

Experimental evaluation of Magnetic Skin effect in silicon-iron core for a High Speed Electrical Machines

Thales A. C. Maia¹, Igor A. Baratta¹ and Braz J. Cardoso Filho², *Fellow, IEEE*

¹Department of Electrical Engineering, UFMG, Belo Horizonte, MG 31270-901 Brazil, thalesmaia@gmail.com

²Department of Electrical Engineering, UFMG, Belo Horizonte, MG 31270-901 Brazil, braz.cardoso@ieee.org

In this paper we present an experimental evaluation of the magnetic skin effect in a silicon-iron stator. The ferromagnetic stator is part of a two pole permanent magnet generator (PMG) running up to 100,000 rpm and rated power of 3.5 kW. Using a Rowland ring arrangement for a small part of the stator's sheets, the losses and BH-curve were evaluated up to 1.6 kHz. To confirm the magnetic skin effect during operation, a prototype of a microturbine direct coupled to an electrical generator was built. The results show a decrease in the induced voltage at higher rotational speeds. Therefore, magnetic skin effect reduce output power and should be considered during sizing procedures of a high speed electrical machines.

Index Terms—core losses, electrical generator, high speed, magnetic skin effect

I. INTRODUCTION

HIGH SPEED electrical machines are required for volume reduction and high power density applications. Employed from dental tools, hybrid vehicles or even microturbine generation systems, numerous applications demand high-speed operation [1], [2], [3], [4].

In addition to several key design concepts for a high speed electrical machine, losses are critical given the rated medium frequency (1 – 10 kHz). Under this topic, core losses becomes a challenge whereas it is exponentially related to the frequency. However, the lack of publications regarding magnetic skin effect in electrical machines enhance the importance of the presented research.

Magnetic skin effect is well known from high frequency transformers, nondestructive testing, remote field eddy current inspection, material characterization and others [5], [6]. In electrical machines, it has been lately discussed [7]. Experimental results indicate that lower flux density such as 0.2 T to 1.4 T modify ferromagnetic behavior and therefore machine's output power.

In this paper, the magnetic skin effect observed from experimental procedures is presented. Using a Rowland Ring experiment, a core losses experiment was performed in a 0.35 mm silicon-iron from a high speed stator machine sheet with frequencies above 60 Hz and bellow 1.6 kHz. Using a high speed permanent magnet electrical generator, a no-load ramp up test was performed which shows that induced voltage decrease along with frequency increase. The observed result indicates the importance of magnetic skin effect and how it can reduce the machine output power.

II. HIGH SPEED ELECTRICAL MACHINE

The magnetic skin effect is a commonly known consequence of high-frequency electric current inside a conductor. Since the magnetic field is proportional to the current, the presence of skin effect is linked to magnetic skin effect.

In the present research, a synchronous high speed electrical generator using a two pole Neodymium permanent magnet

direct coupled to a microturbine is directly affected with power reduction due to magnetic skin effect. The machine is rated to 3.5 kW at 70,000 rpm, which correspond to a power density of 2.8 kg kW⁻¹ [8].

Finite element method (*fem*) [9] was used for sizing the high speed generator. The calculated values indicated a mean air gap flux density of 0.47 T and a air gap peak flux density of 0.74 T.

Initially, the electromagnetic design was made using the BH-curve provided by the manufacturer at 60 Hz. The electrical generator was built and tested to confront the simulated results. For that design, the calculated voltage was 252 V_{rms} at 72,000 rpm which didn't match with the measured 235 V_{rms} running at that same speed.

The induced voltage should be proportional to the rotational frequency, but at higher frequencies the magnetic skin effect acts like a saturation in the core and thus reduces the flux density and induces voltage as shown in Fig. 1.

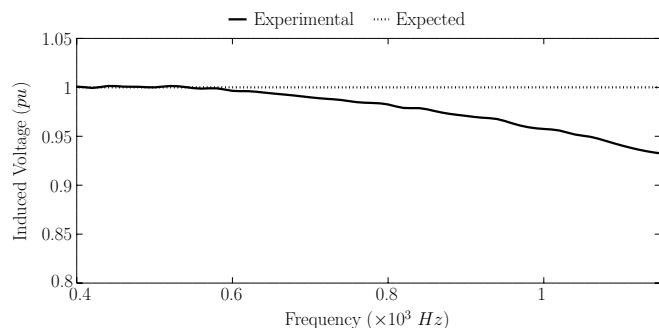


Fig. 1: Experimental no-load induced voltage with the increase of rotational speed.

The results pointed that below 600 Hz the induced voltage is slightly affected, but at 1.2 kHz it is severely reduced to 92.3% of its expected value without magnetic skin effect. This reduction in the output voltage directly disturb the machine output power and must be considered during electromagnetic design.

Few researches cover magnetic skin effect for high-speed machines. However, there are no clear thresholds of frequency and flux density, neither from manufacturer or technical papers. In order to identify this behavior from the silicon-iron stator at higher frequencies, a few sheets was stacked and reeled to build a Rowland Ring test bench.

III. STATOR TEST BENCH

Using a "H-bridge" power device with 20 kHz carrier frequency, a sine wave of 60 Hz up to 1.6 kHz was modulated. This system was used in a *Rowland Ring* experimental setup to evaluate losses and BH-curve from the material. The small piece of the stator used is shown in Fig. 2.

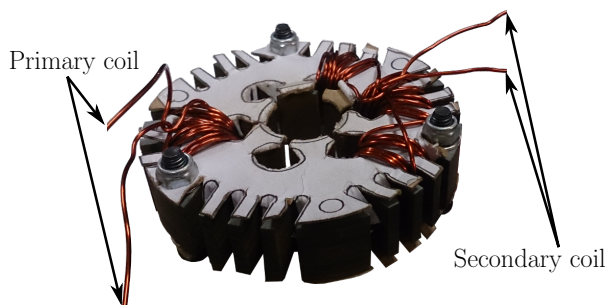


Fig. 2: Small stack from high speed generator coiled as a rowland ring.

The voltage is imposed for the primary coil, then the primary current and secondary voltage are measured which allows the calculation of flux density and flux intensity,

$$B(t) = -\frac{1}{N_2 S_{Fe}} \int V(t) dt, \quad (1)$$

$$H(t) = -\frac{N_1 I(t)}{l_{Fe}}. \quad (2)$$

From Eq. 1 and 2, $N_{1/2}$ is the number of turns on primary and secondary, S_{Fe} and l_{Fe} are the core section area and the core length covered by the flux inside respectively [10], [11].

IV. RESULTS

In the presented experiment, a frequency range between 60 Hz up to 1.6 kHz was used to build ferromagnetic characteristics. Besides the losses, which were also accounted, magnetization curve was evaluated in order to compare magnetic skin effect. The results for low frequency, 60 Hz, and high frequency, 1.6 kHz, are presented in Fig. 3.

At higher frequencies ferromagnetic permeability is affected which changes the electromagnetic design. This effect is related to frequency over flux density, since it changes all the entire BH-curve up to 1.4 T.

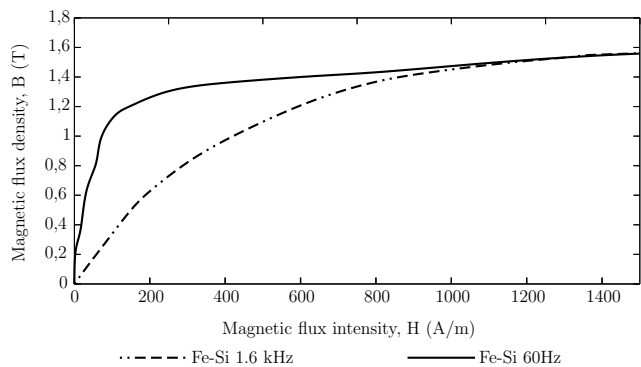


Fig. 3: Experimental BH-curve at 60 Hz and 1.6 kHz.

V. CONCLUSION

The presented research indicates that magnetic skin effect is a great concern for high speed electrical machine design. Increasing the rotational speed will lower the magnetic permeability for the stator core, thus more core material is required to avoid saturation. Therefore, the developed power will be affected compromising electromagnetic design.

The experimental evaluation is a better choice when available, since it has different behavior depending on stators material, cutting, building procedures and lamination thickness. The measured flux can feed back the electromagnetic design and improve design.

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