Theoretical and Experimental Investigations of the Electromagnetic Steel Compositions for Synchronous Reluctance Motors

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Abstract -- **To meet the increasingly stringent regulations on operational efficiencies of electric motors, efforts have been devoted to design and construct motors with less power losses. Without the need of rotor conductors and hence no secondary copper loss, the feasibilities of applying synchronous reluctance motor (SynRM) have attracted many attentions on the related industries. Since the operation of SynRM is mainly based on the reluctance torque, appropriate electromagnetic steel selections for the motors will be the key factors. To adequately evaluate the performance of SynRM, with the available magnetization and hysteresis characteristics of the commercial steel sheets, the SynRMs that are composed by different electromagnetic steels at various operational specifications will be thoroughly investigated. From theoretical analyses of the selected SynRMs by different stator and rotor material compositions along with experimental validations, valuable guidance for related SynRM constructions and operations can thus be provided for steel manufacturers and motor designers.**

Index Terms—**iron loss; laminated electromagnetic steel; magnetic flux path; magnetic saturation; synchronous reluctance motor.**

I. Introduction

To EFFECTIVELY improve the electric motor efficiencies and thus reduce the equivalent carbon-dioxide emissions, the motor manufacturing industries and the associated end-users have consistently devoted to seek feasible motor structures that can meet the increasingly stringent standard regulations that are enforced in many developed and developing countries [1]. With their relatively robust structures, comparatively larger portions of these motors that being applied in the industries are induction motors (IMs). Consequently, no matter it is for new motor installations or for upgrading the existing IM ones, the incurred higher construction efforts and costs must also be evaluated. By maintaining the same stator structures and taking out the rotor conductors, the synchronous-reluctance motor (SynRM) [2] provides a feasible structural and cost-effective alternative for upgrading those applications that the small-power IMs are commonly adopted. Since the stator copper losses are at the same levels as those of the IMs, the system operational efficiencies will mainly be affected by the motor iron losses. As these iron losses of the SynRMs, at the same winding currents, are determined by the stator and rotor electromagnetic steels [3], [4], proper selection guidance about these materials is thus desired. Though the operations of such SynRMs will require some additional driver control circuits for supplying servo-controlled driven forces on metal and related heavy industries [5]-[7], with the fast technology developments in integrated circuits and power electronics, these driver circuit implementations will only occupy very small portion of the entire system installation costs.

Therefore, to implement the SynRMs into the industry production lines, the considerations can be focused on the performance and cost indices of the motor only. As a common sense, the properties of the selected electromagnetic steels for constructing the motor are dependent on their costs. Generally, the more expensive ones will exhibit better property with smaller iron losses. Since the magnetic fluxes in the iron cores of the motors will be dependent on their corresponding positions and operational specifications [8]-[10], to avoid construction over costs, complete design analyses along with experimental measurement supports are certainly desirable for the appropriate selections of electromagnetic steels.

With their relatively limited physical dimensions, the iron losses that were resulted from magnetic saturations will become the dominant factors affecting the operational efficiencies of the small-size SynRMs. In addition, the mechanical punching processes, which are commonly applied to shape those electromagnetic steel sheets, will also change the magnetic characteristics of these steels along the punching edges [11], [12]. If the overall impacts are not negligible, the possible overheads of additional annealing processes to restore the material properties must also be incorporated in the selections of electromagnetic steels.

To summarize, with its relatively more rigorous specifications, an 1-hp, 380-V, 4-pole, 60 Hz SynRM was selected as investigation basis. By selecting different grades of electromagnetic steels for composing the motor stators and rotors, 16 of the SynRM samples have been constructed for

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assessments. From the detailed performance evaluations by both the numerical calculations based on finite element analyses (FEA) and the experimental measurements, the proposed selection guidance can thus be validated.

II. Operational Principles and Performance Indices of the Synchronous Reluctance Motor

Fig. 1 provides the conceptual 1/4 structure of a 4-pole, 24-slot SynRM, the stator and rotor of this motor are generally assembled by electromagnetic steels with relatively small magnetic reluctance to the designed flux conducting paths. Though the amorphous magnetic materials (AMMs) [13] and the soft magnetic composites (SMCs) [14] have also been adopted in some specific motors, the electromagnetic steels are still the most common ones that have been applied for motor constructions.

As the magnetic fluxes that being travelled through the stator and rotor iron cores are generated by the stator winding currents, the operations of the SynRM are mainly based on seeking the paths with minimum reluctances for those generated fluxes. To align the rotor *dr* axis with the generated air-gap rotating magnetic fields, those segments for providing the flux conducting paths must be properly arranged, such that the magnetic fluxes can be evenly distributed among these segments. In addition, by adjusting the equivalent magnetic reluctance projected onto the *dr* and *qr* axes to exhibit maximum difference, the desired large electromagnetic torque generation objective can then be achieved. To properly describe the SynRM system operations, based on Fig. 1, the stator winding 3-phase voltages and currents can be first expressed on the rotor *dr*- and *qr*-axes as

$$\begin{cases} v_{ds}^r = r_s i_{ds}^r + d/dt\,(\lambda_{ds}^r) - \omega_r \lambda_{qs}^r \\ v_{qs}^r = r_s i_{qs}^r + d/dt\,(\lambda_{qs}^r) + \omega_r \lambda_{ds}^r \end{cases}. \qquad (1)$$

where $v_{ds}^r, i_{ds}^r, v_{qs}^r$, and i_{qs}^r are the stator voltage and current components projected onto the rotor *dr*- and *qr*-axes, respectively. r_s is the stator winding phase resistance and ω_r is the rotor angular speed. As the flux linkages λ_{ds}^r and λ_{qs}^r are dependent on their corresponding magnetic reluctance and operational currents on the rotor *dr*- and *qr*-axes, they can be generally expressed as

$$\begin{cases} \lambda_{ds}^r = L_{ds}^r(i_{ds}^r, i_{qs}^r)\cdot i_{ds}^r \\ \lambda_{qs}^r = L_{qs}^r(i_{ds}^r, i_{qs}^r)\cdot i_{qs}^r \end{cases} \qquad (2)$$

Theoretically, if the stator and rotor iron cores are not saturated, the two inductance terms L_{ds}^r and L_{qs}^r can be directly determined from the motor physical structure. However, due to magnetic cross coupling effects, larger operational currents in the *dr*- and *qr*-axes will also influence the corresponding inductance on their counterpart orthogonal

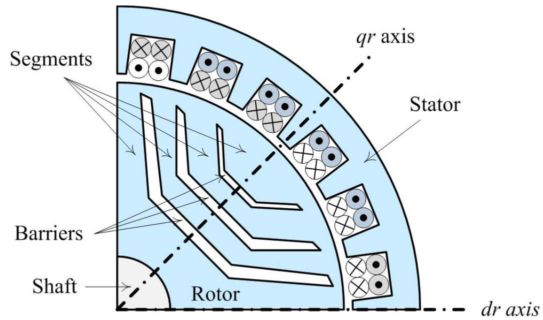

Fig. 1. Conceptual 1/4 structure of a 4-pole, 24-slot synchronous reluctance motor.

axes. Since the rotor operational speed is synchronized to the air-gap rotational magnetic fields that being generated by the stator winding currents of the SynRM, such consistent larger fluxes that are flowing through the rotor segments will reduce the equivalent inductance in the *dr*-axis more dominantly than those will be decreased in the *qr*-axis. Hence, from the decrements in the inductance difference term $(L_{ds}^r - L_{qs}^r)$ that is resulting from the magnetic saturations on the rotor segments, the generated motor electromagnetic torques will accordingly be reduced. Here

$$T_e = (\frac{3}{2})(\frac{P}{2})(\lambda_{ds}^r i_{qs}^r - \lambda_{qs}^r i_{ds}^r) = (\frac{3P}{4})(L_{ds}^r - L_{qs}^r) i_{qs}^r i_{ds}^r \qquad (3)$$

where P is the total number of motor poles.

Apparently, to supply larger torque outputs at the same operating current levels, it is expected that the designed SynRMs can achieve the maximum difference of $(L_{ds}^r - L_{qs}^r)$. However, as indicated in (2), the equivalent inductance on the *dr*- and *qr*-axes will be affected by the operating currents and rotor structures. Hence, in addition to the inductance difference term, a saliency ratio index (ζ) that can characterize this effect is expressed as

$$\zeta(i_{ds}^r, i_{qs}^r) = L_{ds}^r / L_{qs}^r \qquad (4)$$

As this saliency ratio will also be affected by the stator winding current compositions, to evaluate the performance of a SynRM more explicitly, the operational efficiency which being defined as the ratio of the rotor power output to the stator power input is adopted

$$\eta = [P_o/P_{in}]\times 100\% = [P_o/(P_o + P_{loss})]\times 100\%\text{, with} \qquad (5)$$

$$P_{in} = 3V_s I_s \cos(\varphi), \qquad (6)$$

$$P_o = T_e\omega_r - P_{mech},\ \text{and} \qquad (7)$$

$$P_{loss} = P_{copper} + P_{iron} \qquad (8)$$

where P_{mech} is the total mechanical power losses of the rotor shaft, V_s, I_s, and φ are the stator phase voltage, current, and