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Torque ripple, vibrations, and acoustic noise in switched reluctance motors

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Abstract

The paper presents a state of the art review on the subject of torque ripple, vibrations, and acoustic noise in Switched Reluctance Motors (SRM). The approach of the multi-phase operation of SRM is also reviewed. Moreover, further directions of research on these subjects are introduced.

Keywords: Switched reluctance machines, torque ripple, vibrations and acoustic noise

1 Introduction

The Switched Reluctance Motor (SRM) is known as a principle of operation for more than a century, under a more general name of Doubly Salient Variable-Reluctance Motor. However, an intensive research on SRM began about twenty years ago, mainly due to the progress in power electronics and microprocessors [1-9]. Its principal advantages are simple and robust construction, possibility to work at very high rotation speeds, high mechanical torque at low speeds, and simple power electronics driver. SRM principal disadvantages are cumbersome control, relatively high torque ripple, mechanical vibrations, and acoustic noise.

There is plenty of literature on SRM, including torque ripple [10-16], and vibrations and acoustic noise [17-26].

The paper presents a short state of the art concerning methods to mitigate the effects of torque ripple, vibrations, and acoustic noise. It seems that the torque ripple effects are separated and disconnected from the vibration and acoustic noise effects. Therefore, the mitigation of the torque ripple effects does not include, produce, or conduct to a mitigation of the SRM vibrations and acoustic noise. As a result, one should use different approaches and methods to mitigate each one of them separately (Sect. 2 and 3). However, it obviously seems that the vibrations and acoustic noise are interconnected and mitigation of vibrations would also result in acoustic noise mitigation.

A special approach that could produce both torque ripple and mechanical vibrations and noise mitigation could consist of multi-phase excitation of SRM (Sect. 4).

2 Torque ripple

The conventional way to operate a SRM consists in supplying unidirectional current pulses sequentially to each of the SRM phase coils. The current pulse could be controlled by its amplitude and on and off timing. The current pulse form depends largely on the SRM speed, i.e., the voltage drop equivalent to a back electromagnetic force (back emf). Due to its special construction, i.e., the lack of a clear magnetic excitation current and nearly zero mutual inductance between the SRM phases, the equivalent back emf is due to the change of the self-inductance of the excited phase, during the rotor movement. At low and intermediate rotor speeds, due to a low back emf, the source voltage is sufficient to impose a rather rectangular current pulse though the excited phase coil. At high speeds, the back emf becomes quite large. As a result, the current pulse is no longer rectangular but becomes rather triangular.

The mechanical torque on the rotor is due to the force exerted by the excited phase of the stator on the rotor salient poles. This force and, as a result, also the mechanical torque, as average, depend on the number of stator and rotor salient poles, their geometrical dimensions, the number of stator phases, and also the phase current intensity and on/off timing. The instantaneous profile of the torque also depends on these parameters. The instantaneous profile of the torque would determine the torque ripple characteristic of the SRM.

Generally, the demand for a high average torque is contradictory to the demand for a low torque ripple. It seems that any approach producing a lower torque ripple would produce also a lower average torque and vice versa, any approach intended to produce a larger average torque would produce also a higher torque ripple.

It seems that the highest average torque (produced by a commonly used SRM) could be produced by a SRM with three phases, six stator poles, and four rotor poles. This SRM could have the largest ratio between the aligned and unaligned phase inductances. This is due to a large angle between the stator as well as rotor poles. However, these geometrical characteristics are also responsible for the very large torque ripple present with a 6/4 SRM.

The torque ripple could be reduced by using a SRM with more than three phases and more than 6 stator/4 rotor poles. However, again, the average torque would also be lower.

It seems that the torque ripple could also be reduced by rather cumbersome control methods. These control methods are generally presented without any comparison between them. Furthermore, it seems that their effect on the average moment is also not evaluated. The SRM is quite cumbersome to control due to its double salience and also its inherent strong magnetic nonlinearity [10,11].

Reference [12] presents a review of control methods used to mitigate the torque ripple in a SRM. One of the worthy methods that is being mentioned more and more often, is the Torque-Sharing Function Technique [12]. By this method, the subsequent phase in sequence is excited before the initially excited phase is turned off. In this way, there is a short period when two phases are simultaneously excited and both contribute to the SRM torque. It would be possible to use an internal-model control approach to get the suitable current forms [13].

Another technique for torque ripple mitigation consists in injecting suitable current harmonics supplementary to the phase excitation currents [12,15]. The compensation currents could be also provided by an off-line learning [14].

3 Vibrations and acoustic noise

It seems that the main reason of the acoustic noise in SRM is the mechanical vibrations of the SRM stator [17-24]. Therefore, any reduction in the SRM vibration level would produce also a reduction in the SRM acoustic noise level. The SRM vibrations are due to the current pulses through the phase coils of the SRM. These current pulses excite mechanical force pulses on the SRM stator core and frame. The frequency spectrum of the force pulses is quite large and could contain natural resonant mechanical frequencies of the SRM stator core and frame. As a result, a mechanical resonance is excited with large mechanical vibrations and acoustic noise. The force pulses are applied in the aligned position of the rotor salient poles versus the stator salient poles, when the magnetic radial forces between the stator and rotor are at maximum. The literature provides different approaches to the approximation of natural resonant frequencies of the SRM stator and frame [20,22,23]. However, it seems that their precise enough calculation could be performed only by rather cumbersome 3D Finite Element simulations of the SRM mechanical structure [21,24,25]. Furthermore, the natural resonance frequencies could be measured experimentally. The natural resonant frequencies are affected by general mechanical structures the SRM is found in, by mechanical load type, by mechanical joints and the SRM frame. As a result, it could be that the experimental evaluation would be the optimal method to find the SRM natural resonance frequencies.

Here, again, it seems that any approach to reduce the SRM mechanical vibrations would produce also a decrease in the SRM average torque.

The methods used to mitigate the vibrations and acoustic noise in electrical machines could be of worth also for SRM [26,27]. Furthermore, several methods were developed especially for SRM. One of them proposes to spread the spectrum of the acoustic noise excitation by introducing dither into the turn-on and turn-off angles used to control the SRM [17]. Another method proposes to cancel the SRM vibrations by applying an excitation force in anti-phase with the vibration waves [18].

4 Multi-phase excitation of switched reluctance motors

4.1 Introduction

The conventional operation of Switched Reluctance Motors (SRM) consists in sequential excitation of each one of the SRM phases separately, one after another [28,29]. The principal advantage is the simple construction of the power electronics driver and the low number of transistors. The minimum number of transistors could be the number of phases, e.g., a three-phase 6/4 SRM could be excited by only three transistors. This is half the number of transistors found in the power electronics driver of an induction motor or a permanent magnet brushless motor.

The only one phase operation at each moment is also advantageous regarding the control of the SRM. SRM is a nonlinear system due to magnetic saturation of the iron core (especially the stator and rotor teeth) during its operation. Furthermore, SRM is built with a double salience and phase coils are concentrated on the stator teeth. The only one simultaneous phase operation enables to manage the SRM magnetic nonlinearity and double salience.

However, the only one phase operation seems to be disadvantageous regarding the SRM torque ripple and vibrations and acoustic noise.

Due to the magnetic nonlinearity and double salience, the mechanical torque the SRM produces is not constant at a one phase constant current excitation. The torque has a smaller value at the beginning and the end of the current pulse. Therefore, the total torque would be composed of sequential torque pulses produced by each phase alone. This type of operation is responsible for the quite large torque ripple in the SRM torque.

Furthermore, the only one phase operation each time is responsible for a quite large magnetic stress on the stator poles of the excited phase. Moreover, the excitation current has a pulse waveform with abrupt going-up and going-down fronts. As a result, undesired quite strong mechanical vibrations and acoustic noise are excited.

The following section will present the state of the art about the multiphase operation of SRM.

4.2 SRM multi-phase operation (state of the art)

Some sort of multi-phase operation could be seen when the sequential phase is commutated on before the previous phase was commutated off. A true SRM multi-phase operation is reported by Mecrow [30,31]. The conventional SRM has the phase coils as concentrated coils winded around those of the stator teeth. Therefore, the conventional SRM could be seen as a short-pitch coil motor. The SRM proposed by Mecrow, is a full-pitched coil motor. The phase coils are winded around a full stator pole. Mecrow refers to a 6/4 three-phase SRM. However, this configuration could be also applied to other SRM, e.g., 8/6 four-phase SRM. Furthermore, an 8/6 four-phase SRM could be winded with partial-pitched coils [31]. The advantage of a full-pitched SRM, according to the literature, is an increase in SRM torque of 30-90%, depending on the load conditions and excitation sequence. The disadvantages of a full-pitch configuration are more complex power electronics driver with more transistors and more cumbersome operation and control algorithms. The analysis of a SRM with full-pitched coils is described in literature [31-34]. They are based mainly on magnetic circuit models of the mutually coupled SRM [33,34].

A further configuration of multi-phase excitation of SRM is presented in [35]. Here, the phase coils are winded as short-pitch coils around each one of the stator teeth. However, the phase coils are winded in the reverse direction on opposite side poles. Therefore, despite the short-pitch coils, the SRM operation bases on both self-inductance variation and mutual inductance variation of the phase coils. The advantages of this configuration are torque ripple and noise reduction.

4.3 Critical view on SRM two-phase excitation

A two-phase excitation of the SRM was mentioned in the previous section [35]. The phase coils are winded in the reverse direction on opposite side poles [35]. As a result, the 6/4 SRM operates with four stator and four rotor poles each time, instead of two stator and two rotor poles in the conventional one-phase excitation SRM (note that the 6/4 SRM has three phases, six stator teeth or two poles per phase, and four rotor teeth or poles). Therefore, the SRM in this configuration becomes closer to a Synchronous Variable Reluctance Motor (SVRM) with two stator and two rotor pole pairs (four stator and four rotor poles) [36]. Furthermore, the operation and control algorithms of a SVRM could be applied to the SRM with the present two-phase excitation. However, the SRM operates with a much deeper magnetic saturation than the SVRM. Moreover, the SRM has concentrated coils winded around the stator teeth while the SVRM has distributed windings on its stator. As a result, the change of the self and mutual stator inductances versus the rotor rotation angle is also different.

4.4 Future research directions

It seems that it could be of worth to study the arrangement of the SRM with reverse direction coils. The two-phase excitation could be of use while the SRM is operated as an autonomous AC generator with double pumping. The arrangement of double pumping was proposed for a SVRM [37,38]. However, it was explained in Section 4.3 that the SRM with reverse coil directions could be seen as a SVRM. It was shown by simulations that the double pumping AC generator could convert 200-300% more power per volume/weight unit than a conventional AC generator [37,38]. Moreover, it was also shown in [37,38] that the SVRM would be operated with only two of its three phases excited each time, similar to the arrangement of [35]. It would be necessary to develop a more detailed model than the one presented in [35] for the nonlinear magnetic behavior of the Reverse Direction Coils SRM, including the phase self and mutual inductances, before simulations and real experiments would be performed.

It seems that the true three-phase operation of a SRM would also be of a great potential. It consists in simultaneous excitation of all three phases of the SRM. Its advantages could be a better utilization of the SRM, while more coils and iron yoke are used simultaneously, versus the conventional only one-phase one time operation of the SRM. Furthermore, the mechanical stress would be divided at each moment on more than two poles, resulting in less mechanical vibrations and acoustic noise. The disadvantages could be a more cumbersome three-phase power electronics driver and full-pitch coils with more copper and more electrical resistance. However, the three-phase driver becomes more and more common, being employed for most speed adjustable electric drive systems. Moreover, it seems that the same effect produced by full-pitch coils could be obtained by using common short-pitch coils, as found in conventional SRM [31]. The three-phase operation would be quite beneficial as the currents could contain less high harmonics, being even sinusoidal. This would reduce drastically the high harmonic content of the radial forces and, as a result, the mechanical vibrations and acoustic noise [39–41]. The spectrum of the radial acceleration would contain a dominant second harmonic of the sinusoidal SRM currents [41]. The reason is the change of the magnetic reluctance of the SRM due to the salient construction of its rotor [42].

5 Conclusions

The subject of torque ripple and especially the subject of vibrations and acoustic noise in SRM are very cumbersome and complex ones but also very exciting ones, especially due to their complexity. Their research and solutions involve mechanical, electrical, electronics, and control engineering. It seems that the torque ripple phenomena are different as source and mitigation solutions versus the vibration and acoustic phenomena. However, it could be that solutions that mitigate one of them would mitigate also the other.

It seems that it would be useful to continue the research on SRM torque ripple and vibrations and acoustic noise in the following directions:

a experimental work of measuring the vibration and acoustic noise spectrum during SRM operation;

b introducing genetic optimization methods in torque ripple mitigation, in connection with excitation current tailoring [43,44];

c introducing the SRM mutual-inductance approach, regarding the torque ripple and vibrations and acoustic noise;

d introducing the axial air-gap reluctance motor, regarding the torque ripple and vibrations and acoustic noise;

e introducing Soft Magnetic Composites, as an alternative for the SRM stator construction [45];

f introducing simulation methods to evaluate the SRM torque ripple and vibration and acoustic noise effects.

It seems that 'Multi-Phase Excitation of Switched Reluctance Motors', with a special accent on Three-Phase Operation, would be beneficial for torque ripple, vibrations, and acoustic noise mitigation. Plenty of work has to be performed regarding driver capabilities and requests, including generalized power factor, iron and copper losses, control approaches including 'true' vector control (magnetization and torque currents), direct torque control, and sensorless control, simulation methods, mechanical and electrical state variable observers, and optimization approaches.

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