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Design Considerations of Switched Reluctance Motors with Bipolar Excitation for Low Torque Ripple Applications

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Abstract—Switched reluctance motors (SRMs) have been applied to many applications over the past decades due to their simple structure, low cost, and robustness. The primary disadvantage of SRMs is the relatively high torque ripple. In this paper, the machine design is considered under a two-mode bipolar excitation to achieve the optimum performance of a mutually coupled switched reluctance motor (MCSRМ) for low torque ripple applications. Geometrical design equations and practical challenges are investigated. In addition, a six-slot, ten-pole (6/10) SRM with a six-phase winding configuration under the two-mode bipolar excitation is optimized by solving a multiobjective optimization problem using a quasi-Newton optimization method with considering the tradeoff between the torque ripple reduction and the efficiency improvement. The combination of the two-mode excitation scheme and corresponding optimal machine design effectively reduces the torque ripple without sacrificing the average torque produced by the MCSRМ. The design considerations are verified by the finite element method (FEM)-based simulation results.

Keywords—Finite element method (FEM); mutual coupling; switch reluctance motor (SRM); torque ripple reduction.

I. INTRODUCTION

Switched reluctance motors (SRMs) have considerable potential for industrial applications because of their high reliability, low manufacturing cost, mechanical robustness, and fault tolerance [1], [2]. However, a relatively high torque ripple is one of the primary disadvantages of SRMs due to their double salient pole structure. It is necessary to reduce the torque ripple to lower vibration and acoustic noise in low ripple/high performance applications, such as servomechanisms, electrical power steering, and precision tooling. The problem of reducing torque ripple in SRMs can be approached from two different perspectives: modification of motor geometry and implementation of control methods.

The modification of motor geometry mainly includes changes in stator and rotor design of SRMs. In [3]-[4], the effects of different magnetic circuit parameters of SRMs on torque ripple minimization, including major geometry dimensions, were investigated; and some practical geometry determination criteria for SRMs were provided for design consideration. In [5]-[6], air gap was optimized by shaping stator teeth and rotor teeth, respectively. Non-uniform air-gap

induced an asymmetric inductance profile, which was utilized for torque ripple reduction [6]. In summary, the modification of motor geometry is to modify magnetic flux path in SRMs.

Many studies have been performed on utilizing advanced electronic control techniques for torque ripple reduction in SRMs. Traditionally, phases of an SRM were excited independently and in sequence; and the rotor was forced to align with the excited phase to maintain rotation. Based on the traditional excitation scheme, some control schemes were implemented to optimize control parameters, including phase voltage, conduction angle, and phase current level [5]-[11]. This unipolar, single-phase excitation scheme used only a derivative of self-inductance of each phase without considering the mutual coupling effects between the phases. A mutually coupled switched reluctance motor (MCSRМ) with full-pitch winding and one with concentrated winding were introduced in [12]-[13], respectively, and the torque of an MRSRM was produced with bipolar excitation by the change of mutual inductance, as well as by the change of self-inductance. The magnetic characteristics and vibration analysis were reported in [14] and [15], respectively. Compared to the traditional single-phase excited SRM, the MCSRМ has higher power density but also lower torque ripple in high current density [14]. However, high torque ripple is still the issue that needs to be solved for some low torque ripple applications.

Both motor design and electronic control methods mentioned previously reduce torque ripple at the expense of a reduction in specific motor outputs [11]. Recently, a two-mode bipolar excitation scheme considering the shift angle was proposed for torque ripple reduction in [16]. It showed that the two-mode bipolar excitation scheme not only effectively reduces the torque ripple but also increases the average torque of the MCSRМ. In order to achieve optimal performance of the SRMs, the machine design and the control of the excitation currents should be considered together.

In this paper, design considerations for MCSRМs under the two-mode bipolar excitation scheme are investigated to improve torque performance. Due to the nonlinearity of SRMs, the co-energy profiles, instead of inductance profiles, of a six-slot, four-pole (6/4) SRM with a six-phase winding configuration are studied in this paper. Based on the study of

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co-energy profiles under different excitation modes of the two-mode bipolar excitation scheme, a shift angle between the co-energy profiles is taken into account for torque ripple reduction in the MCSRM. The torque performance of six-slot SRMs with difference rotor pole numbers under the two-mode bipolar excitation scheme is compared; and the geometrical dimensions of the machine for torque ripple reduction are investigated. Furthermore, the torque ripple and efficiency of a six-slot, ten-pole (6/10) SRM with a six-phase winding configuration under the two-mode bipolar excitation are optimized by solving a multiobjective optimization problem using a quasi-Newton optimization method. The combination of the two-mode excitation scheme and corresponding optimal machine design effectively reduces the torque ripple without sacrificing the average torque produced by the MCSRM. The design considerations are verified by the finite element method (FEM)-based simulation results.

II. TORQUE PRODUCTION AND TORQUE RIPPLE OF MCSRMS

For MCSRMs, mutual inductance plays a significant role in torque production. For example, for a six-slot MCSRM with the traditional three-phase concentrated winding configuration, the torque equation can be expressed as

$$T = \frac{1}{2} I_A^2 \frac{dL_A}{d\theta} + \frac{1}{2} I_B^2 \frac{dL_B}{d\theta} + \frac{1}{2} I_C^2 \frac{dL_C}{d\theta} + I_A I_B \frac{dM_{AB}}{d\theta} + I_A I_C \frac{dM_{AC}}{d\theta} + I_B I_C \frac{dM_{BC}}{d\theta} \quad (1)$$

where I , L , and M represent phase current, self-inductance, and mutual inductance, respectively. It should be noted that the use of inductance is strictly valid only under the condition that the magnetic circuit in the motor is linear. In practice, SRMs normally operate with their magnetic material near knee point and some areas highly saturated. If the machine goes into saturation, the torque should be calculated using co-energy $W_c(i, \theta)$ as

$$T = \frac{\partial W_c(i, \theta)}{\partial \theta} \quad (2)$$

The co-energy is defined as

$$W_c(i, \theta) = \int \lambda(i, \theta) di \quad (3)$$

where the flux linkage $\lambda(i, \theta)$ is a function of current i and position θ . The co-energy can be computed by the FEM.

In general, the sources of torque ripple in SRMs are a result of:

- Geometry of SRMs;
- Phase current waveforms;
- Electronic controller.

Geometrically induced torque ripple, the majority of torque ripple, is most significant at the torque dips where one phase

commutates to another. The distortion of phase current (e.g., caused by large back electromotive force (EMF) at high speed) can induce torque ripple because torque production is essentially proportional to the current squared. Harmonics induced by electronic controllers can further deteriorate the torque performance. The geometry factors are the focus of this paper. In this paper, the percentage of torque ripple is defined as

$$\Delta T_r = \frac{T_{max} - T_{min}}{T_{avg}} \times 100\% \quad (4)$$

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

III. TWO-MODE BIPOLAR EXCITATION METHOD FOR TORQUE RIPPLE REDUCTION

Compared with a traditional three-phase, 6/4 SRM with the coils wound around diametrically opposite poles connected in series for one phase, a 6/4 SRM is wound as a six-phase motor, as shown in Fig. 1. The six-phase winding configuration makes it possible to excite the windings on opposite poles separately. Fig. 2 shows two possible magnetic flux patterns in the six-phase SRM. In Fig. 2 (a), only one pair of phases on opposite poles is excited; and the resulting flux distribution is similar to that obtained under the traditional unipolar excitation. In Fig. 2 (b), two pairs of phases are excited; the torque is produced due to the rate of changes of both self-inductance and mutual inductance of the four excited phases. In the following, these two excitations are addressed as Mode I and Mode II.

In order to fully analyze the static magnetic characteristics of the SRM under these two excitation modes with considering nonlinearity, the co-energy profiles, instead of inductance profiles, shown in Fig. 3 are examined. The corresponding profiles of co-energy derivative are shown in Fig. 4. Based on (2), the profiles shown in Fig. 4 are also the profiles of torque produced in the SRM under the two excitation modes. From Fig. 3, it can be seen that the maximum value of co-energy under Mode I is at 45 mechanical degrees and the maximum value of co-energy under Mode II is at 60 mechanical degrees. The difference is 15 mechanical degrees or 60 electrical degrees for the 6/4 MCSRM. The difference can be defined as

Fig. 1. Six-phase winding configuration of a 6/4 SRM.

Fig. 2. The flux line distributions for the six-phase MCSRM under (a) with A1 and A2 excited and (b) with A1, A2, B1, and B2 excited.

a shift angle and the shift angle is solely determined by the motor geometry. Once the geometry of an SRM is determined, the shift angle can be expressed in terms of mechanical angle as

$$\theta_{shift} = \frac{360^\circ}{N_s N_r} \quad (5)$$

where N_s and N_r represent the numbers of stator and rotor poles, respectively. Taking the shift angle into consideration is the key for reducing torque ripple with the two-mode bipolar excitation scheme. The existence of the shift angle makes it possible for two excitation modes to be used in sequence to produce torque in SRMs. The two-mode bipolar excitation scheme in [16] includes these two excitation modes, namely Mode I and Mode II, as shown in Fig. 5. Under the excitation scheme, the two excitation modes are produced alternatively in the six-phase MCSRM, producing three more strokes compared with single-mode excitation schemes in a three-phase MCSRM to reduce the torque dips during commutation.

IV. DESIGN CONSIDERATIONS FOR MCSRMS

In this section, MCSRMs were specifically designed such that the motors operate with low torque ripple and high efficiency under the two-mode bipolar excitation discussed in Section III.

Fig. 3. The co-energy of the six-phase 6/4 MCSRM under Mode I and Mode II.

Fig. 4. The co-energy derivative of the six-phase 6/4 MCSRM under Mode I and Mode II.

Fig. 5. Two-mode bipolar excitation scheme for the six-phase MCSRM.

A. Selection of Pole Numbers

Much research has been conducted on SRMs with different combinations of pole numbers and various configurations have been tested to verify their capability for self-start and continuous torque production [1]. Traditionally, SRMs are designed with the combination of stator and rotor poles based on [3]

$$N_r = N_s \pm 2 \quad (6)$$

Recently, a pole design formula was developed for SRMs with higher numbers of rotor poles and expressed as [17]

$$N_r = 2N_s - 2 \quad (7)$$

It is difficult to present a general formula that satisfies all of the configurations. A more general review on the practical combinations of pole numbers of SRMs is provided in [1]. In this paper, the commonly used six-slot MCSRMs are examined, including a 6/4, 6/8, and 6/10 MCSRM.

The excitation scheme discussed in Section III was directly applied to the three six-slot SRMs with different numbers of rotor poles. The stator and rotor outer diameters, stack length, and air gap length of each machine were kept the same. In addition, the number of winding turns and phase current were kept the same. FEM-based simulation results were obtained using ANSYS Maxwell [18]. The comparison of the torque performance of the three SRMs under the bipolar excitation scheme is shown in Fig. 6. The torque ripple was about 143%, 63.8%, and 35.4% for the 6/4, 6/8, and 6/10 MCSRM, respectively. Because of the compensation on the torque dips, the average torque of the MCSRMs increases compared with that of the SRMs excited under the traditional unipolar, single-phase excitation. From Fig. 6, it is clear that there is a tradeoff between the average torque production and the torque ripple minimization. For low torque ripple applications, the 6/10 MCSRM is preferred under the two-mode excitation scheme. In the following sections, the 6/10 MCSRM is used as an example model for further optimization. Table I shows the 6/10 MCSRM initial design dimensions.

Fig. 6. Comparison of the torque produced in the 6/4, 6/8, and 6/10 MCSRM under the two-mode excitation scheme.

TABLE I. DESIGN DIMENSIONS OF PROTOTYPE 6/10 MCSRM

Design Parameter	Prototype
Outer diameter of stator	138 mm
Outer diameter of rotor	70 mm
Length of air gap	1 mm
Stator pole arc angle	22.6 degrees
Rotor pole arc angle	17.2 degrees
Stack length	145 mm
Number of turns per phase	65
Stator poles	6
Rotor poles	10

B. Stator and Rotor Arc Configurations

Traditionally, the stator and rotor pole arcs are set approximately the same to avoid zero torque zones centered on aligned positions. In this way, the effective torque zone, during which one phase produces positive torque, can be extended. For MCSRMs, the stroke is defined as [1]

$$S = N_p N_r \quad (8)$$

where N_p represents the number of phases in the MCSRM.

The stroke represents the number of commutations from one excitation mode to the other in one mechanical cycle for the two-mode bipolar excitation. The corresponding stroke angle is given by

$$\varepsilon = \frac{360^\circ}{S} = \frac{360^\circ}{N_p N_r} \quad (9)$$

in terms of mechanical angle. The ratio of a stroke to an electrical period of an MCSRM is calculated by

$$R = \frac{\varepsilon}{360^\circ / N_r} = \frac{1}{N_p} \quad (10)$$

Equation (9) shows that the stroke angle without advanced turn-on and turn-off is determined by the numbers of rotor poles and phases. For a six-slot, six-phase MCSRM, the stroke angle is 1/6 of its electrical period, and a 6° mechanical angle for the 6/10 MCSRM. The effective torque zone of a phase is required to be greater than the stroke angle; otherwise, a zero-torque zone will be induced.

Traditionally, a fully unaligned position was considered for a 6/10 SRM under unipolar excitation, because the overlap of the stator and rotor pole at the unaligned position induces a zero-torque region [19]. Under the two-mode bipolar excitation, it needs to be reconsidered. Fig. 7 compares the co-energy profiles of MCSRMs with a fully unaligned position and with an overlapped unaligned position under Mode I, and shows that the effective torque zone of one phase is reduced due to the existence of the overlapped pole design. However, under the two-mode bipolar excitation, the effective torque zone will be extended due to the existence of shift angle as shown in Fig. 8. For example, if the SRM is excited under a single-mode excitation, the effective torque zone is θ_4 - θ_2 for Mode-I-type excitation and θ_6 - θ_3 for Mode-II-type excitation; the effective torque zone is extended to be θ_6 - θ_2 for the two-mode excitation. In order to extend the effective torque zone, the MCSRM should be designed to have

$$\frac{1}{2}(\pi/N_r - \left| \frac{2\pi\beta_s}{N_s} - \frac{2\pi\beta_r}{N_r} \right| + \theta_{shift}) \geq \varepsilon \quad (11)$$

where β_s and β_r are stator and rotor pole arc, respectively, as shown in Fig. 9. Equation (11) explains that as long as the

effective torque zone extended with the shift angle is larger than the stroke angle, the two-mode bipolar excitation is useful to reduce torque ripple.

With a higher number of rotor poles, the rotor yoke h_{ry} should be large enough for the pole configurations. This constraint can be described as

$$\frac{2\pi}{N_r} \left(\frac{D_{sh}}{2} + h_{ry} \right) \geq \beta_r \left(\frac{D_{sh}}{2} + h_{ry} + h_{rp} \right) \quad (12)$$

Fig. 7. Comparison of linearized co-energy profiles of two 6/10 MCSRMs, with different stator and rotor pole arc angles, excited under Mode I.

Fig. 8. Illustration of the effective torque zone under single-mode excitation extended by two-mode excitation.

Fig. 9. Geometrical dimensions of the 6/10 SRM.

where D_{sh} is the rotor shaft diameter and h_{rp} is the rotor-pole height. This limit is significant for an MCSRM with a high number of rotor poles, since the space of each pole is relatively smaller. Once this constraint was satisfied, different combinations of stator and rotor pole arc angles were investigated to improve the average torque. The average torque can be estimated by co-energy change rate, which is defined as

$$\Delta W_c = \frac{W_{c_aligned} - W_{c_unaligned}}{\Delta \theta} \quad (13)$$

$\Delta \theta$ is an effective torque zone. The pole embrace is defined as the ratio of the pole arc to the pole pitch. The stator pole embrace was set as a constant value of 0.36 and the rotor pole embrace was varied from 0.2 to 0.48. Fig. 10 shows the relationship between the co-energy change rate and the rotor pole embrace under Mode I and Mode II, respectively. In this paper, an optimal rotor pole arc under the two-mode excitation was selected through multiobjective optimization which is discussed in Section V.

Fig. 10. The relationship between co-energy change rate and rotor pole embrace under Mode I and Mode II.

C. Winding Configurations and Stack Length

Compared with the traditional unipolar and bipolar excitations, the two-mode bipolar excitation needs longer commutation time due to the polarity change of phase currents during commutation. Fig. 11 shows the current waveforms of Phases A1 and A2 under the two-mode bipolar excitation with hysteresis control. For example, as shown in Fig. 11, the current of phase A1 increases from the negative maximum value to the positive maximum value during the commutation from Mode II to Mode I, which takes approximately twice the time required by the commutation under the traditional excitations. In practical operation, the current commutation time cannot be ignored, especially when an MCSRM is operated at a very high speed. The current changes during commutation further deteriorate the torque dip if it is not carefully controlled. The phase voltage equation can be described by

$$v = R \cdot i + \frac{d\lambda(i, \theta)}{dt} = R \cdot i + L(i, \theta) \cdot \frac{di}{dt} + i \cdot \omega \cdot \frac{dL(i, \theta)}{d\theta} \quad (14)$$

when neglecting mutual inductance between phases. From (14), the commutation time is dependent on the applied voltage, phase current, rotating speed and inductance. Therefore, the inductance can be used to decrease the commutation time. The inductance of winding can be calculated as

$$L = \frac{\mu N^2 A}{l} \quad (15)$$

where μ , A , and l represent the effective magnetic permeability, cross sectional area, and the length of flux path, respectively. Neglecting the nonlinearity due to the saturation of magnetic material, once the material and geometrical information is determined, under a certain excitation mode, the inductance is directly proportional to the number of winding turns at one position. It had been shown that the maximum current could be reduced by increasing the number of winding turns in [20]. Based on (15), increasing the number of winding turns would increase the inductance, which would result in a longer commutation time. However, the reduction of maximum current would decrease the commutation time. In order to investigate the effect of the number of winding turns on the commutation time, a practical drive system was coupled with the FEM-based simulation to evaluate the commutation time while the magnetomotive force Ni was kept constant. The relationship between the number of winding turns and commutation time is shown in Fig. 12. It shows that the commutation time increases as the number of winding turns increases. Therefore, in order to reduce the commutation time, lower number of winding turns is preferred in the design. In addition, [21] presented that lower number of winding turns with increased stack length could reduce saturation of the magnetic circuit. The saturation effect on torque ripple under the two-mode bipolar excitation will be discussed in future work.

In addition, the copper loss is directly proportional to the current squared and winding resistance per phase. The winding resistance per phase depends on the stack length and the number of winding turns when concentrated windings are used. In this paper, the maximum number of winding turns, which was used as one of design constraints in design optimization, can be determined by

$$N = N_h N_v \quad (16)$$

where N_h and N_v represent the number of horizontal layers and the maximum number of vertical layers allowed for the windings in the stator slots, respectively. They can be calculated from the unoccupied space between stator poles by [22]

$$N_h = \frac{\pi/N_s - 0.5\beta_s - 0.5Cl}{k_i d_w} \quad (17)$$

$$N_v = \frac{h_{sp}}{k_i d_w} \quad (18)$$

where Cl , k_i , and d_w represent clearance space between windings, insulation factor and the diameter of selected wire. Clearance space depends on different design requirements.

Fig. 11. Current waveforms of Phases A1 and A2 under two-mode bipolar excitation with hysteresis control.

Fig. 12. The relationship between the number of winding turns and commutation time ($\omega = 1000$ rpm).

V. TORQUE PERFORMANCE AND EFFICIENCY

In the previous section, various geometry dimensions were analyzed separately for design considerations to improve the torque performance of an MCSRM under two-mode bipolar excitation. In this section, the tradeoff between torque performance and efficiency of the 6/10 MCSRM is discussed by finding the best combination of the number of winding turns, stack length, rated current, and the stator and rotor pole arc angles. Many researchers focus on modifying the pole arc angle of SRMs to modify the inductance profile. In [21][23], the author demonstrated a method of optimizing the stator and rotor pole arcs to improve the average torque and reduce the torque ripple. However, the number of winding turns constrained by the available slot space was not considered. In this paper, the torque ripple and copper loss of the 6/10 MCSRM under the two-mode bipolar excitation were minimized by solving a multiobjective optimization problem, using a quasi-Newton optimization method [24]. Fig. 13 shows the flow diagram of the method implementation. The objective function $f(x)$ is defined as

TABLE II. RESULTS OF MULTI-OBJECTIVE OPTIMIZATION

w1	w2	Objective function	Stator pole arc (deg)	Rotor pole arc (deg)	Number of winding turns	Current (A)	Stack length (mm)	Average torque per copper loss (Nm/W)	Torque ripple (%)	Efficiency (%)
0.75	0.25	0.329	22.53	16.63	73	7.38	114.6	0.1208	28.4	83.2
0.5	0.5	0.361	22.28	16.75	67	7.58	100.7	0.1297	32.0	83.7
0.25	0.75	0.390	18.39	15.28	73	8.61	101.9	0.1617	50.4	84.8

Fig. 13. The flow diagram of the optimization method implementation.

$$f(x) = w_1 \frac{\Delta T_r}{T_r'} + w_2 \frac{P_{cu}}{T_{avg} T_c'} \quad (19)$$

to minimize a weighted sum of the torque ripple ΔT_r and the copper loss P_{cu} per average torque. The basic values of T_r' and T_c' were taken as the average values of the torque ripple and the copper loss per average torque obtained from two single-objective optimizations for torque ripple reduction and efficiency improvement, respectively. The efficiency consideration in the optimization is described by the second term in (19), the copper loss per average torque. Some design constraints, including maximum stack length and converter current rating, were included in the optimization. For example, the maximum stack length was limited to two times of the stator outer diameter, and the converter current rating was 20A. The optimization results with various weights are listed in Table II. Considering the primary goal of torque ripple reduction, the first optimization result was analyzed. The optimal design has the stator and rotor pole arc angles of 22.53 degrees and 16.63 degrees, respectively, stack length of 114.6 mm, 73 winding turns. When the optimal design of the 6/10 MCSRM is operated with the phase current of 7.38 A, the torque ripple is 28.4% compared to 35.4% with the prototype 6/10 MCSRM used in Section IV. Fig. 14 compares the torque profiles of the optimal design under different excitation schemes, and shows that the machine has the highest average torque and the lowest torque ripple under the two-mode bipolar excitation. Fig. 15 shows that the MCSRM under the two-mode bipolar excitation produces a higher average torque, compared to the traditional unipolar and bipolar excitations for a wide current range. Fig. 16 compares the torque ripple of the machine under the three excitation schemes for the wide current range. It shows that the torque ripple is much lower under the two-mode excitation scheme than under the other two traditional excitation schemes. As shown in Fig. 16, the optimal design has the torque ripple of less than 33% for the wide current range under the two-mode excitation scheme. As shown in Table III, the SRM has higher copper losses under both the traditional bipolar excitation and the two-mode bipolar

excitation, since two more coils are excited simultaneously under the traditional bipolar excitation and Mode II of the two-mode excitation compared with the traditional unipolar excitation. However, the MCSRM has a lower total loss under the two-mode bipolar excitation than under the traditional bipolar excitation. The core loss analysis and the method to reduce the core losses in MCSRMs will be included in future work.

Fig. 14. Instantaneous torque profiles of 6/10 MCSRM.

Fig. 15. Comparison of average torque under different excitations.

Fig. 16. Comparison of torque ripple under different excitations.

TABLE III. LOSS COMPARISON

Excitation Type ($\omega = 1000\text{rpm}$)	Core loss (W)	Copper loss (W)	Total (W)
Unipolar excitation	20.44	14.12	34.56
Bipolar excitation	24.01	29.31	53.32
Two-mode bipolar excitation	30.49	19.93	50.42

VI. CONCLUSIONS

In this paper, design considerations for MCSRMs under a two-mode bipolar excitation scheme are investigated. With considering the shift angle between the co-energy profiles of the MCSRM under the two excitation modes, the effective torque zone can be extended to reduce torque ripple. The design considerations, including pole numbers, stator and rotor pole arcs, number of winding turns, phase current, and stack length are studied under the two-mode bipolar excitation. FEM-based simulation results have shown that the 6/10 MCSRM is preferable under the two-mode bipolar excitation for low torque ripple applications. The 6/10 MCSRM has been optimized by solving a multiobjective optimization problem using a quasi-Newton optimization method with considering the tradeoff between the torque ripple reduction and the efficiency improvement. Results have shown a significant improvement in torque performance of the MCSRM, which would make the MCSRM a good candidate for low torque ripple applications.

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