulsations in the generator air gap, so called „surface losses“ occur in a thin surface layer of the hydrogenerator rotor pole shoes. They are localised in a thin pole iron layer, whereas thickness of that layer is determined by the electromagnetic wave penetration depth and is calculated in accordance with the following well-known equation:

$$\vartheta = \sqrt{\frac{2\rho}{\omega\mu}} \quad mm \tag{2}$$

where: ρ resistance $\Omega .m$, ω angular pulsation frequency s^{-1} and μ iron permeability.

Surface losses due to induction pulsations occur in the damper winding placed in the rotor pole shoes as well, but in significantly lower extent than in iron. They are not considered in this paper.

Analytical calculation of surface losses is very complex and is usually performed using more or less accurate equations which are supplemented by empirical coefficients [2],[3],[4].

Due to the slotted stator core, geometric air gap between stator and rotor increases to a higher equivalent value calculated by means of the so called Carter factor. Increase of geometric air gap by Carter factor affects increase of the air gap excitation current by amount of that factor. Due to increase of excitation current (which is affected by the air gap increase), power losses in field winding also increase.

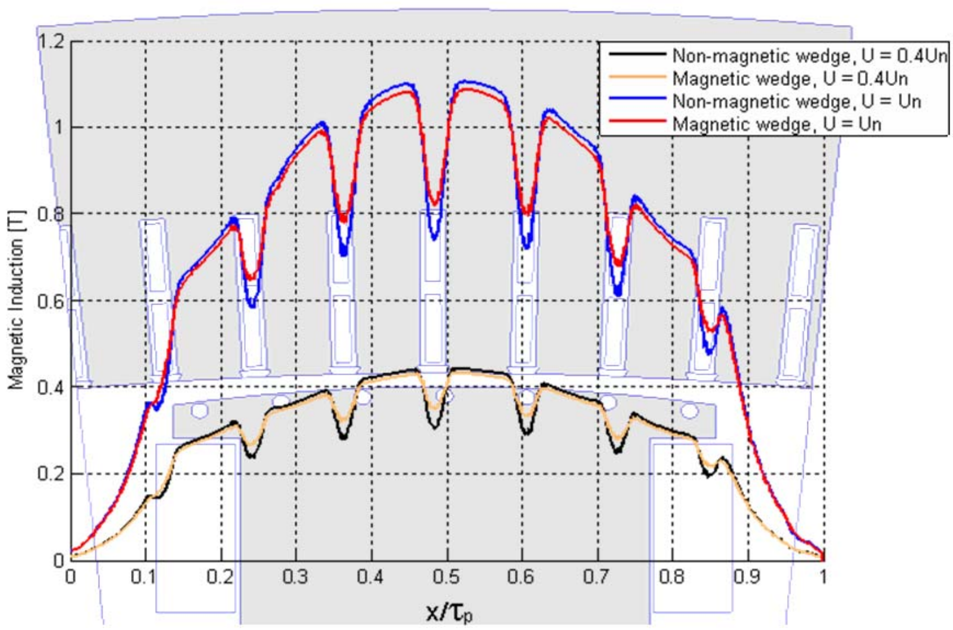

Fig.1 Air gap magnetic flux density distribution along the air gap periphery

Magnetic slot wedges are used in order to reduce rotor pole surface and damper winding losses as well as losses due to magnetizing current. Reduction of all these losses increases the generator efficiency by value which is generally dependent on optimization of generator air gap parameters.

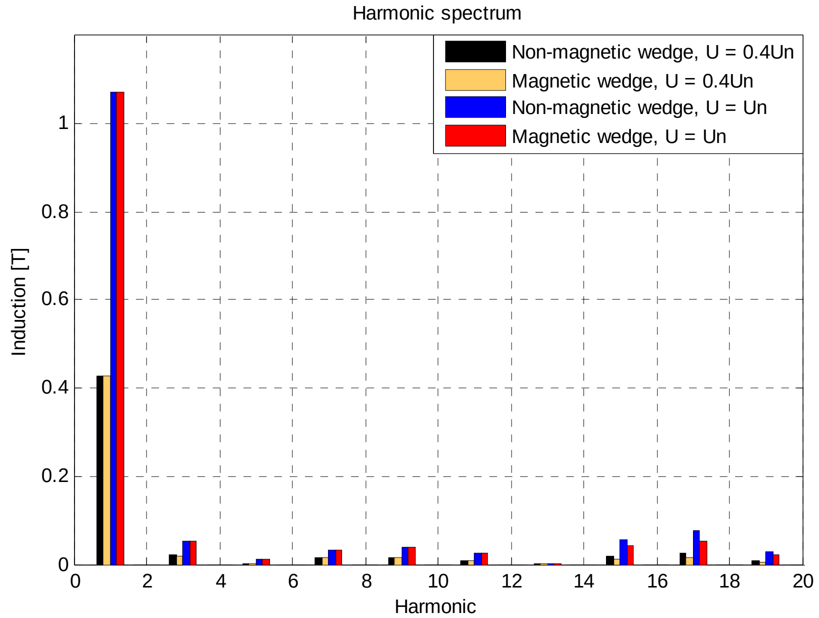

Fig.2 Harmonic spectrum of flux density distribution in air gap, no load

When considering application of magnetic wedges, it is important to emphasize that their using influences generator reactances too, and therefore, when optimizing the wedge properties, the losses shall be minimized and at the same time this should have the minimum possible influence to change of reactances. By means of installation of a magnetic instead of a non-magnetic wedges, the transverse (leakage) magnetic conductivity of the slot section where the wedge is placed increases. The leakage magnetic flux through the magnetic wedge increases the stator winding leakage reactance. Due to increase of the stator winding leakage flux, tooth saturation excitation current and its losses are increasing. Increase of reactances affects reduction of the short circuit current too.

Taking into consideration all the above mentioned consequences occurring due to embedding of magnetic instead of non-magnetic slot wedges, each case should be optimized separately during the generator design, with an aim to minimize the losses and to keep the generator reactances changes as low as possible.

2. EMBEDDING TECHNOLOGY OF MAGNETIC WEDGES IN 34 MVA GENERATORS

The first patents related to magnetic wedges were registered as early as at the turn from the 19th to 20th century. Although the basic theoretical issues were known, application was almost negligible, as the key issues had not been solved, as well as installation technology and operational reliability of the selected concept [5]. The issues related to embedding cost effectiveness and to installation related risk were more important than contribution of magnetic wedges to energy savings by means of increased efficiency of generators and motors.

The major drawbacks of most previous concepts of a stator with magnetic laminated wedges is unreliability of mechanical connection between the wedge and the core sheets, which causes loosening and falling of wedges out of the slots during long time operation. It is particularly present at vertical forms of motors and generators.

In recent technology referring to embedding of magnetic wedges into the slot of a large asynchronous motors, iron putty [6] [7] or composite materials based on soft iron, laminates and polyester resins are applied. Iron putty is a dense plastic substance, made from the specially shaped soft iron particles containing the filling and compacting additives, mixed with epoxy resins. That substance, of relative permeability within the range of $\mu_r = 5 \div 10$, is used for filling the slots of high-voltage motors. After

the wedges embedding the process of curing and drying in furnace, at the temperature of app. 130 °C, (depending on material insulation class) is followed [8].
The stators of 34 MVA generators where the magnetic wedges were embedded are relatively large (stator bore diameter is 5.67 m), therefore application of total vacuum pressure impregnation (VPI) of the whole stator was not possible. In these VPI systems, embedding of magnetic as well as non magnetic wedges is performed prior the impregnation. The wedges during impregnation get stuck to the stator core and to the winding. The cohesion forces among the wedges, stator core and winding bar shall be considerably higher than the electromagnetic forces which act on pulling the wedge out of the slot.

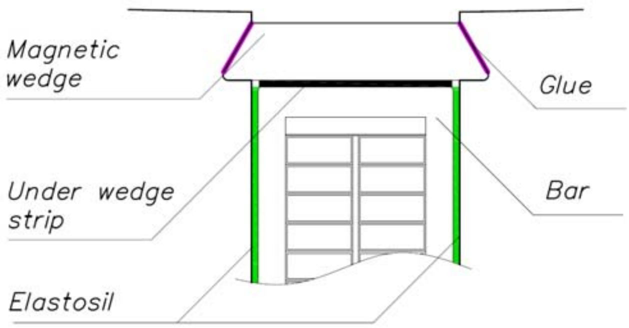

Fig. 3 Slot detail with an inserted magnetic wedge

At these generators, the bars are impregnated by VPI process and tested prior to their inserting into the slots. For inserting and fixing bars and wedges a simple and reliable procedure is required. It is expected that the magnetic wedges will have a lifetime as long as non-magnetic ones i.e. during the entire generator operational lifetime. Based on the experience related to application of magnetic wedges in our practice, the magnetic wedges made from laminate, which consists of a glass fibre as carrier, iron powder and epoxy resin as a binding agent, all in insulation class F, have been selected.
The bars are fixed in the slots with magnetic wedges by hard wedging, using the under-wedge strips of different thicknesses. The magnetic wedges are additionally fixed to the core, by means of two-component epoxy glue. A slot detail of these generators with the magnetic wedge is shown on Fig. 3. Detail of generator production is shown on fig. 4.

Table I. Typical properties of materials for magnetic wedges

PROPERTY	NORM	UNIT	AS DELIVERED	TESTED at 200°C		
				500h	1000h	1500h
Thickness	-	mm	6.01	5.98	5.95	5.92
Density	ISO 1183	g/cm^3	3.508	3.492	3.485	3.478
Bending strength (at 23°C)	ISO 178	MPa	171	170	162	148
Electrical resistance	IEC 60167	$\Omega \cdot cm$	5.7×10^6	7.9×10^6	8.2×10^6	$9{,}4 \times 10^6$
Magnetic permeability at 1 T (μ_r)	Internal	-	1,65	1,52	1,5	1.49

The material for magnetic wedges was supplied by the well-known European company.
Composition of wedge material is: glass fibre 7.8 %, iron powder 74.9 %, epoxy resin 17.3 %.
Prior to the embedding, tests of electromagnetic, mechanical and thermal properties of the wedge material were performed in our laboratory.
Testing of temperature influence on mechanical and electromagnetic properties of magnetic wedges (accelerated ageing) was performed. Results of testing performed at temperature of 200 °C during 500, 1000 and 1500 hours are shown in Table I. No significant changes of properties were registered therefore it can be concluded that the embedded wedges could be able to withstand designed operating conditions for a sufficient period of time. It is to state that the so far achieved experience, based on one or two generators cannot be considered a sufficient reference for more than 25 years long generator operation time. Actual condition of the wedges is monitored and operation data are collected.

Fig. 4 Insertion of wedges in the generator factory

3. INFLUENCE OF MAGNETIC WEDGES TO LOSSES AND REACTANCES

3.1 Reactances and excitation current

As stated in introduction, when magnetic wedges are embedded instead of non-magnetic ones in the same generator stator slots, the reactances, rotor surface losses, excitation current in no-load condition and field winding losses will be changed. In this paper, only the final results of analytical calculations, performed by means of own computer software, are provided.
When performing the reactance calculation for magnetic and non-magnetic wedges, the only changeable geometric value is a slot aperture width at the wedge position (in magnetic sense). The actual slot aperture dimension is replaced by a certain fictive, lower value, whereas the reduction amount depends on relative permeability of the wedge, saturation of leakage path through the stator slot and magnetic conditions in the generator. Accuracy of analytical calculation depends on estimation of wedge influence, which permeability is known, to fictive reduction of the slot aperture.
In our specific calculation case related to wedges which permeability is $\boldsymbol{\mu_r}$ **= 2.8,** the Carter factor decreased from 1.068 (non-magnetic wedges) to 1.011 (magnetic wedges) which is equivalent to reduction of air gap by 5.4%.
The calculated excitation current at generator rated load decreased by 2.88%, whereas the field winding losses decreased by 5.7%. The actual field winding losses reduction will be somewhat higher, as, due to the total decreased losses, the winding temperature decreases.
In accordance with the results of conventional analytical calculation, the leakage reactance of the generator stator winding is 0.156 p.u. if the wedges are non-magnetic, i.e. 0.180 p.u. if the wedges are magnetic, with assumed permeability of μ_r =2,8, which is an increase of app. 15 %.
Due to reduction of excitation current in no-load condition, synchronous direct- and quadrature-axis reactances increase by app. 5% for magnetic wedges. If increase due to leakage reactance is taken into consideration, total increase of synchronous reactances is app. 8%.
The calculated value of unsaturated direct-axis transient reactance X'_d increased from 0.294 to 0.306 %, whereas the saturated value increased from 0.28 to 0.293 p.u. As there is no excitation in quadrature axis, quadrature-axis transient reactance X'_q is equal to synchronous reactance X_q , i.e. it is increased by app. 8%.

The sub-transient reactances in direct- and quadrature-axes also increased, due to increasing of the stator winding leakage reactance. Unsaturated direct-axis sub-transient reactance X''_d is increased from 0.20 to 0.22, whereas the saturated value increased from 0.19 to 0.21 p.u.. Unsaturated quadrature-axis sub-transient reactance X''_q is increased from 0.25 to 0.27, whereas the saturated value increased from 0.24 to 0.26 p.u..

3.2 Power losses

As already mentioned in introduction, installation of magnetic wedges reduces surface losses due to induction pulsations in thin iron layer at the surface of rotor pole shoes. In specific case, the wave penetration depth of the fundamental magnetic induction slot harmonics into the steel sheets at the rotor surface is defined by the equation (2).

$$\vartheta = \sqrt{\frac{2\rho}{\omega\mu}} = \sqrt{\frac{2\cdot 134.7\cdot 10^{-9}}{5181\cdot 4\cdot \pi\cdot 424\cdot 10^{-7}}} = 0.312 \quad mm$$

It is assumed as follows: Resistivity ρ for rotor iron in warm condition, $134.7 \times 10^{-9}\ \Omega$ m

ω - angular frequency of pulsations of the fundamental slot harmonics, 5181 s^{-1} and μ_r - relative permeability of iron, 424.

In this specific case, total iron losses at no-load conditions were calculated by means of conventional analytical equations and thereafter were measured, on the generator with installed magnetic wedges and on the generator with non-magnetic wedges. The only differences were observed in surface losses on the rotor poles. In the design with non-magnetic wedges, total calculated iron losses are 121.7 kW, whereas the total losses with magnetic wedges are 106.4 kW. Reduction of these losses is about 15.3 kW, which is mostly related to the rotor surface losses. These reduced losses in the rotor iron mean that the main goal of installation of magnetic wedges into the generator has been achieved.

Decrease of excitation current due to installation of magnetic wedges is reflected in reduction of losses in field winding, from 107.8 kW to 102.3 kW, which is a reduction of 5.5 kW, i.e. 5.1%.

Total reduced losses due to installation of magnetic wedges are 20.8 kW.

4. TEST RESULTS

4.1 Power losses

On one out of two 34 MVA generators, 10.5 kV, 187.5 min^{-1}, $\cos\varphi = 0.8$, measurements were performed in a power plant, firstly with non-magnetic wedges, then with magnetic wedges. Power losses, reactances and other properties which might be affected by installation of magnetic wedges were measured.

Value of measured losses in iron in no-load conditions with non-magnetic wedges is 143.95 kW at the core temperature of 34.9°C and 124.9 kW at the core temperature of 39.6°C. The measured losses on the same generator with magnetic wedges are 111.7 kW at the core temperature of 49.2°C and 107 kW at the core temperature of 57.4°C.

Table II : Calculated and measured losses in no-load conditions

Losses	Calculated (kW)			Measured (kW)		
	non-magnetic wedge	magnetic wedge	difference	non-magnetic wedge	magnetic wedge	difference
No-load	**121,7**	**106,4**	**15,3**	**124,9***	**107***	**17,9***
Excitation winding	**107,8**	**102,3**	**5,5**	**105,7**	**97,45**	**8,25**

* Measured at slightly different stator core temperatures

The mentioned differences in temperature between the cores with magnetic and non-magnetic wedges occur due to different water flows through the generator heat exchangers and due to different inlet water temperatures.

The measured losses in field winding are 105.7 kW with non-magnetic and 97.45 kW with magnetic wedges. Table II shows results of the performed analytical calculation and results of loss measurement in no-load conditions of the generators.

4.2 Reactances

The measured stator core leakage reactance with non-magnetic wedges is 0.12 p.u, whereas it amounts 0.16 p.u. with magnetic wedges, which is an increase of 33%.
Synchronous reactance in direct axis (saturated value) obtained from ratio of the short circuit and no-load excitation current is 1.04 for non-magnetic and 1.07 for magnetic wedges.

4.3 Excitation currents

The excitation current values for the rated load were obtained from the regulation curves, as the rated load conditions were not fulfilled during measuring. The measured excitation current is 655.4 A with non-magnetic wedge and 630.4 A with magnetic wedges.

5. ANALYSIS OF THE OBTAINED TESTING RESULTS ON THE GENERATORS

The measured excitation currents at rated load with non-magnetic and magnetic wedges match the calculated values quite well; 630.4 A in the generator with magnetic and 655.4 A with non-magnetic wedges. The measurement difference is 3.8 %, whereas the calculation difference is 2.88 %.
Due to the reduced excitation current, the measured losses in the excitation winding are lower by app. 8%, whereas the calculated losses are lower by app 6 %.
Based on the results obtained by measurement the iron losses, performed with magnetic and with non-magnetic wedges, it cannot be precisely stated what is actual contribution of magnetic wedges to reduction of losses due to different core temperatures during the tests with magnetic and non-magnetic wedges. For each stator core design, two measurements were performed, applying different cooling water flows. The first measurement was performed with the adjusted water flow so that increase of cooling water temperature was < 6 K, whereas another one was performed with a reduced water flow, with an aim to get the core temperature adjusted to the rated load operating temperature level. However, the core temperature in the second measurement was again lower than the operating temperature. The measured iron losses are lower when the core temperature is higher, as the rotor surface resistance increases when temperature rises, whereas eddy currents consequently decrease. In design with non-magnetic wedges, reduction of losses is much greater than in design with magnetic ones. Taking into consideration all the above mentioned, it can be concluded, based on measurement and calculation, that the reduction of the specified losses in this case is $15 \div 20\,\%$.
At the generators with non-magnetic wedges, the leakage stator reactance of 0.12 p.u. was measured, whereas the calculated reactance was 0.16 p.u. At the generators with magnetic wedges, the leakage reactance of 0.17 was measured, whereas the calculated reactance was 0.18 p.u. These differences might be caused by inaccuracy of analytical calculation and by discrepancy between the actual and assumed wedge permeability. Namely, the calculation was performed with μ_r = 2.8 in accordance with the technical data sheet provided by the wedge material manufacturer.
Synchronous reactance in direct axis, saturated value, for the generator with non-magnetic wedges, obtained by measurement is 1.05; for the generator with magnetic wedges is 1.075 p.u. Increase is app. 2.5%, whereas the assumed increase as per calculation is 8%.
As per calculation, subtransient direct-axis reactance X''_d is 0.19 for non-magnetic and 0.21 p.u. for magnetic wedges. At the generator with magnetic wedges, 0.34 p.u. was determined from the three phase short circuit oscillograph and 0.30 p.u. was measured in the phase-pair power supply test. The difference between the subtransient reactance values of the generator with magnetic wedges is also caused by measuring which was performed with reduced voltage therefore it was not possible to determine the subtransient reactance at rated voltage. In general, it is to conclude that subtransient, transient and synchronous reactances increase when magnetic wedges are applied. Due to that, static and dynamic stability of generator might decrease, which shall be analyzed separately for each specific case.

6. OPERATION EXPERIENCE ON GENERATORS WITH MAGNETIC WEDGES

The first one out of two generators of 34 MVA, 10,5 kV, 187,5 min^{-1} , with the magnetic wedges has been in commercial operation since September 2005, and the second one since November 2007. Since the first synchronisation, both generators have operated without any difficulties in the designed operating conditions. No user complaints related to generator operation have been received ever since. In May 2006, inspection of all wedges and of whole winding fixation was performed on the first generator. It was confirmed that neither fixation loosening nor loose magnetic wedges were found.

7. CONCLUSION

The results of analytical calculations and results obtained by measurement of the influences of magnetic wedges to parameters and properties of a synchronous vertical hydrogenerator of 34 MVA, 10.5 kV, have been analyzed.
Details of fixation of the magnetic wedges in the generator slot have been described, also the related data collected in more than five years of commercial operation on one out of two generators are presented.
By application of a magnetic slot wedges, surface losses at the rotor poles were reduced by app. 20%, excitation current by app. 3.8% and losses in excitation circuit by app. 8%.
Influence of magnetic wedges to increasing of sub-transient, transient and synchronous reactances has been calculated and measured.
The wedge permeability significantly influences rotor surface losses and slot leakage reactance.
In further researches and application of magnetic slot wedges in large hydrogenerators, it is essential to solve the issues related to embedding of wedges in order to ensure operation reliability, as well as to pay attention to selection of optimal permeability using the finite element method for calculation of influence of magnetic wedges to generator parameters.

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