Development of a straight pole four-phase double-stator switched reluctance machine

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Abstract: This study introduces the development of the straight pole four-phase double-stator switched reluctance machine (SRM) which is considered to provide high torque density and low copper loss. The basic concept behind this design is to combine the features of the mutually coupled SRM and the double-stator SRM. In this study, the analytical method alongside the 2D finite element method (FEM) verification would be presented to reveal the developing path. Moreover, to verify the proposed SRM concept, the prototype machine has been designed and built. The performance result from 2D FEM is presented.

1 Introduction

Nowadays, the concern of environment protection and energy consumption has risen dramatically. The answer to this issue in the automotive industry is electrification. So far, several possible techniques have been widely investigated involving but not limited to hybrid electric vehicle, plug-in hybrid electric vehicle, battery electric vehicle, and fuel-cell electric vehicle. It is still too early to determine which of the above-mentioned methods could dominate the future markets. However, one thing is sure, the electric machine would soon meet its blooming season.

Currently, the permanent magnet synchronous machine (PMSM) and induction machine are dominating the industry. However, the potential of a switched reluctance machine (SRM) should never be underestimated. Based on the point of view from several reviews, the SRM is a promising option for the future no permanent magnet automotive electric propulsion system [1, 2]. However, there are still a few weak points that hold the SRM back from its bright future:

i. Relatively low torque density and efficiency when compared with the mainstream PMSM.
ii. Acoustic noise and vibration that inherent from its unique double salient structure.
iii. Huge torque ripple if without a dedicate control method.

To solve these issues, many investigations have been developed from both machine design and control strategy aspects.

Regarding the machine design aspect, torque enhancement is the focus, and there are several concepts worth to notice. Merrow et al. [3] introduce an SRM (the segmental rotor SRM, and also known as SRSRM) with several segmental rotor structures and claim that this SRM can produce 40% higher torque than a conventional SRM with similar dimensions and copper loss. This advantage is because the segmental rotor structure will generate a very short magnetic circuit and maintain a decent inductance ratio even when the rotor to pitch ratio has exceeded 0.5. However, there are also some weaknesses: first, the SRSRM may consume significant higher volt-ampere (VA) than the conventional SRM. Second, the SRSRM may severely suffer a performance drop from the cross-saturation effects when operating within the highly saturated condition.

In [4], a double-stator SRM (DSSRM) concept is presented. The structure of this SRM can seem like a combination of the previous SRSRM and an additional inner stator. Thus, this DSSRM could inherit the advantages of the SRSRM. Moreover, the double-stator configuration could generate balance axial force on the rotor that reduces the vibration and noise efficiently. Additionally, inner stator would provide higher MMF resulting in the potential higher torque density. However, on the other hand, the DSSRM also inherit the disadvantage from the SRSRM, and issues like cross-saturation effects may become even worse resulting in a lower efficiency compared with the SRSRM. Moreover, it is worth noting that the flux loop of conventional SRM can also be implemented with the double-stator structure [5].

Despite the efforts in the above-mentioned novel structures, the optimising of the conventional SRM still has potential that is far from exhausting. The chance for the conventional SRM is in the saturation region: the classic structure in the conventional SRM will help to maintain a considerable low unaligned inductance even when the aligned position is under highly saturated condition. This feature not only helps the conventional SRM eliminate the gap in the torque production from those segmental rotor competitors but also results in a lower drive VA requirement. In [6], a conventional three-phase SRM is developed to replace the PMSM that is used in the second-generation Toyota Prius and may consider as one of world leading result that has been published so far.

Moreover, the unusual winding configuration that brings mutual coupling effects may also produce an extra option for torque enhancement in conventional SRM. The earliest attempt is the fully pitched SRM [7]. This SRM could guarantee a promising performance in the 2D result, but its remarkable long-end winding ruins the advantage in reality by its extra copper loss. Aside from the fully pitched SRM, the mutually coupled SRM (MCSRM) has been introduced to utilising the mutual coupling effects while maintaining the single-toothed winding [8]. The major drawback of the MCSRM is known as the requirement of the high-cost bipolar inverter. Fortunately, it has been proving to be unnecessary for the MCSRM with even phase number [9].

This paper will summarise the development of the four-phase straight pole DSSRM that has the flux loop similar to the four-phase MCSRM.

2 Development of machine concept

The optimisation of conventional SRM is difficult due to the high non-linearity electromagnetic characteristic. Although the analytical method is less accurate and efficient compared with 2D finite element method (FEM), it is still a method that may help to improve the understanding of the design rule.

2.1 Linear model and analysis of conventional SRM

From the previous experiences, increasing the pole number is one of the common strategies [10, 11].
To be simplified, the analytical method could be first introduced to analyse the influence of air gap. An equation which estimates average torque from air gap has been developed:

\[ T = \frac{\mu_0}{8\pi g} M N D L \beta_s N^2 I^2 k_l (1) \]

In (1), \( \mu_0 \) is the permeability, \( g \) is the air gap length, \( M \) is the phase number, \( N_r \) is the rotor pole number, \( D \) is the air gap radius, \( L \) is the stack length, \( \beta_s \) is the stator pole arc, \( N \) is the turns number, \( I \) is the phase current, and \( k_l \) is a coefficient that represents the relationship between aligned and unaligned inductance: \((1 - (L_u/L_a))\).

To make a brief comparison, the poles combinations 6/4, 8/6, 10/8, and 12/10 as the most common and primitive options have been chosen. Each machine has the same \( D, L, N \), and \( g \), while \( \beta_s \) and \( I \) are inversely proportional to the phase number.

It is easy to assume that \( L_u \) would show an inversely proportional relationship with the phase number. However, the \( L_u \) may not be that straightforward. Fig. 1 shows a typical example of flux distribution at an unaligned position, and flux path is dominated by ‘fringing effect’ which is described in [12].

In this circumstance, the flux path is similar to a 90° curving tube. Moreover, both its cross-section and length can be identified as proportional to the stator pole width which equals to \( D \) times \( \beta_s \). Therefore, the \( L_u \) would maintain at a similar level as the phase number changes.

Take three-phase 6/4 SRM as a standard, the range of \( k_l \) would be between 0.8 and 0.9. For its rival, a four-phase 8/6 SRM with same air gap length \( g \), permeability \( \mu_0 \), bore diameter \( D \), stator pole arc \( \beta_s \), and stack length \( L \), its \( k_l \) would be \((-0.7333–0.8666)\).

Then it can be derived that the torque from 8/6SRM is circa 0.773–0.813 of the 6/4 SRM. Similarly, it can conduct that with the increase of phase number, the torque will experience a decrease (see Fig. 2). The result indicates that the increase of phase number may result in a decrease in torque output if only air gap reluctance is considered. Moreover, the result can be verified by using 2D FEM.

By defining the lamination material to infinite permeability, the 2D FEM result for air gap-only condition is achieved (see Fig. 3).

To analysis the behaviours in a saturated condition, a common strategy is to simplify the psi-I curve into semi-linear model (see Fig. 5). In the above-mentioned figure, \( L_1 \) and \( L_2 \) are the aligned inductance at the linear region for the 6/4 SRM and 8/6 SRM.
Moreover, consider the stroke per revolution in each SRMs, it can be similar to the 8/6 SRM:

\[ L_2 \geq \frac{L_0((k/2) - (k^2/4) + (kb/4) - (k^2b/4))}{(3/4)b - (k^2/2)} \]  

(4)

The k indicates the relation \( k = I_2/I_1 \), which represents the ratio between \( I_2 \) and \( I_1 \). From the physical meaning, this parameter could describe the saturation level of the 6/4 SRM. When \( k \leq 1 \), that means the SRM is operation at saturation condition. Moreover, b indicates the relation \( b = L_1/L_0 \), which represents the ratio between \( L_1 \) and \( L_0 \). This parameter describes the inductance ratio between the unaligned position and aligned position in the 6/4 SRM.

As it is easy to know that \( L_2 \approx 0.866 L_1 \) if the same copper loss is assumed, then a curve that presents the relation from (4) can be drawn (see Fig. 6).

If the selection of \( k \) and \( b \) is beneath the blue curve as shown in Fig. 6, then it indicates that the 8/6 SRM will produce more torque than 6/4 SRM. To achieve that, a deeper saturation condition and a larger inductance ratio is highly suggest. These two conditions are usually the objective for design a high-performance SRM. The physic explanation for this result is that the increase of phase number will reduce the requirement of pole width and eventually reduce the stator yoke. The narrow stator yoke will leave space for a larger rotor radius if there is same copper loss. Thus, a lower reluctance and larger inductance ratio will be achieved.

### 2.3 Analysis of four-phase mutual coupled SRM

Phase interaction condition commonly exists in SRMs, so avoiding this condition will either reduce the torque performance or enlarge torque ripple. According to [13], the phase interaction effects can be divided into two mechanisms: the positive one, mutual coupling; and the negative one, cross-saturation. The MCSRM is an SRM which can utilise mutual coupling effects to enhance performance by rearranging the coils opposite to each other in the same phase. The flux loop difference between the MCSRM and conventional SRM is shown in Fig. 7. Moreover, this flux loop could relieve the local saturation at stator yoke. Therefore, the MCSRM should benefit more from the saturation condition.

Comparing with the three-phase MCSRM, the four-phase MCSRM has several advantages:

1. The even number phase MCSRM has symmetric winding distribution and do not need a bipolar drive.
2. There are always two phases conducting simultaneously, reducing the torque ripple and taking full advantage of mutual coupling.
3. As MCSRM will benefit more from deep saturation condition, it will share the same optimisation trend with the four-phase SRM.

The comparison of the four-phase conventional SRM and four-phase MCSRM is shown in Fig. 8.

In this comparison, both machines have the same geometry design; the only difference is the coil winding arrangement. The utilisation factor in the figure represents the ratio between stator pole arc and stator pole pitch; a larger utilisation factor means a broader stator pole and therefore higher flux linkage. The result reveals that the opposing arrangement of coils could provide higher torque output than conventional winding in four-phase SRM, and this advantage would become evident while the saturation becomes deep.

### 2.4 Analysis of a double-stator structure

From the previous experience, the seek of higher flux-linkage and larger inductance ratio often results in a larger rotor radius. Therefore, optimising the four-phase MCSRM will keep adequate space in the middle of the machine. This condition shows the possibility of introducing a double-stator structure into this machine.

Most DSSRMs that are investigating recently can seem like a combination of an SRSRM and an outer rotor SRSRM that commonly use a rotor together. It is easy to estimate that this kind
of machine would acquire a significant torque density. However, the efficiency of this machine would naturally be lower than a pure SRSRM due to the cross-saturation effects of the commonly used rotor. Not to mention, the optimisation is harder than that of a single-stator SRSRM.

In [14], the possibility of conventional SRM with a double-stator structure has been presented. However, as its magnetic loop is significantly different from the traditional DSSRM, the examining of its electromagnetic characteristic is demanded. The analysis can be simplified by using linear SRM model (see Fig. 9).

Assume the double-stator linear SRM (LSRM) and conventional LSRM have the same uniform cross area, and the stator pole and rotor pole have the same length. In the magnetic circuit, define the length of the stator pole and rotor pole as $l_1$, the length of rotor yoke and stator yoke $l_2$, and the length of the rotor segment $l_3$.

If only consider the air gap reluctance, then the reluctance of the double-stator LSRM is twice that of the LSRM, requiring $2$ times turns number to achieve the same inductance (see (5))

$$L = \frac{N^2}{S} = \frac{\sqrt{2}N^2}{2S}$$ (5)

Moreover, as the slot area of the double-stator LSRM is twice that of the LSRM, the copper loss at this condition will be equal in both machines (see (6))

$$W = \int R = \int \frac{N^2 l}{\mu_A(N)} = \frac{N^2 l}{2\mu_A} = \frac{\sqrt{2}N^2 l}{\mu_A}$$ (6)

Consequently, the performance of both double-stator LSRM and LSRM is at an equilibrium point if only air gap reluctance is being considered. However, this equilibrium will break, if considering the lamination steel. As can be seen from (7), the reluctance of the double-stator LSRM is smaller than twice that of the LSRM

$$\frac{l_1 + l_2 + l_3 + 2l}{\mu_A} < 2$$ (7)

It indicates that the double-stator LSRM will achieve higher inductance while still maintaining the same copper loss. However, the air gap reluctance will dominate the magnetic circuit at the unaligned position. Therefore, comparing with the LSRM, the double-stator LSRM will have higher inductance at the aligned position and similar inductance at the unaligned position. The analysis also reveals that the double-stator structure will take more advantage at deeper saturation condition which is also a proffered design for the four-phase MCSRM.

The condition of rotational SRM could be more complicated as the inner stator is smaller than the outer stator. That slot area difference could slightly ruin the efficiency, but the larger rotor to stator ratio that recommends for the four-phase MCSRM will relieve this issue.

### 3 Machine concept verification

2D FEM can be used to verify the analytical conclusion. For the most convincing effect, a target SRM has been selected from [6]. Not only because this three-phase 18/12 SRM are believed as one of the best design of conventional SRM, but also because its parameters of geometry have been presented in detail. This three-phase SRM with the proposed four-phase MCSRM and four-phase DSSRM are modelled in the same software with the same material, outer diameter, axial length, and air gap length (see Fig. 10). Moreover, the VA rating per phase in the four-phase machine is set to 75% of that in the three-phase SRM to compensate for the higher phase number. Thus, with the same drive volume. The result of dynamic operation is shown in Fig. 11.

### 4 Prototype design and finite element result

Due to the limitation of the test rig, the maximum torque of the prototype machine has to be <100 N m. This restriction will suggest a smaller machine size for the prototype. The final design is shown in Fig. 12, there are 16 stator poles and 12 rotor poles, while stator diameter is set to 210 mm and stator length is set to 75 mm. The volume of this machine is the same as several SRMs that Newcastle University built before (150-mm active length and 150-
mm active diameter). Moreover, its larger stator diameter and shorter shaft length could reduce the manufacture difficulty for the complicated structure in the proposed DSSRM. The 2D FEM result presents a promising result for the prototype machine when comparing with an SRSRM [15]. The result for static energy conversion loop of these two SRMs is displayed in Fig. 13. As the back EMF is proportional to (dLi/dt), it reveals that the proposed four-phase DSSRM could potentially produce more torque while consuming less VA rating.

Moreover, the proposed 16/12 DSSRM also have the apparent advantage of torque per unit copper loss. As can be seen from Fig. 14, the targeting SRSRM only hold the superior position at very low torque scenario. Copper loss would occupy the domination portion of all losses until the SRM reach a very high speed; the result indicates that 16/12 DSSRM will produce much more torque under the same thermal limit.

The prototype has been built recently (see Fig. 15) and will be tested in the lab soon.

5 Conclusion
In this paper, the development of the machine concept that combines the four-phase MCSRM and double-stator structure has been presented. By using the analytical method and 2D FEM, several conclusions have been summarised to underpin this concept.

First, for the conventional SRM, four-phase design possibly brings higher torque per copper loss comparing with the standard three-phase SRM. From the analysis, this condition would tend to be realised when the geometry design with a large rotor to stator ratio and when operating at saturation condition.

Second, the four-phase geometry is ideal for the MCSRM concept, not only because the even phase number could avoid the bipolar inverter that a traditional three-phase MCSRM required, but also because the four-phase SRM will always operate under phase interaction effects which play a positive role in the MCSRM. Moreover, similar to four-phase SRM, the MCSRM will benefit from operation at saturation condition and larger rotor to stator ratio.

Third, the four-phase MCSRM will have a larger rotor to stator ratio than a conventional three-phase SRM, allowing enough space to arrange the double-stator structure. Through the analytical method, this double-stator structure reveals its advantage in efficiency. Moreover, this double-stator structure also benefits from operation at saturation condition and larger rotor to stator ratio.

The concept of the proposed four-phase DSSRM has been verified by comparing with a widely recognised outstanding SRM [6]. The result shows that the proposed DSSRM could provide similar maximum torque at the same dimensions and VA rating to the targeting machine but with a maximum 50% less copper loss.

At last, a smaller prototype for the proposed four-phase DSSRM is presented with its design and simulation result. Its experimental test will soon be arranged shortly.

6 References
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