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Toward including the effect of manufacturing processes in the pre-estimated losses of the switched reluctance motor

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Abstract The estimation of losses plays a key role in the process of building any electrical machine. How to estimate those losses while designing any machine; by obtaining the characteristic of the electrical steel from the catalogue and calculate the losses. However, this way is inaccurate since the electrical steel performs several manufacturing processes during the process of building any machine, which affects directly the magnetic property of the electrical steel and accordingly the characteristic of the electrical steel will be affected. That means the B–H curve of the steel that was obtained from the catalogue will be changed. Moreover, during loading and rotating the machine, some important changes occur to the B–H characteristic of the electrical steel such as the stress on the laminated iron. Accordingly, the pre-estimated losses are completely far from the actual losses because they were estimated based on the data of the electrical steel obtained from the catalogue. So in order to estimate the losses precisely significant factors of the manufacturing processes must be included. The paper introduces the systematic estimation of the losses including the effect of one of the manufacturing factors. Similarly, any other manufacturing factor can be included in the pre-designed losses estimations.

1. Introduction

Theoretically, the foundation of any design of any electrical machine, and how to calculate its losses estimation is based on the characteristic of the unprocessed electrical steel that is obtained from the catalogue without including the effect of manufacturing processes [1]. The previous researches found out that the process of including the effect of manufacturing processes on the steel through the pre-designed loss estimation

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was somehow difficult, and needs a thorough understanding, which complicate the process of loss estimation. That discouraged the machine designers to include these effects in the pre-estimated losses of the electrical machine [1]. For further clarification, the process of designing and building any electrical machines has different aspects such as magnetic circuit, the electrical circuit, the thermal design, the mechanical design, the ventilations, the isolation, the bearing, and the balancing of electrical and mechanical circuits. All those different aspects are related to the design and the building of any electrical machine. Moreover, the machine frequently needs a controller or a sensor. Those factors are more than enough to complicate the process of designing and building electrical machine. However, the manufacturing processes have great impacts on the unprocessed electrical steel and these impacts must be included in the design and pre-estimated losses of the electrical machine [2].

From this point of view, the paper addresses a simple approach to include the manufacturing factors in the design and pre-estimated losses. Since the manufacturing processes affect the B–H characteristic of the electrical steel, which means that if the effect of any manufacturing process on the electrical steel is known through the experiences or previous measurements, then a mathematical formula can be concluded to the relation between the manufacturing process and the flux density to create a new B–H curve of the electrical steel. In other words, the B–H curve of the electrical steel, which is obtained from the catalogue, is now modified according to this mathematical formula, which link between the flux density and the manufacturing factor. Now a new B–H curve can be used in the pre-design process and in the loss estimation without the miscalculation in the previous steps [3].

This paper explains in detail the design and losses estimation process, using an example of an electrical machine with non-linear characteristic and rotational transient operation. This means that this electrical machine has no steady state operation, which means that it has high iron losses. The objective of doing that was to illustrate in detail how the calculation of the iron losses is determined by including a manufacturing factor by simple steps [4].

2. Understanding one of the manufacturing effects in the electrical machine

The manufacturing process of the electrical steel sheet causes distortion, residual stress, etc. in the electrical steel sheet. The distortion and the residual stress of the electrical steel sheet used in the stator and the rotor are the causes of the iron loss increment, which also generates the degradation of the magnetic properties of a magnetic circuit of the machine that built from punched electrical steel sheets [5].

Punching the iron sheets affects the material properties and creates heterogeneous stress inside the sheets. The effect is depending on the alloy composite, whereas the grain size in the sheets seems to be the main influencing factor, especially for operating ranges between 0.4 T and 1.5 T. The influenced region in the sheet due to cutting and punching goes up to 10 mm in distance from the cutting edge, where the permeability is significantly decreased. This reduction in permeability increases the iron losses in the material. Specifically, for geometric parts smaller than 10 mm in width (small stator teeth for example), the punching process can have a significant influence on the iron losses and therefore has to be considered in the loss calculation. Further, the cutting and punching process damages the thin insulation layer. This might lead to have short circuits between several sheet layers. In this paper, the punching effect will be included in the pre-designed losses estimation [5].

3. The proposed electrical machines for design and losses estimation including one of the manufacturing factors

This paper will use the switched reluctance motor as an example for non-linear electrical machines that has a core exposed and all its running time in non-sinusoidal excitation. The switched reluctance motor estimation losses will be illustrated in detail within this paper, using the punching effect as the manufacturing process factor in the losses estimation process [6].

The losses in the switched reluctance motor (SRM) consist mainly of the stator copper losses and the core losses. The copper losses are proportional to the square of the root mean square of the current whereas the core losses are a function of the excitation frequency and the flux density. The iron losses in the SRM cannot be ignored as the SRM always operates in transient operation mode. During transient operations, the high switching frequency increases the iron loss to a significant value compared with the value of copper loss [6].

The process of concluding the SRM iron losses value is complicated, because the frequency of the varying of the flux reversals depends on the place and time. Therefore, the iron losses are different for each part of the motor's cross-sectional area. In addition, the iron losses depend on the flux density, whose waveform varies in different zones of the SRM. Moreover, the current waveforms are non-sinusoidal and they depend on the operating conditions and the type of controller. These factors have significant impact on complicating the process of the estimation of the core losses [7].

The models for the iron losses estimation either can be empirical or based on the solution of Maxwell's equations. The general idea for finding any formula to estimate the iron losses in the SRM is based on separating the specific core losses (W/kg) into three parts (hysteresis, eddy current and excess losses) and to be calculated using the waveforms and time derivatives of the local flux densities.

The equation for estimating the iron losses [7]:

$$P_{\text{iron losses}} = P_{\text{hysteresis}} + P_{\text{eddy}} + P_{\text{anomalous}} \quad (1)$$

4. Design of the SRM in case of excitation by non-sinusoidal excitation

The output torque of any electric machine can be calculated by three different variables. The variables are the air gap flux density B, the machine volume V, and a constant C as follows:

$$T = C \cdot B \cdot V \quad (2)$$

This method usually used in case of designing electrical machines that have linear characteristics. However, this method cannot be used for designing any highly non-linear characteristic electrical machines, because this method function depends on the assumptions of ratios and many