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Effect of Different Cutting Techniques on Magnetic Properties of Grain Oriented Steel Sheets and Axial Flux Machines

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***Abstract*—Various cutting techniques are in use as part of the manufacturing process of electrical machines such as laser cutting, punching, electrical discharge machining and waterjet cutting. The cutting process degrades the magnetic material near the cut-edge. This degradation results in lower magnetic permeability and higher core-loss density. This paper studies the effect of three different cutting techniques namely punching, waterjet and laser cutting on the magnetic properties of the grain oriented electrical steel sheets. A standard Epstein test confirms the different magnitude of degradation depending on the cutting technique. Further, a loss model based on the measurement results has been applied to the yokeless axial flux machine. The comparative analysis shows the superiority of the punching and water-jet cutting techniques over laser cutting which resulted in more than 150% increase in the core losses. Other machine performance parameters such as generated EMF and torque remain unaffected by the cutting method.**

***Index Terms*—Core loss, cutting, cut edge, electrical machines, axial flux machine, grain oriented material, punching, laser cutting, water-jet cutting, steel laminations.**

I. INTRODUCTION

Electrical machines have widespread applications as power conversion devices. For example, electrical motors consume about 40% of the electrical energy consumed in the European Union. Clearly there are efforts worldwide to develop more energy efficient electrical machines. The energy efficiency is closely linked with the different losses associated with these machines. One of the loss components which is often neglected at the design stage is losses related to the cutting of electrical steel sheets. Many reasons such as unavailability of standard loss models for cutting related losses, the dependence of these losses on the cutting technique and operating condition, high computational burden of simulating these losses etc. are accountable for the negligence of these losses by the design engineers.

Fortunately, there is increasing effort by the research community for developing the necessary tools for cutting related losses in the last couple of decades. Electron back scattered images [1], microhardness measurements [2] and local flux density measurements [3], [4] confirm the degradation of the material near the cut edges. Various authors measured the effect of different cutting techniques by a standard Epstein frame or single sheet testers with non oriented materials [5], [6]. The degradation of magnetic properties of nonoriented electrical steel sheets caused by laser, guillotine and spark erosion cutting was studied in [7]. Based on the measurements, different loss models have been proposed to account for the effect of cutting in terms of depreciating permeability and increasing coreloss density. Moreover significant effects on the core-losses have been observed on the simulated and measured

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electrical machines due to the cutting effect [8], [9].

However, most of the research in this challenging area is restricted to studying the effects of cutting on non-oriented steel sheets. There are relatively fewer efforts made to study these effects with respect to grain oriented materials [10], [11]. Authors have not found relevant papers which study the effect of cutting with grain oriented material together with axial flux machine in the literature. Therefore, in this paper three different cutting techniques namely punching, water-jet cutting and laser cutting are studied with respect to grain oriented steel sheets. Standard Epstein frame tests are conducted on the samples and the effect of cutting on the magnetic permeability and the core loss density has been studied.

Based on the measurements, a loss model has been developed to account for the cutting effect. Furthermore, the developed loss model is applied to a yokeless and segmented armature (YASA) double rotor axial flux machine manufactured from the grain oriented material to study the cutting effect on the machine performance. A model based on the magnetic equivalent circuit (MEC) for the YASA machine described in [12] is used to account for the cutting effect. Due to the absence of the yoke these machines have a higher percentage of degradation area due to cutting or cutting length as compared to the machines with a yoke. Therefore these machines are more sensitive towards the cutting effects.

Novelty of this paper comes from the comparative study of the effect of different cutting methods on the grain oriented material and corresponding simulations of the YASA machine. It was observed that the laser cutting has the most degrading effect among the studied three types of cutting techniques. Lower magnetic permeability was observed in the laser cut samples. Furthermore, with respect to the studied YASA machine, the core losses increase of about 6%, 45% and 150% was observed for water-jet, punching and laser cutting respectively.

II. Method

This section is divided into three parts; the first part deals with the standard Epstein frame test results with the three different cutting techniques, the second part describes the cutting loss model in detail and the final part details the magnetic equivalent circuit model for the YASA machine.

A. Measurements

Epstein frame test was conducted on the grain oriented M100-23P samples. The magnetic flux density in the samples was maintained sinusoidal and single-valued *BH* curves are derived from the peak values of corresponding magnetic flux density and magnetic field strength. To analyze the effect of cutting, four different type of samples were prepared. The details are shown in table I. Sample D is standard Epstein frame test sample with 30 mm width. The other samples are obtained by cutting the sample D into 2, 3, 6 parts and referred to C, B, and A sample respectively. All the samples are assembled such that they have the same total width. The samples are shown in Fig. 1. The degradation area due a cutting method was assumed to remain the same during the cutting process. Therefore, different width sample preparation will decrease the amount of degraded material due to cutting under measurement from sample A to D. In addition to the 50 Hz, magnetic measurements are performed for the excitation frequencies; 20 Hz, 100 Hz, 200 Hz and 400 Hz as well. All the experiments on different excitation frequencies show similar results with respect to the cutting effect, i.e. an increase in core losses and decrease in the magnetic permeability. These results are presented in the results section below. The test samples are cut with three different cutting techniques; punching, water-jet and laser cutting. In this study a 1500 W CO2 slab laserbeam was used for laser cutting.

TABLE I
TEST SAMPLES

Sample	Detail	Total width (mm)
A	Six 5 mm samples joined together	$6 \times 5 = 30$
B	Three 10 mm samples joined together	$3 \times 10 = 30$
C	Two 15 mm samples joined together	$2 \times 15 = 30$
D	Standard Epstein frame sample of 30 mm	$1 \times 30 = 30$

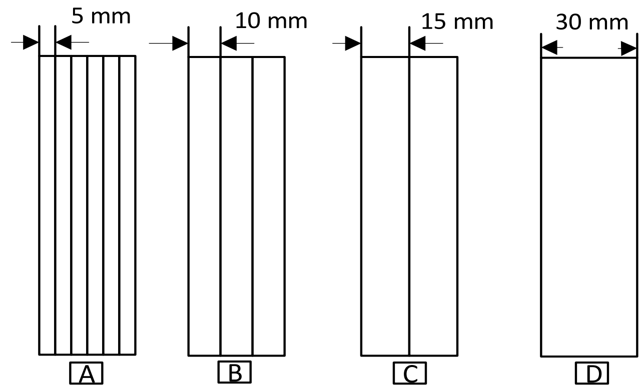


Fig. 1. Samples of different widths joined together for the Epstein frame measurements.

B. Loss model for cutting effect

Based on the measurement results, it is clear that the effect of cutting depends on the distance from the cutting edge and saturation. These factors are taken into consideration in the loss model presented in [9] and this paper applies the same loss model with some modifications. The effect of cutting is included by deriving local analytical functions of the magnetic permeability and core loss density.

1) Local permeability: The local magnetic permeability $\mu(H,x)$ is presented in (1) which is a function of the magnetic field strength H and the distance from the cut edge x. Here $\Delta\mu(H)$ and a are fitting parameters whereas μ_n is the

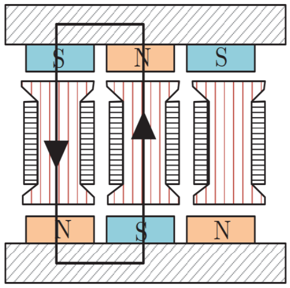


Fig. 2. Yokeless and segmented armature (YASA) double rotor axial flux machine.

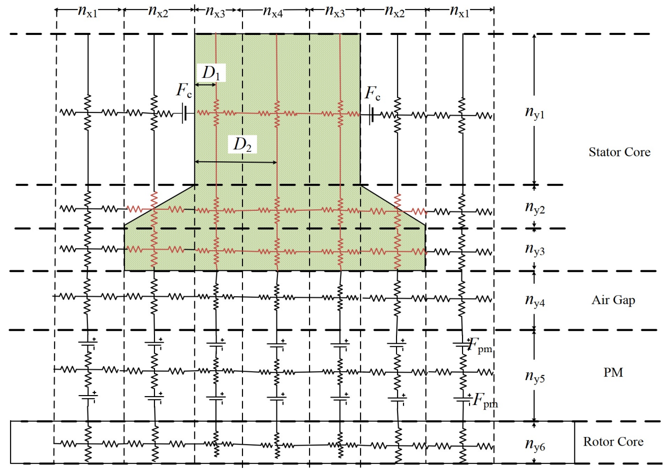


Fig. 3. The basic principle of MEC model including the cutting effect.

magnetic permeability of non-degraded sample. This paper treats the standard Epstein frame test sample D (30 mm width) of water-jet cutting as the non-degraded sample for obtaining μ_{n} as water-jet cutting is proved to exert lowest stresses as compared to other two cutting techniques. While modifying the loss model [9], the fitting parameter a is made H-dependent to provide better fitting results for all three cutting techniques studied in this paper. This modification helps in fitting the high variation in the permeability of the laser cut samples.

$$\mu(H,x) = \mu_{\mathrm{n}}(H) - \Delta\mu(H)e^{-a(H)x} \tag{1}$$

2) Local core loss density: The core loss density depends on the distance from the cut edge x and the local magnetic flux density $B(H,x)$. The three-component core loss formula is applied i.e. the losses are divided in the hysteresis loss, classical eddy current loss and excess loss respectively in (2). The effect of cutting is included in the hysteresis and excess loss coefficient as presented in (3) and (4). Here the fitting parameters α, K_e, K_{h0} and K_{ex0} are independent of the cutting effect.

$$\begin{aligned} P(B,x) &= K_{\mathrm{h}}(B,x)B^{\alpha(B)}f + K_{\mathrm{e}}(B)B^2f^2 \\ &\quad + K_{\mathrm{ex}}(B,x)B^{1.5}f^{1.5} \qquad (2) \\ K_{\mathrm{h}}(B,x) &= K_{\mathrm{h0}} + \Delta K_{\mathrm{h}}(B)e^{-b(B)x} \qquad (3) \\ K_{\mathrm{ex}}(B,x) &= K_{\mathrm{ex0}} + \Delta K_{\mathrm{ex}}(B)e^{-c(B)x} \qquad (4) \end{aligned}$$

One important aspect observed during the measurement of different steel samples is the effect of cutting at higher excitation frequencies. In general the effect of cutting diminishes at higher excitation frequencies and it is included in the hysteresis loss component only. However there was considerable cutting effect observed at higher excitation frequencies with the laser cutting. To account for this effect the excess loss coefficient was also made dependent on the cutting distance and saturation level. The excess loss coefficient was selected over eddy current coefficient as traditionally excess losses are defined as the difference between the total measured losses and hysteresis and classical eddy current losses. For uniformity purpose, the same loss model was applied to all the three cutting methods.

TABLE II
MACHINE DATA

Shaft Power	4 kW
Voltage	150 V
Frequency	267 Hz
Connection	Star
Pole pairs	8
Number of stator slots	15
Stator outer diameter	150 mm
Stator inner diameter	100 mm

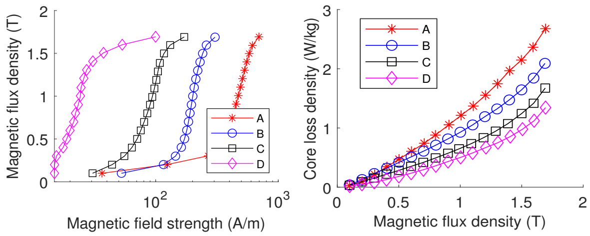
C. Magnetic equivalent circuit model (MEC)

Electromagnetic simulation of 4 kW YASA machine is performed with the help of magnetic equivalent circuit (MEC) method. The construction of the machine is shown in Fig. 2 and the machine parameters are presented in Table II. The MEC model is based on dividing the YASA machine into a number of slices in the radial direction. The total solution is obtained afterwards by computing the electromagnetic parameters for each slice and summation is done to obtain the 3D effect.

At each slice, the MEC model is divided to a number of nodes. At each node, a reluctance mesh is created. The basic principles and equations of this network are described in more details in [12]. In [12], a 3D FE model, a 2D FE model and experiments are provided to prove the robustness of the model.

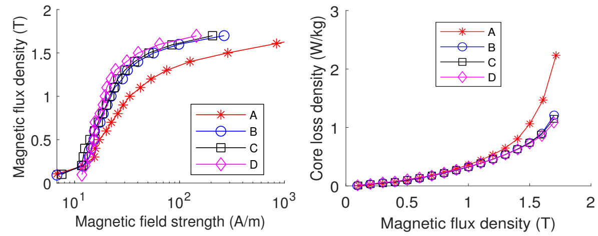
Fig. 3 shows the used MEC model for the YASA machine for a certain radial slice for one tooth pitch. The number of nodes in the circumferential direction are n_{x1} in the air gap area, and n_{x2} in part of the tooth tips. The tooth is circumferentially divided into $2n_{\mathrm{x3}}$ and n_{x4} nodes as described in Fig. 3. The tooth, air gap, permanent magnets, and rotor core regions are divided into the axial discretizations into n_{y1}, n_{y2}, n_{y3}, n_{y4}, n_{y5} and n_{y6} respectively. The red colored reluctances present the non-linear ones.

Moreover, to account for the cutting effect, the BH curve at each reluctance network is determined by how far is this



(a) (b)

Fig. 4. Magnetic measurements at 50 Hz of steel samples cut by laser cutting. (a) Magnetization measurement (b) Core loss density measurement.



(a) (b)

Fig. 5. Magnetic measurements at 50 Hz of steel samples cut by water-jet cutting. (a) Magnetization measurement (b) Core loss density measurement.

node from the nearest cutting edge. Fig. 3 shows the distances D_1, and D_2 for certain nodes from the tooth nearest edge. These distances are used afterwards to determine the material BH curve and the loss coefficients for each reluctance as per equations (1) − (4).

The discretizations used in the simulations equal ($n_{x1} = n_{x2} = n_{x3} = 8$, $n_{x4} = 10$), ($n_{y1} = n_{y2} = n_{y5} = 3$, $n_{y3} = n_{y4} = n_{y6} = 2$). The element discretization near the cut-edge i.e. the distance between two elements is about 0.1 mm.

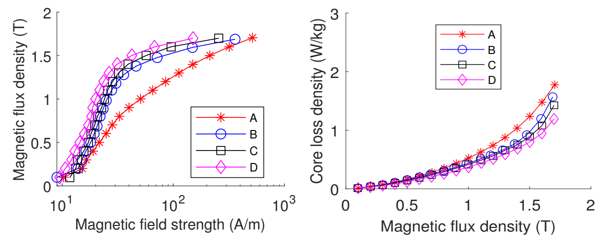
III. Results

This section is divided into three parts. First part deals with the Epstein frame test results and derived local BH and core loss density curves with the help of the loss model described in the section II B. In second part, we will compare the measured results from steel samples with three different cutting techniques. At last the electromagnetic analysis of the axial flux machine is performed with the help of the presented cutting loss model and the MEC model. The effect on core losses is then analyzed across different cutting techniques.

A. Magnetic measurements and derivation of local BH and core loss curves

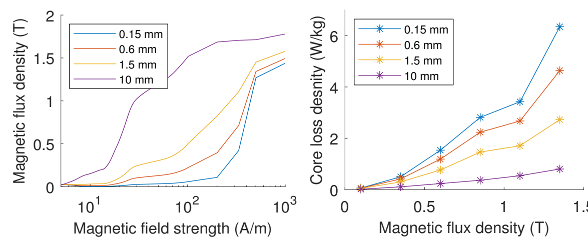
The Epstein frame test has been conducted on samples listed in Table I at different excitaion frequencies. Here, magnetization and core loss density at 50 Hz of samples cut with all three cutting techniques are presented in the Figs 4, 5 and 6. The effect of cutting can be analyzed in terms of lower permeability and higher core loss density with increasing degrading material under measurement. The highest % degraded material corresponds to the sample A whereas the sample D represents the least degraded sample.

The loss model presented in the section II B is applied to all three different cutting methods. The fitting was performed with the help of least square curve fitting tool box of MATLAB. As a result, we obtain the *local* BH and *local* core loss density curves. The Figs. 7, 8 and 9 represent the derived *local* magnetic properties of the laser, waterjet and punched samples respectively. For clear representation, *local* curves at 4 different distances (0.15 mm, 0.6 mm, 1.5 mm, 10 mm) from the cut-edge is presented. However, for simulation of the YASA machine 11 different such *local* curves were applied upto a distance of 12 mm from cut edge. According to the



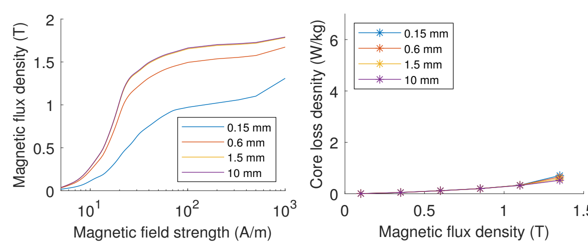
(a) (b)

Fig. 6. Magnetic measurements at 50 Hz of steel samples cut by punching. (a) Magnetization measurement (b) Core loss density measurement.



(a) (b)

Fig. 7. Fitted local (a) Magnetization (b) Core loss density at 50 Hz of steel sample cut by laser cutting at different distances from the cut-edge.



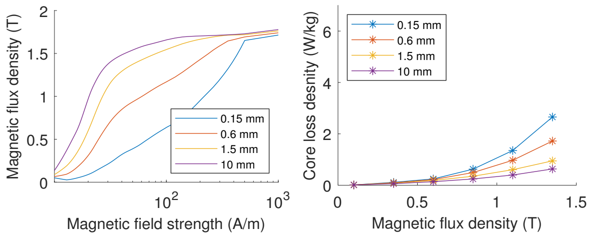
(a) (b)

Fig. 8. Fitted local (a) Magnetization (b) Core loss density at 50 Hz of steel sample cut by watejet cutting at different distances from the cut-edge.

fitting the cut-edge effect was almost negligible after a distance of about 10 mm from the cut-edge.

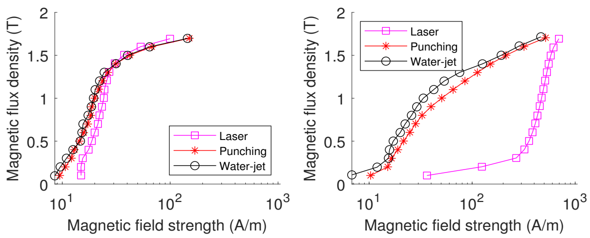
B. Comparative analysis of the cutting techniques

As part of the measurements, the standard Epstein frame test has been performed on the samples cut by three different



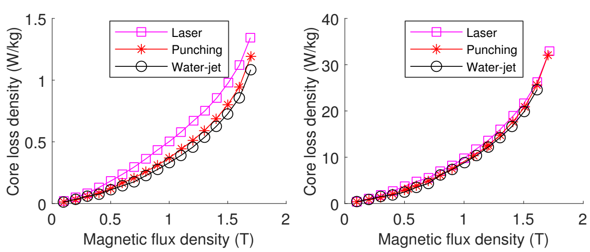
(a) (b)

Fig. 9. Fitted local (a) Magnetization (b) Core loss density at 50 Hz of steel sample cut by punching at different distances from the cut-edge.



(a) (b)

Fig. 10. Magnetization curve (BH) measurements at 50 Hz of steel samples cut by different cutting techniques. (a) D (30 mm width) sample (b) A (5 mm width) sample.

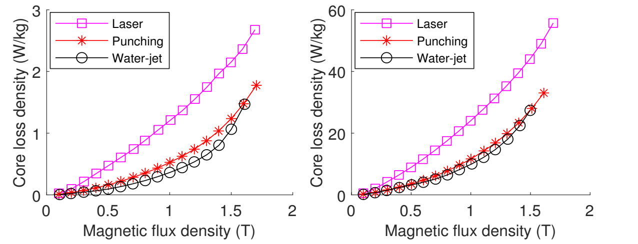


(a) (b)

Fig. 11. Core loss measurements of D (30 mm width) steel samples cut by different cutting techniques at (a) 50 Hz (b) 400 Hz.

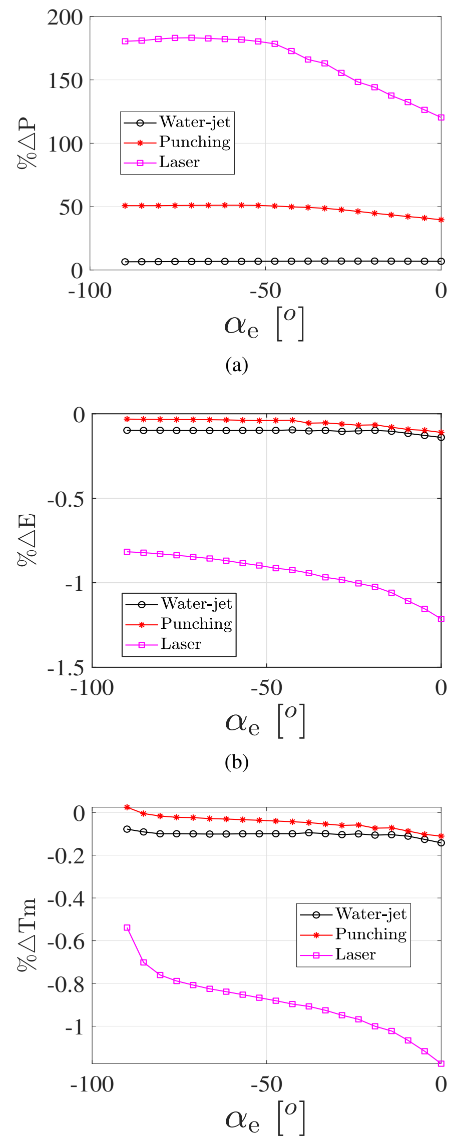
cutting techniques; punching, water-jet cutting and laser cutting. The magnetization curves (BH) and specific core loss curves have been recorded at different excitation frequencies. In comparative analysis, water-jet cutting proved to be a superior cutting technique as compared to punching and laser cutting studied in this paper. Further laser cutting performed worst among all three techniques. The Figs. 10, 11 and 12 show the magnetization and core loss curves of samples A (5 mm width) and D (30 mm width). The comparative core loss results are shown at two different excitation frequencies at 50 Hz and 400 Hz.

Further, it can be said that as the excitation frequency increases the effect of cutting decreases especially in the cases of punching and waterjet cutting. The cutting dependent excess loss coefficient helps in modeling the cutting effect at higher excitation frequencies such as observed in the laser cutting case.



(a) (b)

Fig. 12. Core loss measurements of A (5 mm width) steel samples cut by different cutting techniques at (a) 50 Hz (b) 400 Hz..



(a) (b) (c)

Fig. 13. Relative difference of (a) Core loss (b) EMF c) Mean torque due to different cutting methods with respect to the without cutting effect case at the different current angles.

C. Cutting effect on Axial flux machine (YASA)

The cutting loss model is applied to a current source MEC model of 4 kW YASA machine. The magnetization curves and core loss data obtained from standard Epstein frame measurement of water-jet cut sample D (width = 30 mm) was considered non-degraded. Hence this case is used as a reference case to analyze the effect of cutting due to the different cutting techniques. For comparison purpose, simulations at different electrical current angles are performed keeping the absolute value of the current at the rated value. The axial flux machine was divided into 6 two dimensional slices and a total of 50 time steps per supply period were considered.

The effect of cutting on core losses at different current angles is presented in Fig. 13a in terms of relative difference with respect to the reference case (without cutting effect). As per the results it is quite clear that the core loss increases due to the cutting effect. The relative increase in core losses fall in the range of 180%-120%, 50%-40% and 6% for laser, punching and waterjet cutting respectively. This observation is in line with the measurements of magnetization and core losses of different cutting techniques presented in section III A and B.

This paper further observed the cutting effect on the machine performance parameters such as torque and generated EMF. Figs. 13b and 13c show a comparison of the effect of the investigated cutting techniques on the machine performance parameters. The effect on torque and generated EMF is not so prominent due to cutting as compared to the core losses. The torque and EMF are strongly dependent on the phase inductances which are function of the reluctance of the associated magnetic circuit. The major contribution of the reluctance comes from the airgap reluctance. This reluctance is unaffected by the cutting process, hence a relatively negligible cutting effect is observed on the calculated torque and EMF.

IV. Conclusion and discussion

The magnetic properties of the grain oriented steel sheets have been measured to study the effect of cutting. Three different cutting techniques namely laser cutting, punching and water-jet cutting were considered. The analytical functions of the magnetic permeability and core losses are modified accordingly to account for the cutting effect. Further, the YASA machine was studied with respect to the cutting effect. Both measurement and simulation present significant effect on magnetic properties of steel sheet as well as on the core losses of the studied machine. It is specifically prominent in case of the laser cutting. It should be noted that relative difference of core losses due to different cutting techniques depends on several parameters such as properties of electrical steel, setting of the cutting process etc. The effect of laser cutting depends on the laser type and the losses may differ on a case to case basis as presented in [13]. Even in [13] the degradation effect of all three different types of laser cutting techniques were higher as compared to punching. As laser cutting is relatively cost-effective for small scale production and prototype building; inclusion of the cutting effect should be encouraged at the design stage. Measurement of the core losses with the machine prototypes with different cutting techniques will be part of future work.

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