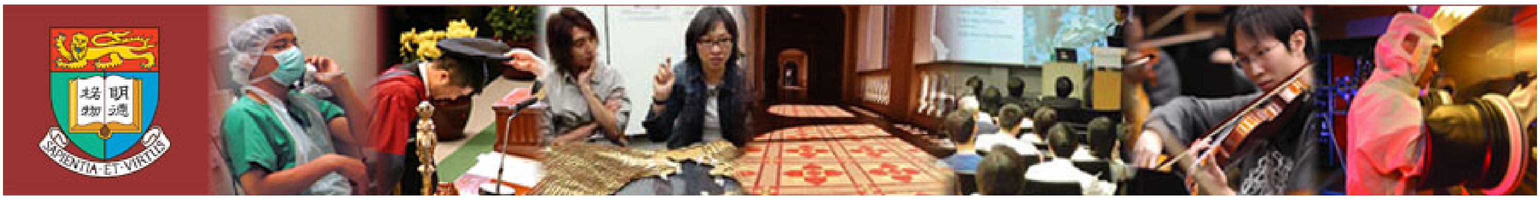

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Quantitative Comparison and Analysis of Magnetless Machines With Reluctance Topologies

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This paper quantitatively compares three advanced magnetless machines, namely the switched reluctance (SR) machine, double-stator SR (DS-SR) machine and DS multitoothed SR (DS-MSR) machine. The DS-SR machine is particularly favorable for low-torque high-speed operation while the DS-MSR machine is desirable for high-torque low-speed operation. Because of more effective power transfer by using two stators, the two DS machines achieve better performances than the single-stator counterpart. All machine performances are analyzed by using the time-stepping finite element method.

***Index Terms*—Double-stator machine, magnetless machine, multitoothed structure, reluctance machine.**

I. Introduction

THERE is an accelerating pace on the development of electric machines due to the increasing demands on the energy utilization and hence protection of the environment. Namely, the electric machines have to offer high efficiency, high power density, high controllability, wide speed range, and maintenance-free operation [1]. To achieve these goals, the permanent-magnet (PM) machines have been actively developed [2], [3]. However, the PM material cost has been soared drastically while the corresponding supply is limited and fluctuating. Thus, the advanced magnetless machines are becoming more and more attractive [4].

Compared with the PM machines, the switched reluctance (SR) machine takes the definite advantages of low cost, high robustness and excellent high-speed operation, but suffers from relatively poor torque density [5] and is not preferable for high-torque low-speed operation. To cope with these deficiencies, the multitoothed SR (MSR) machine was proposed [6], which is particularly favorable for high-torque low-speed operation. Meanwhile, the concept of double-stator (DS) topology was proposed [7], which can significantly improve the torque density of different kinds of machines.

The purpose of this paper is to newly incorporate the DS concept into the SR machine and the MSR machine to form the DS-SR machine and the DS-MSR machine, respectively. The design criteria and operating principles of these three advanced magnetless machines, namely the SR, DS-SR and DS-MSR, will be discussed. Hence, their machine performances will be analyzed by using the time-stepping finite element method (TS-FEM) [8], and then quantitatively compared.

II. Machine Design

Fig. 1 shows the topologies of the three advanced magnetless machines, namely the 12/8-pole SR machine, the 12/8-pole DS-SR machine and the 36/32-pole DS-MSR machine. Both DS topologies have 12 stator poles in both the outer and inner stators, The MSR topology has 3 teeth per stator pole, resulting in 36 equivalent stator poles.

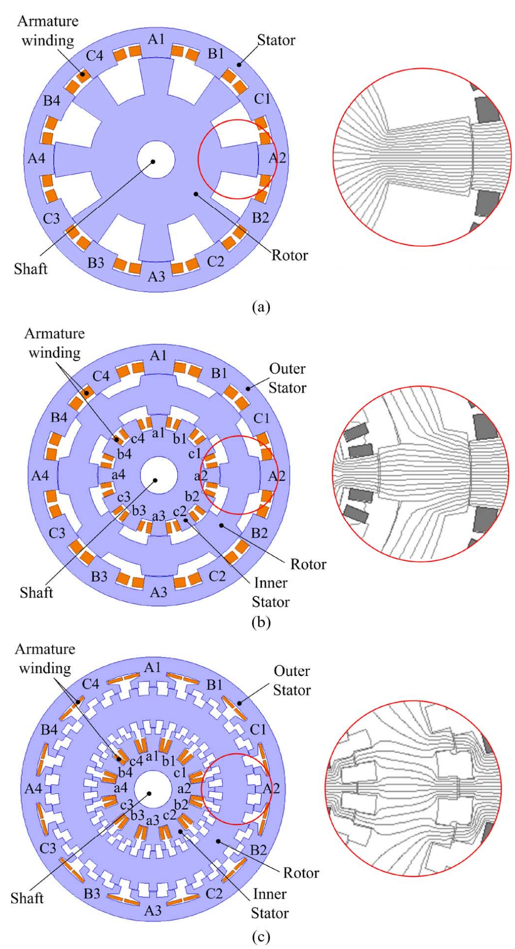

Fig. 1. Machine topologies: (a) 12/8-pole SR machine. (b) 12/8-pole DS-SR machine. (c) 36/32-pole DS-MSR machine.

Since the DS-SR machine is derived from the incorporation of DS concept into the SR machine, it needs to comply with the pole arrangement of the SR machine as governed by:

$$\begin{cases} N_s = 2mk \\ N_r = N_s \pm 2k \end{cases} \quad (1)$$

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where N_s is the number of stator poles, N_r the number of rotor poles, m the number of phases, and k a positive integer.

Since the DS-MSR machine is derived from the incorporation of DS concept into the MSR machine, the design criteria of its pole arrangement are extended from that of the MSR machine as given by:

$$\begin{cases} N_{sp} = 2mj \\ N_{se} = N_{sp}N_{st} \\ N_r = N_{se} \pm 2j \end{cases} \tag{2}$$

where N_{se} is the number of equivalent stator poles, N_{sp} the number of stator poles, N_{st} the number of stator teeth per pole, and j a positive integer.

For the SR and DS-SR machines, by selecting $k = 2$ and $m = 3$, it ends up with $N_s = 12$ and $N_r = 8$. In order to have a fair comparison among all three machines, the number of conduction phases and winding configurations should be the same. Therefore, for the DS-MSR machine, by selecting $j = 2$ $N_{sp} = 12$ and $N_{st} = 3$, it yields $N_{se} = 36$ and $N_r = 32$. As compared with the SR machine, the DS-SR and DS-MSR machines involve higher manufacture complexity due to the use of double stators. Nevertheless, the corresponding construction is practicable as revealed in [7], particularly when there are free from PM material.

The key features of all advanced magnetless machines are summarized as follows:

• For the SR machine, most of the inner rotor spaces are not utilized; therefore the torque density is degraded and its performance is far worse than that of the PM machines.

• The DS machine topologies can utilize its inner space to accommodate the inner stator for power transfer, hence improving the overall torque density to be comparable with that of the PM machines.

• With the flux-modulation effect, the MSR machine can offer higher torque density than its SR counterpart. The MSR machine behaves similarly with the magnetic-geared machine [3] since both adopt the flux-modulation effect; however, the MSR enjoys the definite cost-benefit due to its magnetless structure. With the additional DS concept, the DS-MSR machine can achieve higher torque density.

III. Principle of Operation

For the SR machine, two pairs of opposite coils A1, A3, A2 and A4 are conducted in series for the phase A while the phases B and C hold the similar patterns such that the magnetic field is symmetrical, leading to form the magnetic polarities of N-S-N-S-N-S-N-S-N-S-N-S. For the DS machines, the inner coils named with the lower case have the same magnetic arrangements as the outer one so that both stators can perform power transfer simultaneously.

All three machines adopt the same operating principle. Fig. 2 shows the theoretical waveforms where i is the armature current which is applied during the period of increasing self-inductance L and T_e is the resulting electromagnetic torque. The torque equation is governed by:

$$T_e = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{3}$$

Similar to the SR machine, the DS-SR and DS-MSR machines adopt the same speed control technique. The operating speed is governed by the value of N_r and the operating frequency as given by:

$$n = \frac{60 f_{PH}}{N_r} \tag{4}$$

where n is the rotor speed, and f_{PH} the commutating frequency of a particular phase. Obviously, the value of N_r of the DS-MSR machine is much larger than that of the SR and DS-SR machines. Thus, the DS-MSR machine can operate at low speed while achieving high torque under the same operating frequency. Nevertheless, the efficiency of the MSR machine is lower than its SR counterpart during high-speed operation since the core loss increases with the commutating frequency.

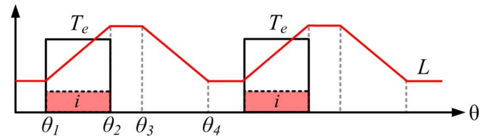

Fig. 2. Theoretical operating waveforms.

TABLE I
Machine Key Data

Item	SR	DS-SR	DS-MSR
Rotor outside diameter	216.0 mm	216.0 mm	216.0 mm
Rotor inside diameter	40.0 mm	131.2 mm	131.2 mm
Outer stator outside diameter	280.0 mm	280.0 mm	280.0 mm
Outer stator inside diameter	217.2 mm	217.2 mm	217.2 mm
Inner stator outside diameter	N/A	130.0 mm	130.0 mm
Inner stator inside diameter	N/A	40.0 mm	40.0 mm
Outer and Inner airgap length	0.6 mm	0.6 mm	0.6 mm
Stack length	80.0 mm	80.0 mm	80.0 mm
No. of phases	3	3	3
No. of armature turns in outer stator	80	80	80
No. of armature turns in inner stator	N/A	80	80

IV. Comparison of Machine Performances

All the magnetless machines are compared under the fair condition. Namely, the stack length, the outer stator diameter, shaft diameter and airgap length are set to be equal. Also, all machines are designed to avoid magnetic saturation so that their core losses are minimized and can be fairly compared. The key design data of the machines are shown in Table I. By using the TS-FEM to analyze all three machines, all important machine performances can be deduced. Hence, a quantitative comparison among them can be performed.

Firstly, the airgap flux density distributions of the machines are analyzed as shown in Fig. 3. As expected, the SR and DS-SR machines have the same pattern of waveforms since both of them adopt the same machine structures and operating principles. Meanwhile, the airgap flux density distributions of the DS-MSR machine are different from the others, namely the original flux of each stator pole is modulated into three portions in accordance with the number of teeth per each stator pole. In addition, it can be observed that the outer-airgap flux density and the inner-airgap flux density of both DS machines have the same pattern. This indicates that the outer and inner airgap fluxes do not significantly distort one another. Furthermore, it can be found that the inner-airgap flux density of the DS-MSR machine is slightly smaller than its outer-airgap flux density, which is due to the fact that there is higher possibility

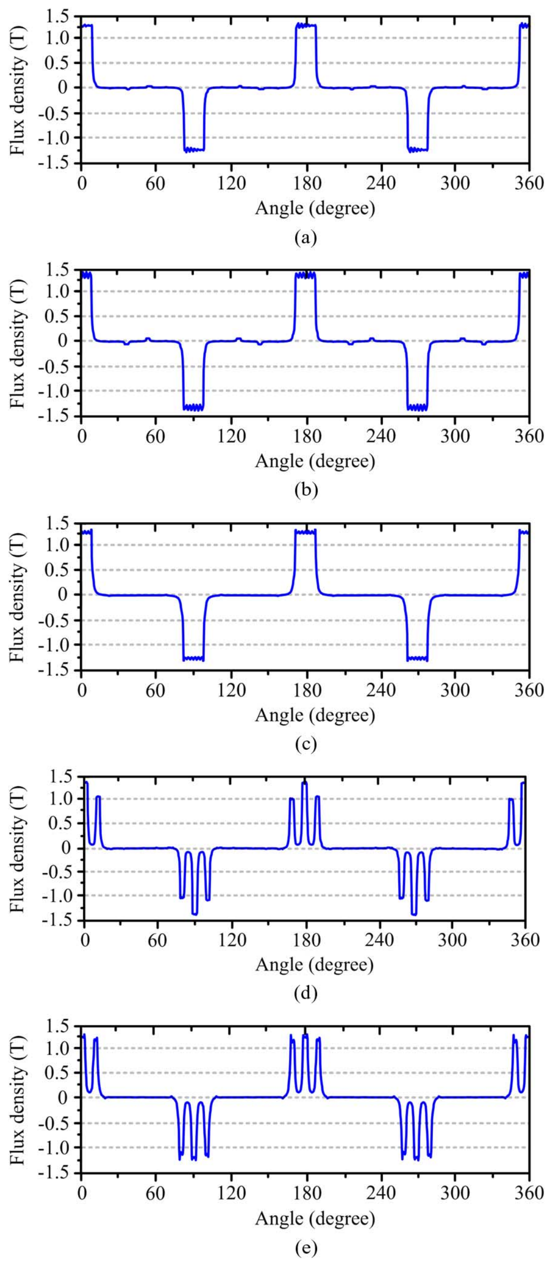

Fig. 3. Airgap flux densities: (a) SR machine. (b) Outer airgap of DS-SR machine. (c) Inner airgap of DS-SR machine. (d) Outer airgap of DS-MSR machine. (e) Inner airgap of DS-MSR machine.

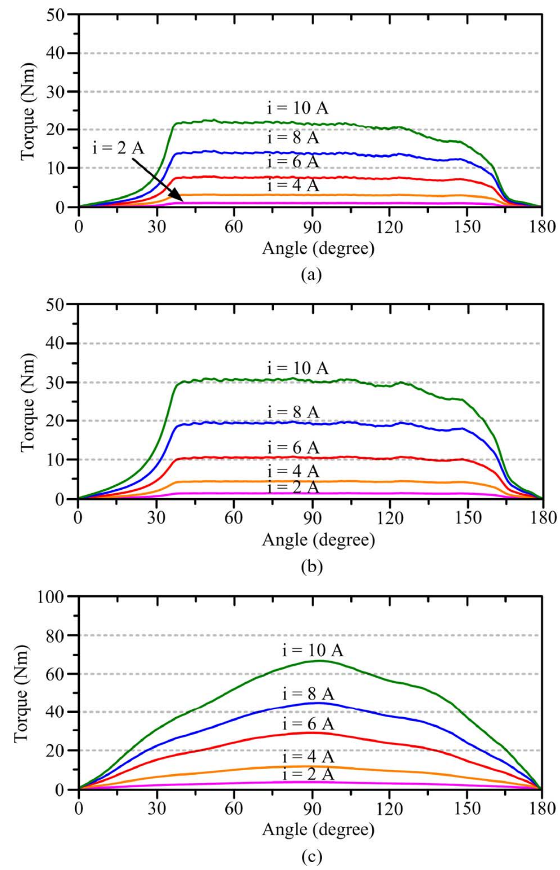

Fig. 4. Static torque capabilities: (a) SR machine. (b) DS-SR machine. (c) DS-MSR machine.

to have saturation in the inner stator and this happens relatively more severe for the multitoothed structure.

Secondly, the machines are fed with different armature currents from 2 A to 10 A with a step of 2 A so that the static torque capabilities between the aligned and unaligned positions can be obtained as shown in Fig. 4. It can be observed that all machines agree with the design criterion given by (3). This implies that the machines do not suffer from magnetic saturation, and confirms that the DS-MSR can produce the highest torque under the same armature current.

Thirdly, the output torque waveforms of the machines are simulated as shown in Fig. 5. It can be observed that the average torques of the SR, DS-SR and DS-MSR machines are 19.1 Nm, 27.9 Nm and 54.1 Nm, respectively. Compared with the SR machine, the torque enhancement of the DS-SR and DS-MSR machines are 46.1% and 183.2%, respectively. Based on similar machine dimensions, the PM machines can offer the rated torque ranging from 30 Nm to 70 Nm [3]. Therefore, the proposed DS topology, even magnetless, can achieve the torque level comparable with the PM machines. In addition, the average torque values of the DS-SR machine when the inner stator is conducted alone, outer stator is conducted alone and both stators are conducted together are 9.6 Nm, 18.7 Nm and 27.9 Nm, respectively. It illustrates that the total torque developed by both stators is roughly equal to the summation of the torque developed by the individual stators, hence confirming that both stators can contribute power transfer to the rotor simultaneously. This holds the same case for the DS-MSR machine. Furthermore, it can be observed that the torque ripples of all machines are acceptable, while the ripple frequency of the DS-MSR machine is higher than the others which are due to the multitoothed structure.

Finally, the core loss waveforms of the machines operating at the rated load are simulated as shown in Fig. 6. It can be observed that the average core losses of the SR, DS-SR and DS-MSR machines are 24.6 W, 38.1 W and 84.3 W, respectively. As expected, the SR machine has the lowest core loss since it operates with one stator only, whereas the DS-MSR machine has the highest core loss because of its DS mutlitoothed structure. In addition, since the power levels and core losses of all three machines are 1–1.36 kW and 2.5–6.1%, respectively,

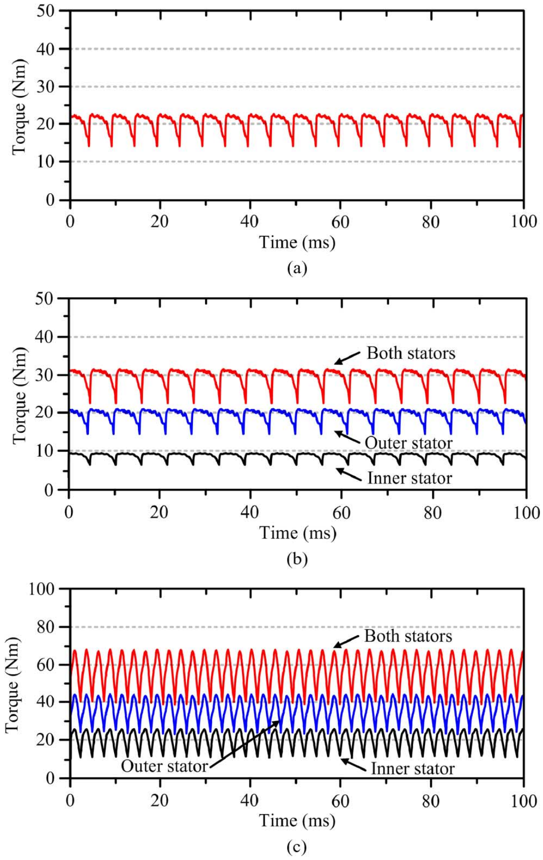

Fig. 5. Output torque waveforms at rated speed: (a) SR machine. (b) DS-SR machine. (c) DS-MSR machine.

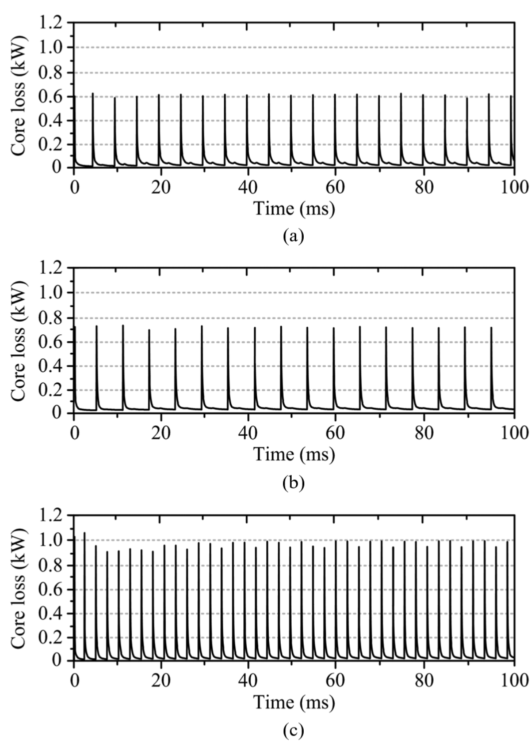

Fig. 6. Core loss waveforms at rated load: (a) SR machine. (b) DS-SR machine. (c) DS-MSR machine.

the core thermal dissipation is not a problem which can be easily handled by using forced air cooling.

TABLE II
MACHINE PERFORMANCE COMPARISON

Item	SR	DS-SR	DS-MSR
Power	1000 W	1280 W	1360 W
Rated speed	500 rpm	440 rpm	240 rpm
Outer airgap flux density	1.29 T	1.41 T	1.38 T
Inner airgap flux density	N/A	1.37 T	1.26 T
Rated torque	19.1 Nm	27.9 Nm	54.1 Nm
Torque enhancement	N/A	46.1%	183.2%
Core loss	24.6W	38.1 W	84.3 W

V. CONCLUSION

In this paper, three advanced magnetless machines, namely the SR, DS-SR and DS-MSR, have been analyzed and then quantitatively compared. The comparison results are summarized in Table II which concludes that the DS-SR machine is preferable for low-torque high-speed operation whereas the DS-MSR machine is preferable for high-torque low-speed operation. The DS-SR and DS-MSR machines can offer higher torque density than the single-stator SR counterpart by 46.1% and 183.2%, respectively. Although they both suffer from higher core loss than the SR one, such core losses are well acceptable. Particularly, both DS machines, especially the DS-MSR machine, can achieve the torque density comparable with the PM machines. Due to the absence of costly PM material, the magnetless DS machines take the definite merit of higher cost-effectiveness than the PM machines. All three machines are suitable for application to electric vehicle propulsion in which cost-effectiveness and magnet-free are concerned. Particularly, the DS-MSR machine is very suitable for in-wheel direct-drive application.

ACKNOWLEDGMENT

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