Optimum Design of an IE4 Line-Start Synchronous Reluctance Motor Considering Manufacturing Process Loss Effect

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***Abstract*—As a kind of direct-on-line motor, super premium efficiency (IE4) line-start synchronous reluctance motors (LS-SynRMs) were developed recently and are now used in many applications, including fans, pumps, and compressors. This paper presents an optimum design and comparative study of LS-SynRMs with additional losses and impact during the manufacturing process (electrical steel cutting/punching damage as well as squirrel-cage die-casting with bubble effects). The work results indicate that the LS-SynRM design with the "manufacturing process loss" effect should be considered and compensated for the design in order to achieve an IE4 class efficiency and ensure synchronization. Furthermore, the LS-SynRM rotor with multilayer flux barriers and rotor slots is investigated in detail. The influences of optimum design geometrical parameters (flux barriers thickness, segments thickness, length of rotor slots, etc.) on the performances of the basic model and optimum design model are evaluated with finite-element analysis (FEA) results. For more accurate results, the effects of saturation, saliency ratio, inductance difference, and the change in the B-H/B-P curve in damaged motor core edges are considered. Meanwhile, in the squirrel cage, the porosity rate distributions are considered. The copper loss, iron loss, starting torque, power factor, efficiency, and synchronization ability are investigated. The experimental results verify the accuracy of the process presented in this paper.**

***Index Terms*—Cutting/punching effect, die-casting, IE4, line-start synchronous reluctance motors (LS-SynRM), manufacturing process loss, minimum energy performance standards (MEPS), response surface method (RSM).**

I. Introduction

In most countries, electric motors consume up to two-thirds of the electricity generated. On average, the cost of the energy consumed by an induction motor (IM) during its life cycle is 60–100 times the initial cost of the motor [1]. Hence, this usage makes electric machines especially attractive for the applications of efficiency improvements. To cater to the minimum energy performance standards, the international motor efficiency classes (IE1–IE4) were enacted, defined in Standard IEC60034-30-1. Premium/IE3 efficiency class motors are now mandatory in North America and the Ultrapremium/IE5 efficiency class is to be defined in the second edition of the IEC 60034-30 standard [2]–[4].

Recently, there is a relatively new technology instead of IMs, namely, synchronous reluctance motors (SynRMs). Different than an IM, the SynRM has a large saliency ratio structure that can produce a large reluctance torque to maintain power density when using a variable-speed drive (VSD) or electronic controller [5]–[7]. However, in fan, pump, and compressor applications, only constant speed operation is usually required. Hence, the SynRM along with the VSD system costs considerably more than a squirrel cage induction motor (SCIM). In order to get self-starting capability without the VSD system and achieve a high efficiency, a motor with the squirrel cage (SC) structure combined with a high saliency ratio structure is considered one of the best solutions. This is called a line-start synchronous reluctance motor (LS-SynRM).

The main reason an LS-SynRM has received notice is that it has the ability to line-start like an SCIM and then runs at synchronous speed without a secondary copper loss. This secondary copper loss in an SCIMs is typically 25% of the total loss [2]. LS-SynRMs can perfectly replace IMs in order to achieve higher efficiency levels. The rotor of the LS-SynRM contains SC rotor slots, multilayer flux barriers, multilayer ribs, etc. [8]. Such complex rotor structures must take into account the additional losses caused from manufacturing processing, e.g., electrical steel cutting/punching damage [9]–[12], and SC die-casting with bubble effect [8]. These are considered as "manufacturing processing losses" in this paper.

In a previous study [13], a three-phase LS-SynRM was proposed and analyzed. It was shown through the optimal design, the machine exhibits high performance. However, there is a small difference between the predicted and measured losses, synchronization process differences, etc., which may be attributed to the manufacturing process. In order to address the possible impacts of the manufacturing process, this paper provides detailed rotor design schemes that can improve LS-SynRM's overall efficiency in order to achieve the IE4 class, and outlines an approach to simulate the effects of cutting/punching damage and bubbles on LS-SynRM performance using finite el-

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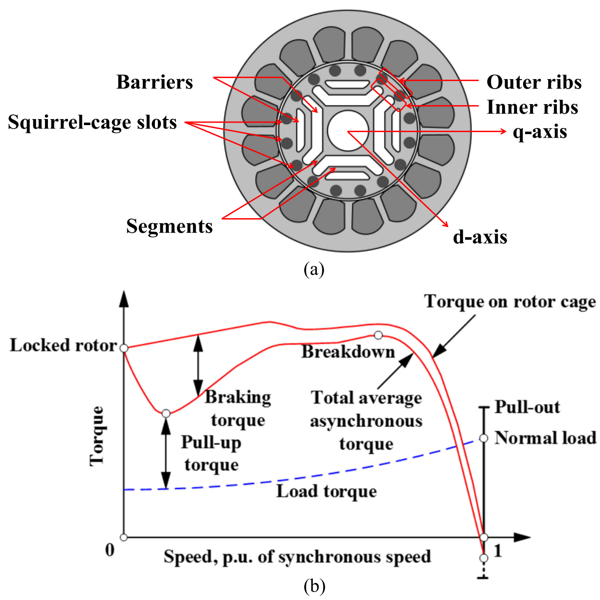

Fig. 1. Configuration of the LS-SynRM. (a) Components of the rotor and (b) torque/speed curve [13].

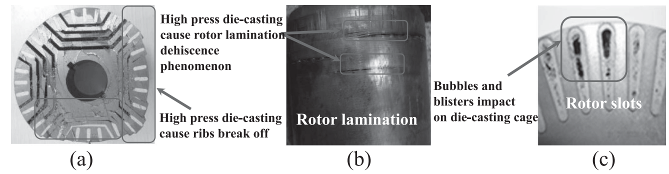

Fig. 2. Manufactory problems during die-casting process. (a) Ribs broken off. (b) Rotor lamination breaks. (c) Bubble impacts on the SC.

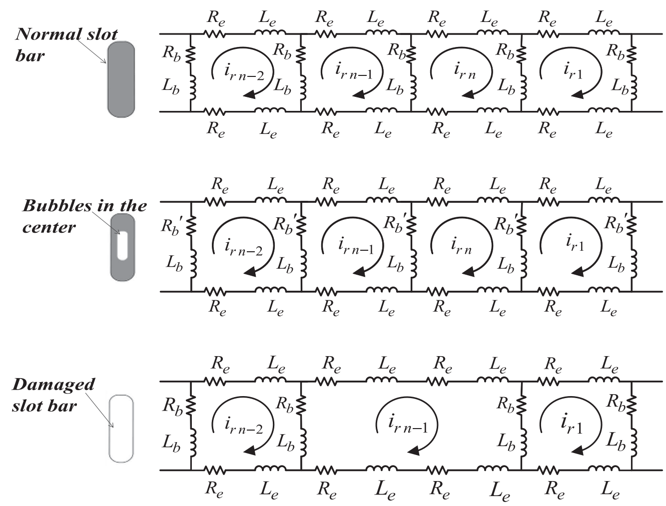

Fig. 3. SC resistance loop of LS-SynRM. (a) Normal SC. (b) Rotor bar with bubbles effect. (c) Broken bar.

ement analysis (FEA). In addition, the authors use a single-sheet tester (SST) to determine the change in the B-H/B-P curve due to damaged core edges. The authors also conduct a comprehensive analysis of the effects of different porosity rates and bubble distributions in the rotor slots on LS-SynRM synchronization. Section II discusses the start-up and steady-state characteristics of the LS-SynRM and the effects of the manufacturing process loss. Section III shows the comparison of basic models using the FEA results considering/ignoring bubbles and punching damage. Section IV introduces the optimization design process of the LS-SynRM in detail. Section V shows the comparison of the basic model, optimal model, and the SCIM experimental results. Finally, the concluding remarks are given in Section VI.

II. Analysis of the Characteristics of LS-SynRM and Manufacturing Process Effects

A. Torque on the Rotor SC of the LS-SynRM and Die-Casting Process Effects

Fig. 1(a) shows the structure of a four-pole LS-SynRM. Since there are additional multilayer flux barriers and the SC in the rotor lamination, the starting process of the LS-SynRM has two separate phases: asynchronous run-up and synchronization. The SC rotor provides the asynchronous run-up torque, similar to SCIMs, when starting from rest. As the speed approaches the synchronous speed, the slip tends to be zero and the LS-SynRM enters the synchronization phase. The torque on the rotor SC T_c can be expressed as

$$T_c = K_T \Phi_m I_2 \cos\varphi_2 \tag{1}$$

where K_T is the torque constant, Φ_m is the mutual flux, and I_2 and $\cos\varphi_2$ are the rotor equivalent current and the power factor, respectively. Fig. 1(b) shows the typical torque/speed curve of the LS-SynRM.

In order to achieve higher reluctance ratios of the direct and quadrature axes, the barriers in the rotor are often designed for multiple layers and even an axially-laminated-type SynRM [14]. With the SC rotor slots, in order to increase the saliency ratio the rotor slot is generally designed to align with the end of multilayer flux barriers to reduce the *d*-axis magnetic flux leakage. Therefore, the structure must inevitably produce inner ribs which lead to structural fragility. In the die-casting process of LS-SynRMs, the rotor-laminated electromagnetic steel encounters top–down forces. Because of the high pressures involved in the die-casting of SCs, top–down forces from the end-ring die-casting commonly yields segment deformation, as conceptually depicted in Fig. 2(a). Moreover, the application of these forces commonly results in laminate rotor damage, as conceptually depicted in Fig. 2(b). Introduced as a structure, the flux barriers are filled with an electrically conductive material [15]. However, in this situation the rotor end-ring must change to a disk shape to cover the entire flux barrier. This results in an unnecessary waste of the conductive material while producing a large amount of eddy-current loss. To avoid these production problems, a general technique is introduced that reduces the pressure acting on the SC during die-casting. Consequently, compared to common SCIMs the overall manufacturing of LS-SynRM generates bubbles which affect the SC. This phenomenon is shown in Fig. 2(c).

In order to simulate the bubble impact in a large area that damaged the slot bar, the SC loops need to be distributed according to the pattern shown in Fig. 3. The resistance of the rotor bar in the rotor slot is modified as follows:

$$R_b = \rho \frac{L_{\mathrm{stk}}}{S_b} \tag{2}$$

$$R_b' = \rho \frac{L_{\mathrm{stk}}}{S'_b}. \tag{3}$$