Abstract—This paper describes analytical and numerical approaches to losses estimation and methods of losses decrease in permanent magnets of a permanent magnet machine. A segmentation of magnets was proposed and different numbers of segments with different segmentation directions were compared. Finally, a design rule for minimizing the losses was proposed.

Index Terms—Finite Element Method, Losses, Permanent magnet machines.

I. INTRODUCTION

It is a well-known fact that in permanent magnet machines containing rare-earth magnets eddy current losses in these magnets may occur. Up to now a precise calculation method for these losses and definite design rules for loss reduction are lacked. The most common way of reducing the losses in magnets is to divide them into smaller parts [1]. The main aim of this paper is to find the optimum number of magnet segments and also to decide what the optimum segmentation direction is.

II. ANALYTICAL CALCULATION

In the first step an analytical approach was used to state what is the optimum magnets division. It was assumed that all the losses in magnets are caused by magnets resistance. In order to simplify the consideration, one rectangular magnet was considered. The eddy current path as presented in the Fig. 1 using dotted line was assumed. This assumption was based on the experience of other authors [1, 2].

For the resistance calculation of the example magnet the following equations were used:

\[ \oint E dS = -\frac{d}{dt} \oint B dA \]  
(1)

where \( E \) is the electric field strength and \( B \) is the magnetic flux density.

\[ U = \frac{d\Psi}{dt} = \frac{d}{dt} Bbl \]  
(2)

where \( \Psi \) is the flux linkage.

With the standard definition of resistance

\[ R = \frac{\rho h}{S} \]  
(3)

where \( \rho \) is the resistivity, \( h \) the magnet height and \( S \) the cross section surface, the eddy current in magnet can be estimated with the following term:

\[ I = \frac{U}{R} = \frac{-\frac{db}{dt}bl}{\rho \frac{h}{S}} = \frac{-db}{dt} \frac{h^2}{\rho h} = \frac{-db}{dt} \frac{h^2}{\rho} \]  
(4)

It has to be noticed that this model assumes that the current distribution is not dependent on the magnet height. In addition, skin effect is neglected. If we consider magnet geometry as in the Fig. 1 we receive the following equation:

\[ R = \rho \frac{\frac{2l}{2} + \frac{2b}{2}}{\frac{b}{2} + \frac{l}{2}} = \rho \frac{2l^2 + 2b^2}{bhl} \]  
(5)

Consequently, if we divide the magnet across the shorter side into two pieces of the same size, we receive the resistance of one segment as following:

\[ R_{seg} = \rho \frac{\frac{2l}{4} + \frac{2b}{4}}{\frac{b}{4} + \frac{l}{2}} = \rho \frac{4l^2 + 4b^2}{4bhl} \]  
(6)

A similar calculation can be performed for larger number of segments and for both magnet sides. For the calculation a magnet model with a ratio of magnet length to magnet width amounting to 2.7 was used. The losses were calculated using the following equation:

\[ P = \frac{U^2}{R} \]  
(7)

The results of the calculation are presented in Fig. 2. It can be noticed that the cutting of the shorter magnet side seems to result in higher losses reduction than cutting of the longer side, assuming the same number of cuts.
III. FEM SIMULATION

In order to confirm the results obtained during the analytical calculation, a 3D-FEM model of a PM machine was built as presented in the Fig. 3.

Because of high number of mesh elements in the machine, one eighth of the machine was modeled. It led to a significant simulation time reduction but the time required for one calculation step was still on an unacceptable level. Therefore another method of the simulation duration limitation was searched for.

We assume that considering a machine with several embedded permanent magnets the neighbouring magnets do not have influence on each other. That is why, if we choose the smallest possible machine symmetry, it is enough if we calculate the losses only in one magnet and multiply the achieved results by the number of magnets. In order to prove this mentioned assumption, a permanent magnet machine model with 20 permanent magnets was simulated. A simulation step of 1° was chosen.

In the first step, the simulation has been adjusted so that conductivity was assigned to all magnets. This allowed the transient solver to calculate losses in all magnets. The results are presented in Fig. 4.

In the second step, the conductivity was assigned only to one magnet and all other magnets were non-conducting. The reason for this change is that the simulation time increases with the number of current conducting mesh elements. This change required, after the simulation was ready, to reconstruct the losses in the other magnets by shifting the results (in this case 6°) obtained in each calculation step and adding it to the losses of the previous magnet. It can be better understood when we consider the Fig. 5.
When we directly compare the two simulation methods it can be noticed that there is almost no difference between them, as shown in Fig. 6. This means that it is enough if only one magnet in the machine model conducts current and due this remark the simulation duration time is reduced by 75%.

In the next simulation step different magnet segment numbers and segmentation directions (axial and circumferential) were compared. For the first simulation, a rotor model with square magnets was used. The results are presented in Fig. 7.

![Fig. 7. Comparison between two different segmentation directions of square magnet](image)

It can be noticed that in case of both segmentation directions the loss vs. segments number functions can be interpolated using exponential function. The same function shape was noticed by other authors working on a similar topic [2, 3].

It may be noticed that in the case of the square magnets the losses decrease equally for axial and circumferential magnet segmentation. The small difference in the results may be caused either by the mesh quality or by end winding effects. The similar losses in both segmentation directions confirm the assumptions made for the analytical calculation.

In the next simulation, the same magnet size as in the case of the analytical simulation was used. The results are presented in Fig. 8.

![Fig. 8. Comparison between two different segmentation directions of rectangular magnet](image)

In the case of the rectangular magnets, according to the Fig. 8, it is more reasonable to divide the magnets so that possibly many thin segments are created. The only limitation of segment numbers is the mechanical durability of the magnets.

It can be noticed that when comparing Fig. 2 and Fig. 8, the numerical results do not correspond with the analytical results. Both losses vs. number of segment curves are e-functions. Both calculation methods confirm that the shorter magnet side should be segmented in order to reach the lowest losses. The different exponents of the e-functions in case of the two mentioned calculation methods may be caused by a current path different than the simplified path assumed in the analytical calculation. A similar but more precise method of analytical loss calculation which implies the different current paths for different frequencies of flux linkage was published in the meantime in [4].

An additional simulation was made to confirm the remark that it always makes sense to make possibly thin segments. The previously calculated losses value for a machine with magnets divided circumferentially into 3 parts was compared with a machine with magnets divided 2 times circumferentially and 1 time axially. The results of the simulations (47% more losses in the second case compared to the first case) confirmed the correctness of the mentioned segmentation rule.

### IV. CONCLUSIONS

In the paper an analytical method of losses estimation was presented. It did not provide as precise results as the numerical calculation but the losses functions shape was similar in both calculation types. It allowed us to draw a very important design rule saying that the shortest magnet side should be segmented in order to reach possibly lowest eddy current losses. Also the comparison between simulations with one and all conducting magnets showed that a significant simulation time reduction can be reached in case of PM machines with embedded magnets when using the proposed method of simulation with only one magnet conducting current.

### REFERENCES


