Power Electronic Converters for 12/8 Switched Reluctance Motor Drives: A Comparative Analysis

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***Abstract*—In this paper, five popular power electronic converters for three-phase 12/8 switched reluctance motor (SRM) drives including asymmetric power electronic converter, N+1 power electroic converter, split AC power electronic converter, split DC power electronic converter, and C-dump power electronic converter are investigated and compared in terms of device ratings, cost, efficiency, torque ripples, average torque, and copper losses. Comparison results show that C-dump converter is a more promising candidate in high-performance SRM drives, while split AC converter is recommended in low-cost applications.**

I. INTRODUCTION

Switched reluctance motor (SRM) drives are gaining interest in various applications due to their simple and rigid structure, four-quadrant operation, and extended-speed constant power range [1-5]. SRMs are reliable and cost effective in harsh environments due to the lack of rotor windings and permanent magnets. Power electronic converters for SRM drives play an important role in searching for cost effective solutions in SRM applications, because costs of switches take up a large amount of the total costs in motor drives. Asymmetric power electronic converter for a three-phase SRM shown in Fig. 1 is the most widely used power electronic converter in SRM drives. It allows independent control of different phases and, therefore, it mainstains good control peformance in terms of torque ripple reduction. However, it has two switches and two diodes per phase, which is challenging in low-cost applications.

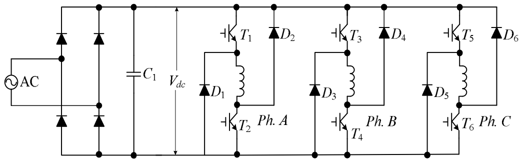


Fig. 1. Asymmetric power electronic converter.

Some converters [6] such as N+1 power electronic converter shown in Fig. 2 with reduced number of switches have been proposed to reduce the costs compared with the asymmetric bridge converter. However, these converters cannot achieve independent current control, which will result in undesirable torque ripples during commutation. In spite of the lower number of switches, device ratings of switches and diodes are increased and power losses are increased accordingly. The switches with higher power rating are more expensive and the total cost need to be calculated in specific applications to determine whether it is reduced or not.

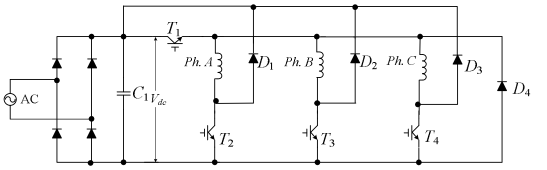
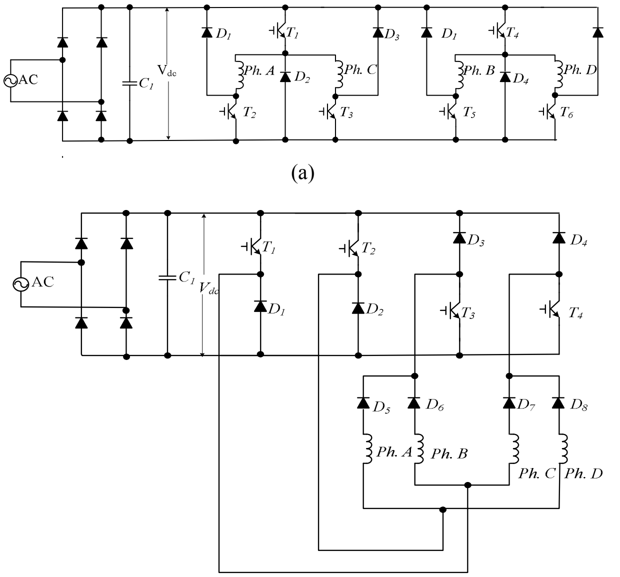


Fig. 2. N+1 power electronic converter.

In addition, the converters shown in Fig. 3 with reduced number of switches are only applicable for SRMs with even number of phases. Therefore, these converters are not choices for three-phase 12/8 SRMs.

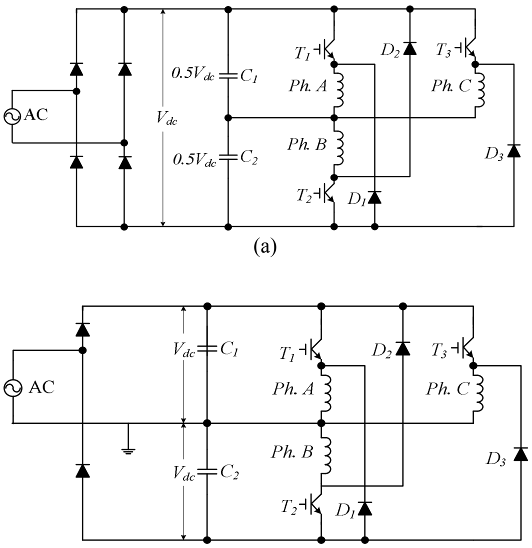


(a)

(b)

Fig. 3. Power electronic converters for SRMs with even number of phases.

With reduced number of switches and comparable control performance, split DC and split AC power electronic converters are gaining interest in SRM drives. Both split DC and split AC power electronic converters shown in Fig. 4 have one switch and one diode per phase. Compared to the N+1 power electronic converter, it allows partial independent control during commutation, leading to lower torque ripples.

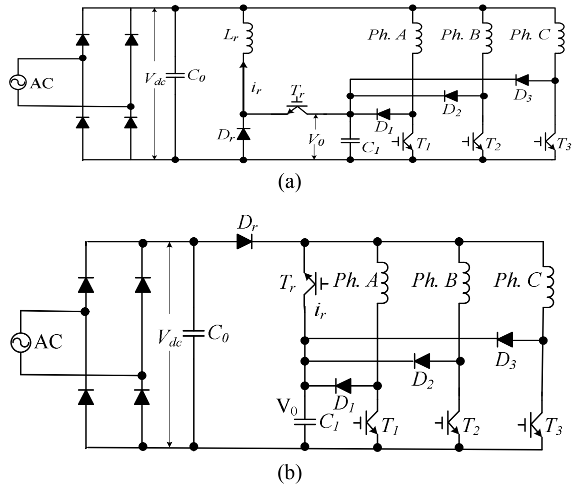


(a)

(b)

Fig. 4. Split DC and Split AC power electronic converters for SRM. (a) Split DC Converter. (b) Split AC Converter.

The drawbacks of SRMs lie in their high torque ripples especially during commutation. C-dump converter shown in Fig. 5 can provide higher magnetization voltage by controling the the voltage of the capacitor C_1.



(a)

(b)

Fig. 5. C-dump converters. (a) Conventional C-dump converter. (b) Free-wheeling C-dump converter.

C-dump converter shown in Fig. 5(a) does not allow freewheeling, which adds to acoustic noise and swithching losses. However, C-dump converter requires additional capacitor and inductor. The free-wheeling C-dump converters without the inductor is shown in Fig. 5(b).

In [7-8], some converters are proposed to provide higher magnetization and demagnetization voltage to achieve faster commutation; however, they suffer from higher losses and much higher number of the switches.

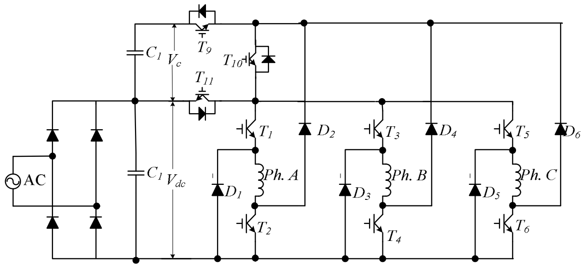


Fig. 6. A power electronic converter with higher demagnetization voltage.

In [9], several types of power electronic converters for two-phase SRMs are compared in terms of cost, efficiency, and acoustic noise. The control performances such as torque ripples, copper losses, and average torque of the motor are not investigated.

In this paper, five power electronic converters including asymmetric power electronic converter, N+1 power electronic converter, split AC power electronic converter, split DC power electronic converter, and C-dump power electronic converter are reviewed and compared regarding device ratings, conduction losses, switching losses, number of switches and diodes, and number of passive components including capacitors and inductors. Then, control performance of power electronic converters are compared in terms of torque ripples, copper losses of the machine, and average torque over a wide speed range through a simulated 2.3kW, 6000rpm, three-phase 12/8 SRM. Based on the tradeoff between the cost and performance, conclusions regarding the power electronic converters for three-phase 12/8 SRMs are made.

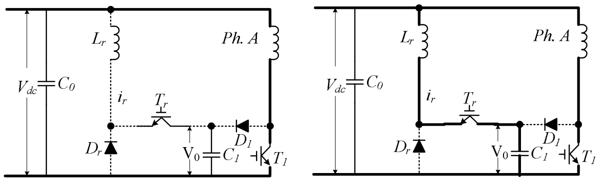
II. COMPARISONS OF POWER ELECTRONIC CONVERTERS FOR 12/8 SRMS

The five power electronic converters including asymmetric power electroninc converter, N+1 power electronic converter, C-dump power electronic converter, split DC and split DC converters are compared in terms of device rating, switching losses, conduction loss, and control peformance in this section for three-phase SRMs. The maximum RMS phase current of the motor is I_d and the DC link voltage is V_{dc}. The VA (volt-ampere) rating of the converter is an important criterion to evaluate the cost of the converter. The converter volt-ampere (VA) rating is defined as $N \times V \times I$ where V and I are the voltage rating and RMS current rating of the switches; N is the number of the switches. For easier comparison, the normalized power losses are used. The switching loss of single IGBT with V_{dc} voltage stress and I_d current stress is assumed to be 1 p.u. The conduction loss of IGBT or diode with I_d current is also assumed as 1 p.u.

Asymmetric power electronic converter shown in Fig. 1 has two switches and two diodes per phase. When the phase A current is below the reference, T_1 and T_2 are turned on. When the phase current A rises above the reference, T_1 and T_2 are turned off. The energy stored in the motor will keep the current circulating until it decreases to zero. This is called as hard switching strategy for asymmetric power electronic converter. The difference between soft switching and hard switching is freewheeling of the diodes. The energy stored in the phase inductor of the motor can keep circulating by only turning off T_2. Considering the voltage drop of the switches and diodes, much lower voltage is applied to the motor and the phase current decreases more slowly compared with that in hard switching strategy. Soft witching strategies help reduce the switching losses and acoustic noise compared with the hard switching. The advantage of the asymmetric power converter is that it allows independent control of different phases. Therefore, torque ripples of the SRM can be reduced during commutation. However, the costs are relatively high considering two switches and two diodes per phase. In asymmetric converter, the voltage rating and maximum RMS current are V_{dc} and I_d and, therefore, asymmetric power converter has 6VA rating in three-phase SRMs. The IGBT in asymmetric power converter has V_{dc} voltage stress and I_d current stress and, therefore, switching loss of the IGBT is 1 p.u. In hard switching mode, its total switching loss is 6 p.u. In soft switching mode, asymmetric converter has 3 p.u. switching loss since only three switches are turned off. Similarly, asymmetric power converter has 6 p.u. IGBT conduction loss and 6 p.u. diode conduction loss when working in hard switching mode. In soft switching mode, IGBT conduction loss is increased to 12 p.u. and diode conduction loss is decreased to 3 p.u.

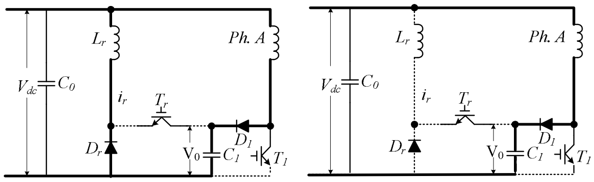
The N+1 converter shown in Fig. 2 has four switches and four diodes per phase. When the current of phase A is below the reference, T_1 and T_2 are turned on. When the current of phase A rises above the reference, T_1 and T_2 are turned off and $-V_{dc}$ is applied. The energy stored in the phase inductor of the motor will keep the current circulating through D_1 and D_4 until it decreases to zero. This is valid for non-commutation intervals. During the commutation intervals, the phase B is built up by turning on T_1 and T_3. Thus, the phase A freewheels through T_1 and D_1 and only zero voltage can be applied to phase A. Therefore, demagnetization voltage for N+1 power converter is zero. In order to achieve fast current turning off, $-V_{dc}$ is preferred. This topology achieves non independent control of the current, which might be undesirable for high performance motor drives. The costs may be reduced with the lower number of switches and diodes. However, the power ratings of T_1 and D_4 are much higher than those of other switches and diodes due to repeated switching. The shared switch T_1 in N+1 converter has $3I_d$ current stress and V_{dc} voltage stress. Other three switches in N+1 converter have I_d current stress and V_{dc} voltage stress. Therefore, N+1 converter has 6VA rating in total. For N+1 power converter, T_1 has three times switching power loss due to repeated switching and therefore total switching loss is also 6 p.u. Similarly, N+1 power converter has 6 p.u. IGBT and diode conduction losses.

C-dump converter shown in Fig. 5(a) has four switches, four diodes, one inductor, and two capacitors. To analyze the VA rating and losses of the C-dump converter, its operational principles are described. Five modes are illustrated in Fig. 7.



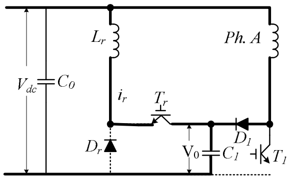
Mode 1: T_1 on, Tr off

Mode 2: T_1 and Tr on



Mode 3: T_1 and Tr off

Mode 4: Commutaion



Mode 5: T_1 off, Tr on

Fig. 7. Five modes of the C-Dump converter.

When phase A current is below the reference, T_1 is turned on and V_{dc} is applied. Phase A flows through C_1 and T_1 in mode 1 or 2. When the current of phase A rises above the reference, T_1 is turned off and V_{dc}-V_0 is applied. The phase A is working in mode 3, 4, or 5. When the current of phase B needs to be built up, T_2 is turned on and T_1 is turned off. The current of phase B flows through C_0 and T_2. The current path of phase A flows through D_1, C_0, and C_1 and charges C_1. Thus, the C-dump converter allows independent control of different phases. T_r is used to control of the voltage V_0 to provide higher demagnetization voltage during the commutation. The additional inductor and switches/diodes are needed, which may increase the costs. Also, it does not achieve freewheeling, which may increase the acoustic noise and switching losses. When the voltage V_o of the C-dump converter is controlled at $2V_{dc}$ and $3V_{dc}$, the maximum voltage for switches is $2V_{dc}$ and

$3V_{dc}$. The VA rating of C-dump converter is increased to $4\times 2V_{dc}\times I_d$ and $4\times 3V_{dc}\times I_d$, respectively. The switching loss is 8 p.u. and 12 p.u. in two cases. With the same current rating of IGBT and diode, the conduction loss of IGBT and diode in C-dump converter is decreased to 4 p.u. since the number of switches and diodes are decreased.

Split DC converter shown in Fig. 4(a) has three switches, three diodes, and two capacitors. When the current of phase A is below the reference, T_1 is turned on, and $0.5V_{dc}$ is applied. Current of phase A flows through C_1 and T_1. When the current of phase A rises above the reference, T_1 is turned off and $-0.5V_{dc}$ is applied. The current of phase A flows through D_1 and C_2. When the current of phase B needs to be built up, T_2 is turned on and T_1 is turned off. The current of phase B flows through C_2 and T_2. The demagnetization voltage of phase A is $-0.5V_{dc}$, leading to higher commutation torque ripples. The split DC converter allows partial independent control of different phases. Moreover, efforts have to be made to balance the voltage of C_1 and C_2. In addition, the increased number of capacitors adds additional costs to the system and lowers the power density concerning the bulky capacitors. The voltage rating of three switches in split DC converter is V_{dc} and, therefore, the split DC converter has $3\times V_{dc}\times I_d$ VA rating. The total switching loss of split DC converter is 3 p.u. considering V_{dc} voltage stress and I_d current stress. The conduction loss of IGBT and diode in split DC converter are both 3 p.u.

Split AC converter shown in Fig. 4(b) has three switches, three diodes, and two capacitors. When the current of phase A is below the reference, T_1 is turned on and V_{dc} is applied. Current of phase A flows through C_1 and T_1. When the current of phase A rises above the reference, T_1 is turned off and $-V_{dc}$ is applied. The current of phase A flows through D_1 and C_2. When the current of phase B needs to be built up, T_2 is turned on and T_1 is turned off. The current of phase B flows through C_2 and T_2. The demagnetization voltage of phase A is $-V_{dc}$. The split AC power converter also allows partial independent control of different phases. Compared with the split DC power converter, split AC converter provides higher magnetization/demagnetization voltage, which decreases the commutation torque ripples. Moreover, no efforts have to be made to balance the voltage of C_1 and C_2. The voltage rating of three switches in split AC converter is $2V_{dc}$ and, therefore, the split AC converter has $3\times 2V_{dc}\times I_d$ VA rating. The VA rating of split AC converter is the same as the asymmetric power electronic converter. The total switching loss of split AC converter is increased to 6 p.u. considering $2V_{dc}$ voltage stress. Since current rating of split AC converter and split DC converter is the same, the split AC converter has the same conduction loss as the split DC converter.

Detailed comparison of the five studied power electronic converters in terms of VA rating, power loss, and control performance is listed in Table 1. N+1 power electronic converter and split AC power electronic converter have the same VA rating as the asymmetric power electronic converter despite the reduced number of switches and diodes. Therefore, these three converters have similar costs. C-dump converter has the same magnetization/demagnetization voltage as split AC and asymmetric converters when the voltage V_o of the capacitor is controlled at $2V_{dc}$. However, it has higher VA rating and switching losses. Therefore, split AC and asymmetric power converters are more effective in terms of cost and control performance. In simulations, V_o of the C-dump converter is controlled at $3V_{dc}$ rather than $2V_{dc}$ to compete with the other converters in terms of control performance.

TABLE. 1. COMPARISONS OF THE POWER ELECTRONIC CONVERTERS.

Converter	Asymmetric Converter		N+1 Converter
	Hard switching	Soft Switching	
Number of Switches	6	6	4
Number of Diodes	6	6	4
Number of Capacitors	1	1	1
Number of Inductors	0	0	0
Magnetization	V_{dc}	V_{dc}	V_{dc}
Demagnetization Voltage	$-V_{dc}$	$-V_{dc}$	$-V_{dc}$
Total Power Ratings (VA)	$6V_{dc}I_d$	$6V_{dc}I_d$	$6V_{dc}I_d$
IGBT Switching Losses(p.u.)	6	3	6
IGBT Conduction losses (p. u.)	6	9	6
Diode Conduction Losses(p.u.)	6	3	6
Phase Independence	Yes	Yes	No
Freewheeling	No	Yes	Yes

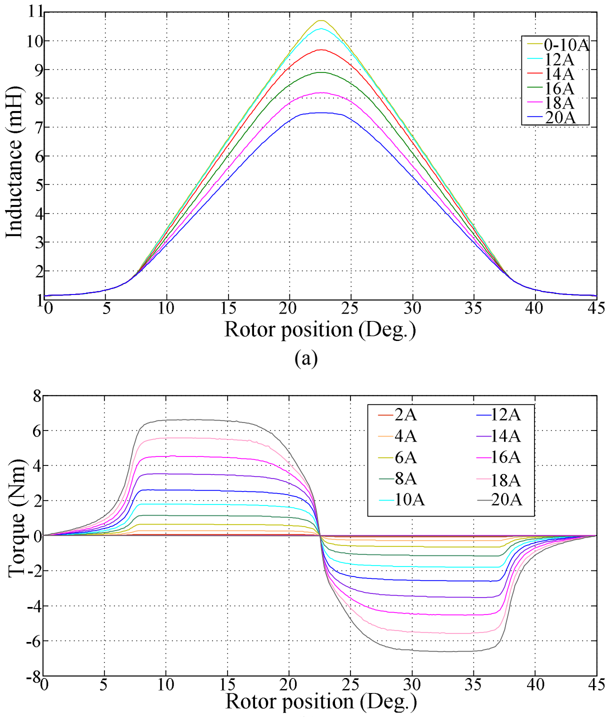
TABLE. 1. (CONTINUED)

Converter	Split DC Converter	Split AC Converter	C-dump Converter	
Capacitor Voltage V_0			$2V_{dc}$	$3V_{dc}$
Number of Switches	3	3	4	4
Number of Diodes	3	3	2	2
Number of Capacitors	2	2	2	2
Number of Inductors	0	0	1	1
Magnetization	$0.5V_{dc}$	V_{dc}	V_{dc}	V_{dc}
Demagnetization Voltage	$-0.5V_{dc}$	$-V_{dc}$	$-V_{dc}$	$-2V_{dc}$
Total Power Ratings (VA)	$3V_{dc}I_d$	$6V_{dc}I_d$	$8V_{dc}I_d$	$12V_{dc}I_d$
IGBT Switching Losses (p.u.)	3	6	8	12
IGBT Conduction losses (p.u.)	3	3	4	4
Diode Conduction	3	3	4	4

Losses (p.u.)				
Phase Independence	partial	partial	yes	yes
Freewheeling	No	No	No	No

III. SIMULATION VERIFICATION

A 2.3kW, 6000rpm, three-phase 12/8 SRM simulation model is built by Matlab/Simulink, using torque as well as inductance profiles shown in Fig. 8. These profiles are obtained from finite element analysis (FEA) using JMAG software [10]. Torque control using linear torque sharing function (TSF) [11-14] is applied and control diagram is shown in Fig. 9. T_{e_ref} is the total torque reference and $T_{e\_ref\ (k)}$ is the reference torque for k^{th} phase. The torque reference of each phase is defined by linear TSF. Then, phase current reference is derived according to this equation. Hysteresis current control with 0.5A hysteresis band is applied and DC-link voltage V_{dc} is set to 300V. The torque reference is set to 1.5Nm.



(a)

(b)

Fig. 8. The FEA inductance and torque profiles of 12/8 SRM. (a) Inductance profiles. (b) Torque profiles.

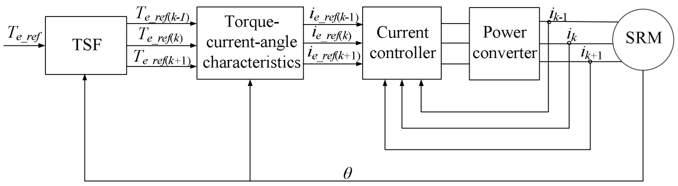


Fig. 9. Illusration of torque control of SRM.

Linear TSF is represented as in (1), and its waveform is shown in Fig. 10. $f_{rise}(\theta)$ is the rising TSF for the incoming phase, $f_{fall}(\theta)$ is the decreasing TSF for the outgoing phase. θ_{on}, θ_{off}, θ_{ov} and θ_p are turn-on angle, turn-off angle, overlapping angle, and pole pitch, respectively. In this simulation, turn-on angle θ_{on}, turn-off angle θ_{off}, and overlapping angle θ_{ov} of linear TSF are set to 5˚, 20˚ and 2.5˚, respectively.

$$\begin{aligned} f_{rise}(\theta) &= \frac{1}{\theta_{ov}}(\theta-\theta_{on}) \\ f_{fall}(\theta) &= 1-\frac{1}{\theta_{ov}}(\theta-\theta_{off}) \end{aligned} \tag{1}$$

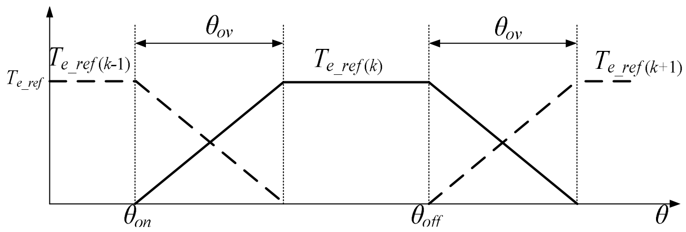


Fig. 10. Linear TSF

The torque ripples and RMS current are expressed as (2) and (3), respectively.

$$I_{rms} = \sqrt{\frac{1}{\theta_p}\left(\int_{\theta_{on}}^{\theta_{off}} i_k^2 d\theta + \int_{\theta_{on}}^{\theta_{off}} i_{k-1}^2 d\theta\right)} \tag{2}$$

$$T_{rip} = \frac{T_{\max} - T_{\min}}{T_{av}} \tag{3}$$

where T_{av}, T_{max}, and T_{min} are the average torque, maximum torque, and minimum torque, respectively.

The comparison of torque ripples, the average torque, and RMS current of the power converters is shown in Fig. 11, Fig. 12, and Fig. 13, respectively. As shown in Fig. 11, C-dump converter shows the lowest torque ripples up to 6000rpm due to higher demagnetization voltage. Since split AC and asymmetric power converters have the same magnetization/demagnetization voltage, they have the same torque ripples, average torque and RMS current. Split AC has the same VA rating, switching losses, and lower conduction losses compared with asymmetric converter and, therefore, split AC power converter is preferred in terms of efficiency. The phase current is not independently controlled in N+1 power electronic converter, leading to 200% torque ripples and much lower average torque at higher speed. Although N+1 converter has the same VA rating, conduction loss and switching loss as asymmetric power converter, N+1 power electronic converter is worse in terms of torque speed performance. N+1 converter is not recommended for this reason. Split DC converter produces around one fifth of average torque of split DC and C dump converters at 6000rpm with one half of VA rating, conduction loss and switching loss. Therefore, split AC converter and C-dump converter are the possible candidates for low-cost and high-performance SRM drives. They have similar RMS current and average torque up to 6000rpm. However, split AC converter shows almost twice torque ripples over the wide speed range with one half of VA rating and switching losses compared with the C-dump converter. In conclusion, split AC converter is a better candidate in low-cost SRM drives, while C-dump converter is more promising in high performance motor drives.

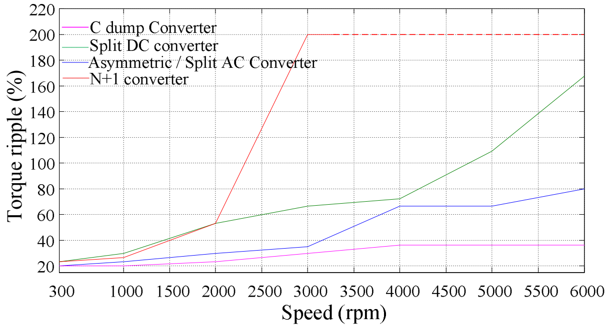


Fig. 11.Comparison of torque ripples.

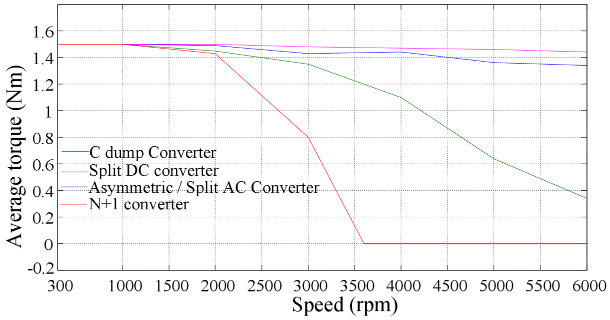


Fig. 12. Comparison of average torque.

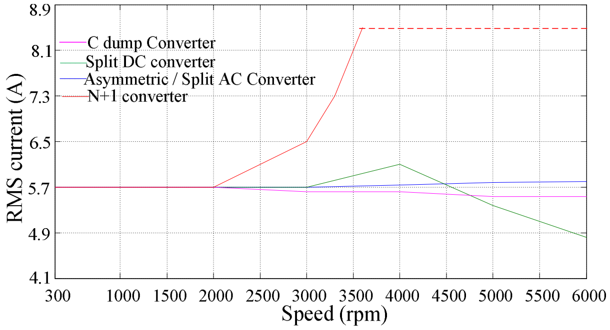


Fig. 13. Comparision of RMS current.

IV. CONCLUSION

In this paper, a comparative evaluation of five power electronic converters including asymmetric, N+1, split AC, split DC, and C-dump converters is presented for three-phase SRMs. The evaluation is based on VA rating, conduction loss, switching losses, torque ripples, average torque, and RMS current. Among five listed power electronic converters, split AC and C-dump converters are promising candidates in terms of efficiency and torque-speed performance. C-dump converter has much lower torque ripples over a wide speed range. However, it has higher VA rating and additional inductor and capacitor. Therefore, C-dump converter is recommended in high-performance SRM drives. Split AC converter has relatively lower cost and good performance over a wide speed range, which is recommended in low-cost applications.

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