Comparative Evaluation of Power Converters for 6/4 and 6/10 Switched Reluctance Machines

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***Abstract*—Switched reluctance machine (SRM) emerges as a promising solution in automotive applications due to its rugged structure and wide extended constant power speed range. Compared to 6/4 SRM, 6/10 SRM has a higher static torque capability with lower torque ripples. The design parameters of the power converters of these two machines are not the same because 6/10 SRM has a different inductance profile and a higher number of strokes. This paper presents a performance comparison for 6/10 and 6/4 SRMs driven by an asymmetric bridge converter and N+1 switch converter, respectively. Performance parameters are based on the current ratings of the devices and switching frequency of the current control algorithm.**

I. INTRODUCTION

Switched reluctance machine (SRM) is gaining interest in electrified powertrain applications due to its simple and rugged structure, four-quadrant operation, and wide extended constant power speed range [1]. SRM is promising as a reliable and cost effective solution in harsh environments due to the lack of windings or permanent magnets on the rotor. However, SRM suffers from high torque ripple, acoustic noise, and vibration [1]. 6/10 SRM based on a novel pole design (PD) formula offers a better static torque capability and, due to the higher number strokes, it produces higher torque per unit volume with lower torque ripples as compared to a conventional 6/4 SRM with a similar power rating and volume [2]-[4]. Since these two machines have different inductance profiles and number of strokes, design of power converter for 6/10 SRM may differ from that of 6/4 SRM in terms of current ratings and switching frequency.

There are many types of power converters for SRM drives, and, among them, the asymmetric bridge converter is the most popular one (Fig. 1). It is capable of independent phase control and, hence, reducing the torque ripple during commutation. There are two modes in asymmetric bridge converter: hard switching mode and soft switching mode. Widespread use of asymmetric bridge converters in low cost SRM drives is limited due to the requirement of two switches and two diodes per phase. Other reduced-switched converters such as N+1 switch converter, split DC converter and split AC converter are attractive candidates in low cost SRM drives [5]-[6]. Split AC converter and DC converter are only available for SRMs with even phases. The circuit diagram of N+1 switch converter is shown in Fig. 2, where N denotes the number of phases. For a three-phase machine, it includes four switches and four diodes in total. Hard and soft switching modes are also available in this converter. One switch is shared by the three phases and, therefore, the phases are not totally independent. A drawback of this converter is that only zero voltage can be applied during commutation, which results in higher torque ripples.

This paper presents a comparative evaluation of converter requirements for 6/10 and 6/4 SRMs driven by asymmetric bridge converter and N+1 switch converter, respectively. Parameters including the device current ratings and switching frequency of the current hysteresis control algorithm are evaluated in different conditions. The models of both machines are implemented using the inductance and torque profiles from the finite element simulations of 6/4 and 6/10 SRMs [2].

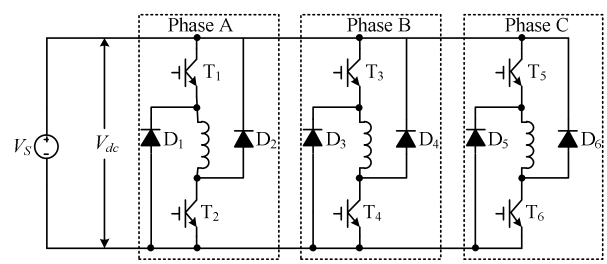

Fig. 1. Asymmetric bridge converter.

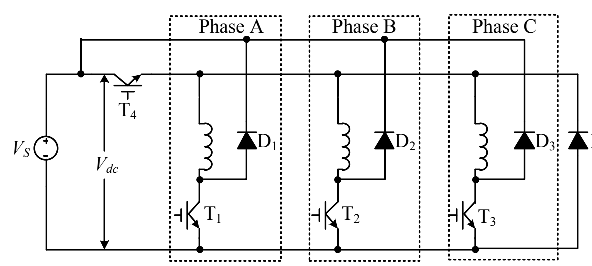

Fig. 2. N+1 switch converter.

II. FUNDAMENTALS OF SRM

Switched reluctance machine has salient pole construction both in its rotor and stator. Therefore, the airgap between the rotor and stator poles and, hence, the phase inductance varies with rotor position. When a phase is energized, the rotor pole

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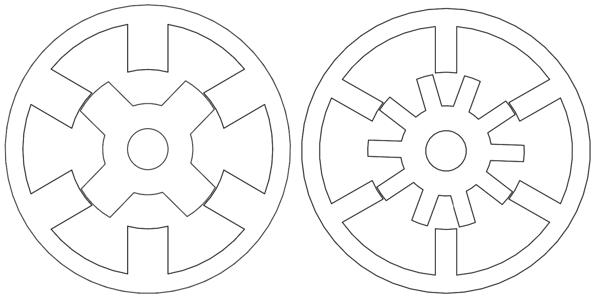
is pulled towards the stator pole to reduce the reluctance in the magnetic circuit.



(a) 6/4 SRM (b) 6/10 SRM

Fig. 3. Cross Section View of 6/4 and 6/10 SRMs.

The equivalent circuit of SRM is very similar to that of series excited DC machine [4]. However, since SRM has single source of excitation, both the inductance and back-emf profiles are nonlinear functions of rotor position and excitation current.

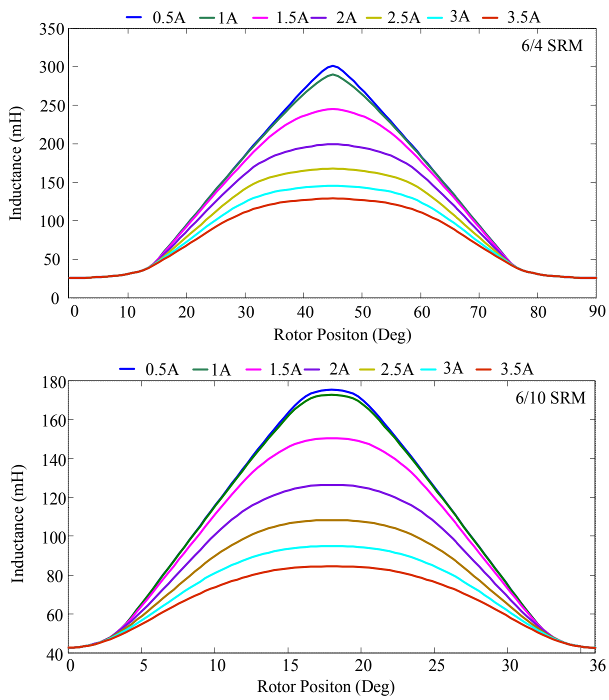


Fig. 4. The FEA inductance profiles of 6/4 and 6/10 SRMs.

Neglecting the mutual inductance, phase terminal voltage equation of SRM can be obtained as:

$$v = Ri + L(\theta,i)\frac{di}{dt} + \frac{dL(\theta,i)}{d\theta}\omega_m i \tag{1}$$

where i is phase current; R is resistance; θ is the rotor position, $L(\theta, i)$ is incremental phase inductance; ω_m is the angular speed.

Instantaneous electromagnetic torque of k^{th} phase can be represented as:

$$T_{ek}(\theta,i) = \frac{1}{2}\frac{\partial L(\theta,i_k)}{\partial\theta} i_k^2. \tag{2}$$

The equation for mechanical dynamics is expressed as:

$$T_e = \sum_{k=1}^{N} T_{ek} = T_L + B\omega_m + J\frac{d\omega_m}{dt} \tag{3}$$

where T_e is the total electromagetic torque generated by SRM; T_L is the load torque; B is the friction constant; J is the inertia of the machine.

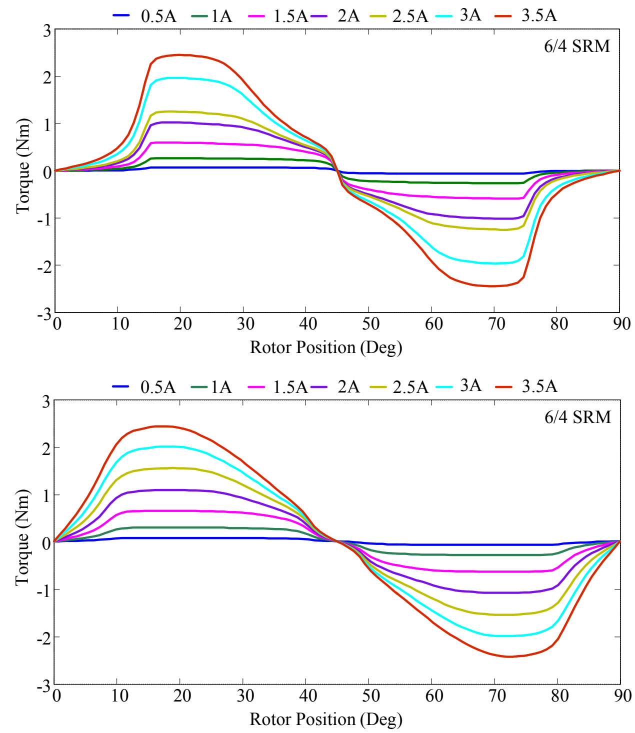


Fig. 5. The FEA torque profiles of 6/4 and 6/10 SRMs.

Fig. 3 shows the cross section view of the three phase 6/4 and 6/10 SRMs, respectively. Conventional SRM configurations have higher number of stator poles than the number of rotor poles, as shown in Fig. 3(a). Using PD formula, several new SRM configurations can be created where the number of rotor poles is higher than the number of stator poles as shown in Fig. 3(b). 6/4 SRM and 6/10 SRM given in Fig. 3 are designed to have the same airgap length, stator and rotor outer diameters, method of cooling, and stack length based on the same power ratings [2]. It can be observed that the width of the poles and the unaligned position is smaller in 6/10 SRM. This results in a higher unaligned and lower aligned inductance as shown in Fig. 4. However, due to higher number of strokes, and hence, a higher rate of change of inductance in one stroke, its torque profile is similar to 6/4 SRM as shown in Fig. 5 [2].

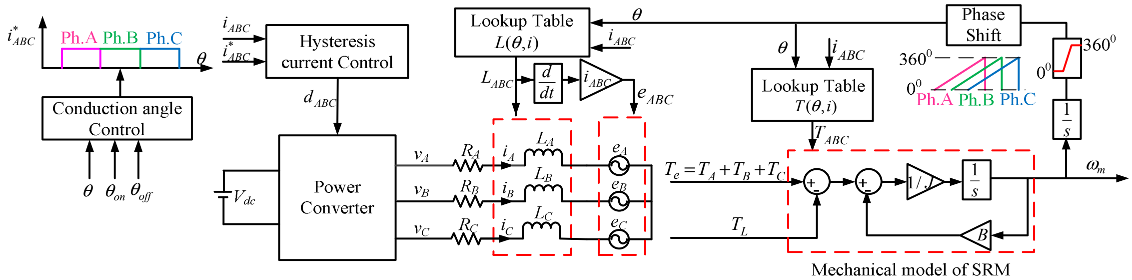


Fig. 7. Block diagram of the simulation model of switched reluctance machine.

RMS values of switches and diodes in an SRM converter can be represented as:

$$I_{T_n} = \sqrt{\frac{1}{\theta_{rp}} \int_0^{\theta_{rp}} i_{T_n}^2 d\theta} ; I_{D_n} = \sqrt{\frac{1}{\theta_{rp}} \int_0^{\theta_{rp}} i_{D_n}^2 d\theta} ; \theta_{rp} = \frac{2\pi}{P_r} \tag{4}$$

where I_{Tn} and I_{Dn} are RMS currents of switch T_n and diode D_n; i_{Tn} and i_{Dn} are the instantenous currents of switch T_n and diode D_n; θ_{rp} is the rotor pitch; P_r is the number of rotor poles.

III. Comparision of Design Parameters of Power Converters for 6/4 and 6/10 SRMs

In a 6/10 SRM, the pole pitch angle, which shows the mechanical angle covered by each stoke, is lower due to the higher number of strokes. In another meaning, in every 36^0 of the mechanical rotor position, inductance profile repeats itself for each phase. Therefore, since there are 3 phases, the inductance profile repeats 30 times in one revolution of the rotor as shown in Fig. 6a. In 6/4 SRM, due to lower number of rotor poles, each stroke ends in 90^0 and this results in 12 strokes in one revolution as shown in Fig. 6b.

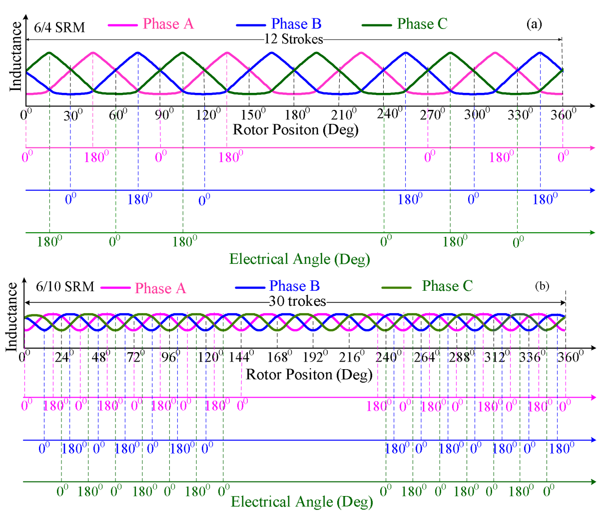


Fig. 6. Conduction angles for 6/4 and 6/10 SRMs in one revolution.

Therefore, the fundamental frequency in 6/10 SRM is 2.5 times faster than in 6/4 SRM, due to the higher number of strokes and this requires a faster phase commutation. 6/10 and 6/4 SRMs have different inductance profiles and phase commutation intervals, but similar torque profiles. Therefore, this might cause differences in the performance of the converter for 6/10 and 6/4 SRM drives. Due to faster phase commutation, the switching frequency of the hysteresis control algorithm of 6/4 and 6/10 SRM may be different and needs to be compared. For this purpose, simulation models of 6/10 and 6/4 SRMs have been developed in MATLAB/Simulink environment using (1) and RMS values of the currents of power electronic converters are evaluated, to identify the effect of the difference in inductance profiles on the converter performance. The same hysteresis current control algorithm is applied in both drive models. In order to get more accurate solutions, torque and inductance profiles from finite element simulations of these two machines have been implemented as look-up tables. The block diagram of the simulation model is shown in Fig. 7.

A. Comparison with the asymmetric bridge converter

In the simulation, asymmetric bridge converter works in hard switching mode. The mechanical turn on angle θ_{on} and the turn off angle θ_{off} are 3^0 and 15^0 for 6/10 SRM, and 7^0 and 37^0 for 6/4 SRM, respectively. The hysteresis band is set to be 0.5 A.

(1) Constant excitation current:

Fig. 8 and Fig. 9 show the waveforms of phase current and converter device current for 6/10 and 6/4 SRM respectively with a constant excitation current of 3A. Comparative results of design parameters are shown in Table. 1. There are slight differences in RMS current between 6/10 and 6/4 SRMs. Switching frequency of 6/4 SRM is slightly higher than that of 6/10 SRM, due to the different torque and inductance profiles. Also, this is valid for all simulations considering that the fundamental frequency of 6/10 SRM is 2.5 times faster than 6/4 SRM. It should be noted that, both figures show only three strokes and, hence, the ranges of the rotor position axes are different. Therefore, the current waveform in Fig. 8 for 6/10 SRM is naturally a closer view.

Table 1. Comparison of design parameters of converter using the same current ratings.

Parameters	6/10 SRM	6/4 SRM
RMS of phase Current (A)	1.738	1.753
RMS of switches T_{1-2} current (A)	1.326	1.32
RMS of diodes D_{1-2} current (A)	1.15	1.172
Maximum switching frequency (Hz)	4000	8000
Average switching frequency (Hz)	3000	3667

(2) Closed loop constant speed operation with same controller dynamics:

The performance of the converters has been evaluated also for the same shaft speed. For this purpose a closed-loop speed control model is created with an average torque control. For constant turn-on and turn-off angles, the phase excitation current is adjusted according to the speed error. Fig. 10 and Fig. 11 shows the current, torque and speed waveforms of closed-loop controlled 6/4 and 6/10 SRM respectively for same controller dynamics and speed reference. Both the current level and electromagnetic torque in the transients is larger than that in steady state due to saturation of PI controllers. To reduce the effect of saturation of PI controller, parameters of PI controller can be decreased, which will be done in closed loop constant speed operation with same trasient response time.The results for the transients and steady responses are also listed in Table 2.

Response time of 6/10 SRM is 0.18s, which is faster than 6/4 SRM (0.225s). Due to the smaller torque pulsation, RMS current of power converter during steady response for 6/10 SRM are lower than that of 6/4 SRM. The average switching frequency of hysteresis control algorithm in 6/4 SRM is slightly higher than in 6/10 SRM.

(3) Closed loop constant speed operation with same transient response time:

It can be observed from Fig. 10 and Fig. 11 that, due to difference in inductance profiles and torque ripples, 6/10 and 6/4 SRMs have different response times with the same controller dynamics. Therefore, the parameters of controller have been adjusted to get similar transient response in both machines for the same speed reference as shown in Fig. 12 and Fig. 13. The response time for 6/10 and 6/4 SRM are both 0.28s. Table 3 summarizes the results of transients and steady response of both machines. RMS current of power converter during steady response for 6/10 SRM is lower than that of 6/4 SRM considering the same speed response, due to lower torque ripples of 6/10 SRM.

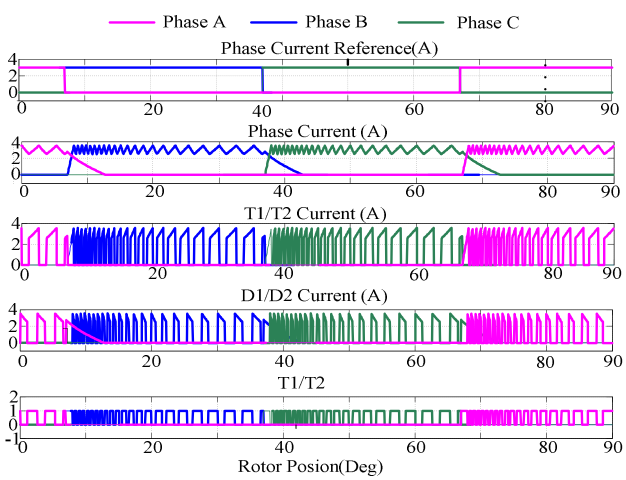


Fig. 8. Simulation results of 6/4 SRM for the constant current excitation with asymmetric bridge converter.

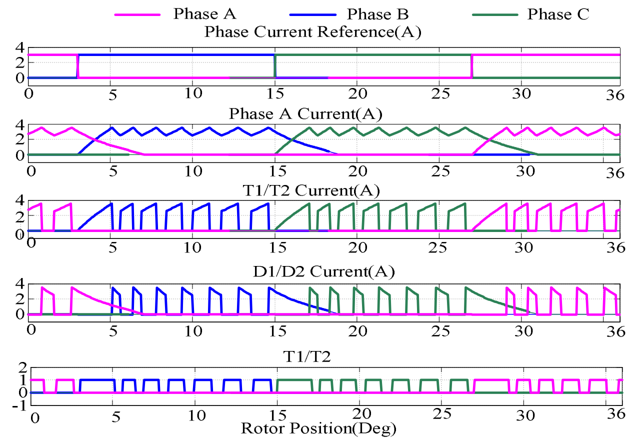


Fig. 9. Simulation results of 6/10 SRM for the constant current excitation with asymmetric bridge converter.

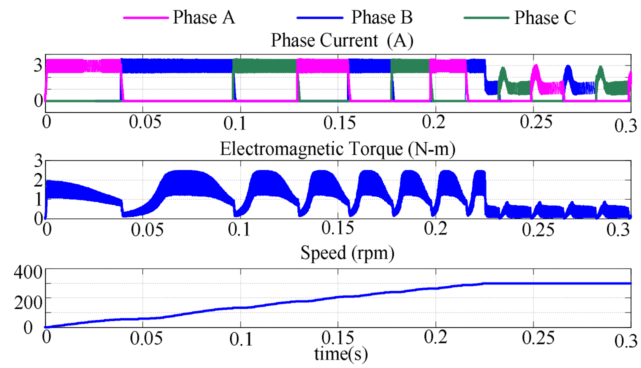


Fig. 10. Simulation results of 6/4 SRM for the constant speed operation with same controller dynamics with asymmetric bridge converter.

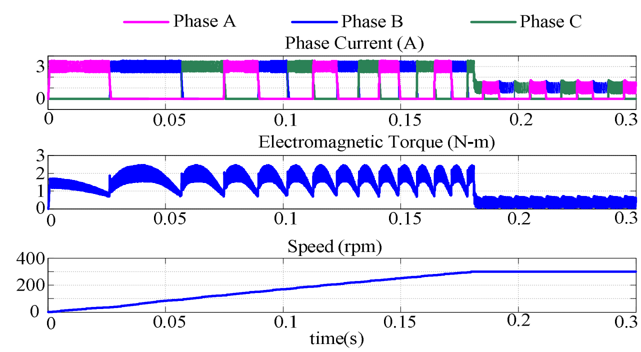


Fig. 11. Simulation results of 6/10 SRM for the constant speed operation with same controller dynamics with asymmetric bridge converter.

Table 2. Comparison of design parameters of converter using the same speed reference.

Parameters	6/10 SRM		6/4 SRM	
	Transient	Steady state	Transient	Steady state
RMS phase current (A)	1.74	0.626	1.74	0.838
RMS current of switches $T_{1\text{-}2}$ (A)	1.27	0.468	1.27	0.62
RMS current of diodes $D_{1\text{-}2}$ (A)	1.2	0.438	1.22	0.558
Average switching frequency (Hz)	Variable	2615	Variable	3055

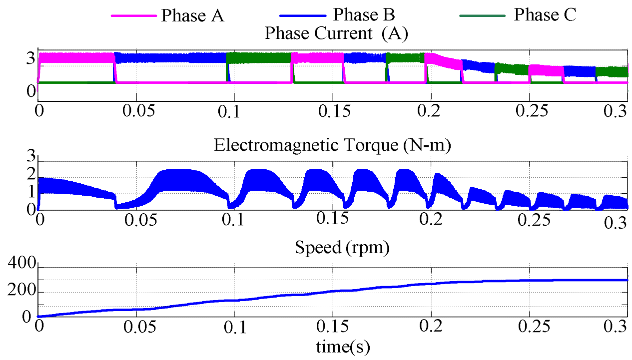


Fig. 12. Simulation results of 6/4 SRM for the constant speed operation with same transient response time with asymmetric bridge converter.

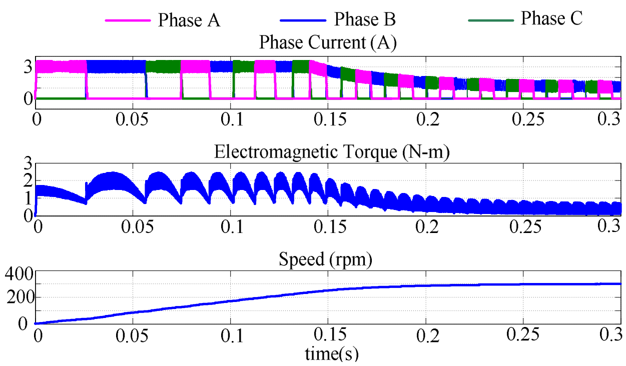


Fig. 13. Simulation results of 6/10 SRM for the constant speed operation with same transient response time with asymmetric bridge converter.

B. *Comparisons with the N+1 switch converter*

Similar to asymmetric bridge converter, comparative evaluations have been conducted in N+1 switch converter working in hard switching mode. For further comparisons with asymmetric bridge converter, the mechanical turn on angle θ_{on} and the turn off angle θ_{off} are also 3^0 and 15^0 for 6/10 SRM, and 7^0 and 37^0 for 6/4 SRM, respectively. The hysteresis band is set to be 0.5 A.

Table 3. Comparison of design parameters of converter considering the same transient response.

Parameters	6/10 SRM		6/4 SRM	
	Transient	Steady state	Transient	Steady state
RMS of phase current (A)	1.74	0.65	1.74	0.74
RMS of switches T_{1-2} current (A)	1.27	0.488	1.27	0.548
RMS of diodes D_{1-2} current (A)	1.2	0.456	1.22	0.517
Average switching frequency (Hz)	Variable	2615	Variable	3438

(1) Constant excitation current:

Fig. 14 and Fig. 15 show the waveforms of phase current and power device current for 6/10 and 6/4 SRM, respectively with a constant excitation current of 3A. Comparative results of design parameters are shown in Table 4. There are slight differences in RMS current between 6/10 and 6/4 SRMs. Switching frequency of 6/4 SRM is slightly higher than that of 6/10 SRM, due to the different torque and inductance profiles.

Table 4. Comparison of design parameters of converter using the same current ratings.

Parameters	6/10 SRM	6/4 SRM
RMS of phase current (A)	1.974	1.806
RMS of switch T_4 current (A)	2.32	2.77
RMS of diode D_4 current (A)	2.575	2.42
RMS of switch T_1 current (A)	1.326	1.325
RMS of diode D_1 current (A)	1.428	1.79
Maximum switching frequency (Hz)	4000	8000
Average switching frequency (Hz)	3000	3667

Also, note that due to slower commutation, the waveforms of the phase current in N+1 switch converter varies from that in asymmetric bridge converter. This results in the different device current ratings as listed in Table 4. However, slower commutation does not influence the average switching frequency of the hysteresis control algorithm and, thus, the switching frequencies of asymmetric bridge converter and N+1 switch converter are the same. Further, T_4 and D_4 are shared switches and diodes for three phase currents and thus have much higher current ratings than other switches and diodes.

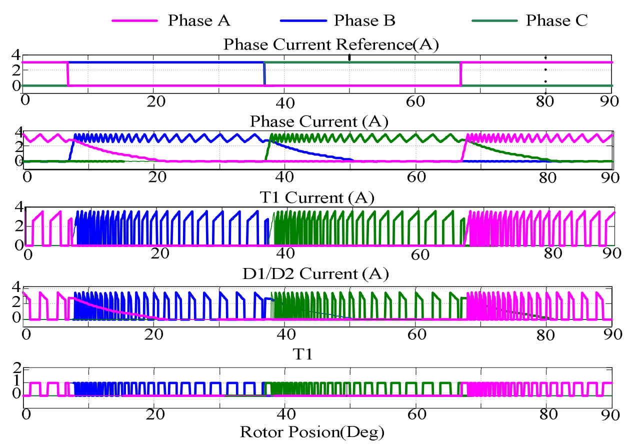


Fig. 14. Simulation results of 6/4 SRM for the constant current excitation with N+1 converter.

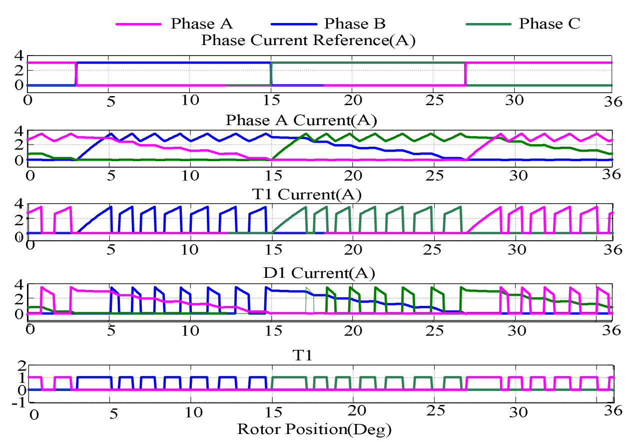


Fig. 15. Simulation results of 6/10 SRM for the constant current excitation with N+1 converter.

(2) Closed loop constant speed operation with same transient response time:

It can be observed from Fig. 16 and Fig. 17 that, due to difference in inductance profiles and torque ripples, 6/10 and 6/4 SRMs have different response times with the same controller dynamics. The response time for 6/10 and 6/4 SRM are both 0.28s. Table 5 summarizes the results of transients and steady-response of both machines. RMS current of power converter during steady response for 6/10 SRM is lower than that of 6/4 SRM considering the same speed response. Since shared Switch T_4 conducts three phase currents, it has much higher current rating than other switches.

Table 5. Comparison of design parameters of converter considering the same transient response.

Parameters	6/10 SRM		6/4 SRM	
	Transients	Steady Response	Transients	Steady Response
RMS of phase current (A)	1.79	0.627	1.75	0.717
RMS of switch T_4 current (A)	2.5	0.86	2.24	0.95
RMS of diode D_4 current (A)	2.16	0.72	2.12	0.85
RMS of switch T_1 current(A)	1.27	0.464	1.245	0.52
RMS of diode D_1 current (A)	1.27	0.45	1.25	0.515
Average switching frequency (Hz)	Variable	2615	Variable	3438

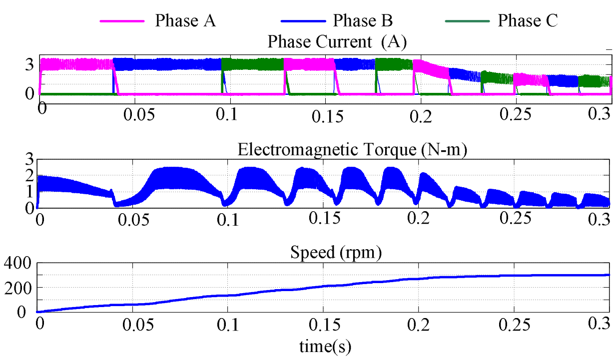


Fig. 16. Simulaton results of 6/4 SRM for the constant speed operation with same transient response time with N+1 converter.

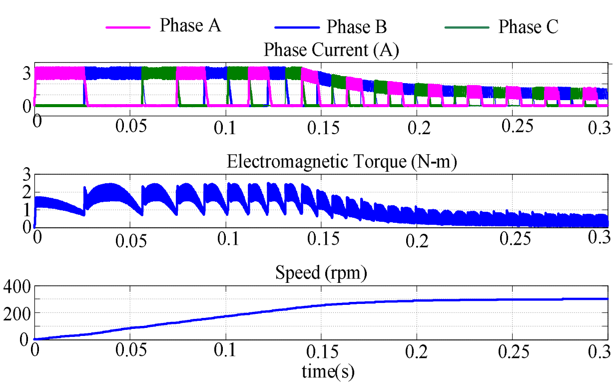


Fig. 17. Simulation results of 6/10 SRM for the constant speed operation with same transient response time with N+1 converter.

IV. Conclusion

The performance of asymmetric bridge converter and N+1 switch converter for 6/10 SRM and 6/4 SRM are compared in this paper. Design parameters including the current ratings and switching frequency for 6/10 SRM differ from that of 6/4 SRM due to the difference in their inductance and torque profiles. For a proper evaluation, dynamic models of the machines have been implemented where inductance and torque profiles from FEA analysis have been used as look-up tables. Using the same hysteresis control algorithm, the phase commutation frequency in 6/10 SRM is still 2.5 times faster than 6/4 SRM for the same speed. However, it has been shown that the average switching frequency of 6/4 SRM in one stroke is slightly higher than that of 6/10 SRM in asymmetric bridge converter and N+1 switch converter. This is mainly because of the difference in their inductance profiles.

For the same shaft speed with the same controller parameters, it has been observed that 6/10 SRM has slightly shorter response time and lower RMS current at steady-state in both asymmetric bridge converter. This is because of the lower torque ripples due to higher rate of change of inductance profile. Considering the same speed transient response, RMS current of the power converter during the steady response for 6/10 SRM is still lower than that of 6/4 SRM in both asymmetric bridge converter and N+1 switch converter. For comparisons of design parameters between asymmetric bridge converter and N+1 switch converter, there are slight differences in the RMS current of the diodes and switches, due to the longer commutation. The switching frequency of the hysteresis control algorithm of N+1 switch converter is nearly the same as that of asymmetric bridge converter due to the same inductor profiles during operation.

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