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Analysis of torque ripple reduction effect on acoustic noise of a synchronous reluctance machine

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ABSTRACT—this paper aims to present the relation between acoustic noise and torque ripple. An equation evaluating the variation of acoustic noise caused by reducing torque ripple in synchronous reluctance machine (SynRM) is proposed. First, qualitative relation between the torque and the radial magnetic pressure (RMP) is presented. A quantitative relation between the RMP and torque is defined. Thirdly, based on the proposed equation, the influence of torque ripple reduction on electromagnetic noise is studied. The evaluation method is also computed thanks to the vibro-acoustic software Manatee. It can be concluded that the proposed approach can analyze effect of reducing torque ripple on acoustic noise.

Keywords—torque ripple, vibration, acoustic noise, synchronous reluctance machine, radial magnetic pressure

1. INTRODUCTION

Synchronous reluctance machine (SynRM) has been studied widely because of its high efficiency, robust structure and less cost [1]. However, this machine also has several disadvantages such as torque ripple and lower power factor [1]. To improve its performances, researches are mainly performed from two aspects: design and control. Authors [3][4] pay more attention to the design of its rotor structure such as rib, flux barriers and insulation to get higher saliency ratio, higher power factor and lower torque ripple. Other authors [5][6] focus on gaining higher performance with different control methods such as direct torque control and Kalman filter.

Besides, when SynRM is applied for electrical vehicle, another important requirement is its vibration and acoustic noise which can greatly affect the comfortableness. The electromagnetic acoustic noise existing in electrical machines has been studied extensively. Authors [7][8] study the noise theoretically while some authors [8][10][11][12] analyze and reduce noise by optimizing the design with finite element software such as Flux 2D, Nastran and MANATEE. In addition, other authors [13][14] apply optimal currents to reduce the noise. A widely validated and accepted conclusion [15] is that the magnetic acoustic noise is mainly caused by radial magnetic pressure which acts on the stator teeth. Therefore, we can study acoustic noise by analyzing the radial magnetic pressure.

However, when it comes to SynRM, there are few researches about its vibration and noise. As stated in [16], shaping currents can be an important method to diminish the acoustic noise in switched reluctance machine. But how to determine the optimal shaped current which is restricted by other performances such as efficiency and torque is not given. Authors [17] present that reduction of noise by different methods can also lead to lower torque. What’s more, it has been pointed out that torque ripple can cause acoustic noise [18]. However, noise and torque ripple are analyzed independently and how the torque ripple affect the emission of noise is not analyzed. Authors [19] decrease the torque ripple by switched reluctance machine and point out that the acoustic noise is also reduced. But the authors do not give any proofs to present the reduction of noise. Consequently, the relation between diminishing torque ripple and variation of acoustic noise is still not clear. As the electromagnetic noise is mainly produced by the radial magnetic pressure, it’s interesting to know the relation between reduction of torque ripple and variation of radial magnetic pressure. In this paper, we propose a method to evaluate the variation of electromagnetic acoustic noise when the torque ripple in SynRM is reduced.

In addition, the reduction of torque ripple of the studied SynRM is the first goal. During the reduction of torque ripple, SynRM can be controlled by different strategies such as maximum torque per ampere control (MTPAC), maximum efficiency control (MEC) and maximum power factor control (MPFC). The MTPAC method is usually applied because MEC can be obtained at the same current angle ($\beta=45^\circ$) with MTPAC. So the MTPA approach is used during the analysis of the relation between torque ripple reduction and acoustic noise.

This paper is organized as four parts. The first part presents the qualitative relation and quantitative relation between RMP and torque; the second part gives the acoustic equation which is calculated by RMP and also expresses the acoustic variation by the electromagnetic torque; the third part presents the acoustic noise and vibration obtained by vibro-acoustic software Manatee; at last, the fourth part concludes the paper.
Hence, considering that torque is produced by TMP, a parameter \( k' \) is added to represent the link between TMP and torque as shown in (4). According to the origins of acoustic noise and torque, the qualitative relation between RMP and torque can be defined by (5).

\[
\frac{p_n(a,t)}{p_t(a,t)} = \frac{p_n(a,t)}{k'T_e(t)} = \tan(a,t) \tag{4}
\]

\[
\frac{p_n(a,t)}{T_e(t)} = k'\tan(a,t) \tag{5}
\]

2.2. Quantitative relation

Based on the analysis of the origins of acoustic noise and torque, a qualitative relation has been defined and in this part, the quantitative relation is proposed.

To define the quantitative relation, at first we have to introduce the equations to calculate torque and RMP. The torque expression for synchronous reluctance machine can be expressed by (6) for the MTPA control strategy. It has been validated and the detailed deduction can be found in [23].

\[
T_e(t) = K_r(t)i_d^2 \tag{6}
\]

Where \( K_r(t) \) is the torque function which is a function of rotor position or time; \( i_d \) is the current of d-axis.

The RMP can be calculated by the Maxwell stress tensor method with neglecting the tangential flux density [8][24]

\[
P_n(a,t) = \frac{b_n(a,t)}{2\mu_0} \tag{7}
\]

In order to find the quantitative relation between torque and RMP, the RMP should be represented by the current \( i_d \) which is similar to (6). For the synchronous reluctance machine, the windings exist only on stator and there are no windings on rotor. The flux density can be expressed by surfacic permeance \( \Lambda \) and the magnetomotive force \( f_{mm} \) [25]. General speaking, the surfacic permeance \( \Lambda \) is a function of the structure of the machine and the magnetomotive force is a function of the distribution of the stator phase winding \( N_{sp}(a) \) and stator currents \( i_{sp}(t) \). The analytical equation of flux density is [26]

\[
B(a,t) = \Lambda(a) f_{mm}(a,t) \tag{8}
\]

The radial and tangential surfacic permeances are

\[
\begin{align*}
\Lambda_n(a) &= \Lambda_0 + \sum_{k=1}^{k_{max}} \Lambda_{kn} \cos(kZ_e a) \\
\Lambda_t(a) &= \sum_{k=1}^{k_{max}} \Lambda_{kt} \cos(kZ_e a)
\end{align*} \tag{9}
\]

Where \( \Lambda_0, \Lambda_{kn}, \) and \( \Lambda_{kt} \) are the amplitudes and \( Z_e \) is the number of stator teeth.

\[
f_{mm}(a,t) = \sum_{sp=1}^{3} N_{sp}(a)i_{sp}(t) \tag{10}
\]

Where \( sp \) is the stator phase.

Substituting (9) and (10) into (8) in order to represent the radial flux density by stator currents,

\[
B_n(a,t) = \left( \Lambda_0 + \sum_{k=1}^{k_{max}} \Lambda_{kn} \cos(kZ_e a) \right) \sum_{sp=1}^{3} N_{sp}(a)i_{sp}(t) \tag{11}
\]

Then, replacing the flux density in (7) by (11), the RMP can be presented as
In the machine, stator currents can be represented by the currents $i_d$ and $i_q$ in the rotating dq-frame which can be obtained by the Park transformation. What’s more, the SynRM is usually controlled to get the maximum torque per ampere which means $i_d$ equals $i_q$.

$$\begin{pmatrix} i_d(t) \\ i_q(t) \end{pmatrix} = \left[ \begin{array}{cc} \cos \theta & \sin \theta \\ -\sin \left( \theta - \frac{2\pi}{3} \right) & \cos \left( \theta - \frac{2\pi}{3} \right) \end{array} \right] \begin{pmatrix} i_d \\ i_q \end{pmatrix}$$

(13)

Where $\theta$ is the rotor electrical position. As a result, $\tan \frac{\theta}{2} = \frac{\sin \theta}{\cos \theta}$.

$$\begin{pmatrix} 3 \sum_{sp=1}^3 N_{sp} (\alpha) i_{sp}(t) \end{pmatrix}^2 = \left( \sum_{sp=1}^3 N_{sp} (\alpha) f_{sp}(t) \right)^2 i_d^2$$

(14)

Where $K_{fmm}(\alpha, t)$ represents the calculation of the square value of the magnetomotive force $f_{mm}$ by current $i_d$. $f_{sp}(t)$ represents the change from $i_d$ to stator currents. For example when $sp=1$, $f_{sp}(t)$ is

$$f_{sp}(t) = \sqrt{\frac{2}{3} (\cos \theta - \sin \theta)}$$

(15)

Therefore, substituting (14) into (12), the RMP can be calculated

$$P_n(\alpha, t) = \left( \frac{L_0 + \sum_{k_{sp}=1}^{3} L_{k_{sp}} \cos (k \theta)}{2\mu_0} \sum_{sp=1}^3 N_{sp} (\alpha) i_{sp}(t) \right)^2 = K_{pt}(\alpha, t) i_d^2$$

(16)

Where $K_{pt}(\alpha, t)$ is the pressure torque function which is 2D and presents the relation between RMP and torque. The pressure torque function of the studied SynRM, is obtained and shown in Fig. 2. Besides, if the torque is known, the RMP can be expressed by

$$P_n(\alpha, t) = K_{pt}(\alpha, t) T_e(t)$$

(19)

In order to verify that for different currents (without saturation) $K_{pt}(\alpha, t)$ is the same, we calculate this parameter for different sinusoidal stator currents whose maximal values ($I_m$) are 20A, 30A and 40A. To compare its values for different currents simply, we just compare the values when $\alpha$ equals $78.3^\circ$ as shown in Fig. 3 (at this point the radial pressure is maximal).

Therefore, the relation between electromagnetic torque and RMP is defined in (19). Besides, all the RMP mainly produce the vibro-acoustic phenomena. As a result, the noise could be evaluated based on the electromagnetic torque which will be presented in the following section.

3. ACOUSTIC NOISE ANALYSIS

The electromagnetic noise has been analyzed theoretically by [27]. The analytical equation of sound power is

$$L_\text{w} = 10 \log_{10} \left( \frac{P_e}{P_{\text{ref}}} \right)$$

(20)

Where $P_e$ is the sound power caused by radial force; $P_{\text{ref}}$ is the reference sound power ($10^{-12}$W).

Based on the expression (19), the RMP can be calculated thanks to the torque. Then, the effect of torque ripple reduction on noise can be evaluated by torque and the derivation is presented in the Appendix.
ΔL_W = 20\log_{10}\left(\frac{\text{FFT2D}(K_{pE}(s)T_{\text{ext}}(t))}{\text{FFT2D}(K_{pE}(s)T_{\text{comp}}(t))}\right) \quad (21)

Where \( T_{\text{ext}}(t) \) is the uncompensated torque and \( T_{\text{comp}}(t) \) is the compensated torque.

Therefore, the variation of acoustic noise resulted by reducing torque ripple with supplying optimal currents can be evaluated by torque. In the next part, we will compare the variation of acoustic noise when the torque ripple of synchronous reluctance machine is reduced.

4. SIMULATION

4.1. Simulation and result

To test the proposed method, the maximal value of sinusoidal stator current is 30A and the speed is 1500rpm. The sinusoidal stator currents and optimal stator currents are presented in Fig. 4. The uncompensated torque and compensated torque are introduced in Fig. 5. It can be seen that the optimal currents are effective for the purpose of reducing torque ripple which is reduced from 109.08% to 5.08%. Besides, the RMP corresponding with these two torques are calculated by (19) and presented in Fig. 6 and Fig. 7. It’s obvious that the RMP are changed by reducing torque ripple.

What’s more, the stator natural frequencies are analyzed by the finite element method. They are presented in Fig. 8. The natural frequencies and the vibrational modes of the stator cannot change when the stator has been designed. Hence, in the proposed method, the natural frequencies of stator are viewed as constant for uncompensated torque and compensated torque. It has been presented out that the significant vibration and acoustic noise are usually caused by the RMP whose frequency is close to the natural frequency of the stator and the force order is the same as the circumferential vibrational mode of stator [18][28]. The spatial order \( m \) and temporal order \( n \) of radial force can be calculated [28]

\[
(m, n) = (IZ \pm 2kp, 2kp) \quad (22)
\]

Where \( l \) and \( k \) are natural number, \( p \) is the number of pole pairs. The temporal frequency \( f_{\text{em}} \) is calculated by the temporal order and the rotor’s mechanical frequency or rotor speed \( n_c \)

\[
f_{\text{em}} = nf_m = n \frac{n_r}{60} \quad (23)
\]

Therefore, the resonance will occur when \( m \) equals the stator’s circumferential vibrational mode and \( f_{\text{em}} \) are close to the stator’s natural frequencies at the same time. At these resonance frequencies, if \( \Delta L_w \) is greater than zero, it means that the noise has been reduced; on the contrary, a negative \( \Delta L_w \) indicates that the noise has been increased. At other frequencies which cannot cause resonance the value of \( \Delta L_w \) is not important for the noise.

Based on (21) the variation of noise is calculated and is presented in Fig. 9. Besides, the natural frequencies of stator are also introduced in Fig. 9. The x-axis is the spatial order of \( \Delta L_w \) and y-axis is the temporal frequencies of \( \Delta L_w \). It can be seen from Fig. 9 that \( \Delta L_w \) is increased for some frequencies while it is decreased for other frequencies. But the frequencies do not correspond with the stator natural frequencies. It means that the noise will not be influenced for most frequencies. When the...
frequency is about 21 kHz, \( \Delta L_w \) has the identical frequency as the stator natural frequency whose spatial order is 4. For the frequency 21 kHz, the spatial order of \( \Delta L_w \) should be \( \pm 4 \) in order to produce resonance. The corresponding temporal order of 21 kHz is 72 \([28]\), hence according to (22), the number \( l \) can be calculated and the results are \( l = \pm 6.33 \) or \( \pm 5.67 \) which is not an integer. As a result, the radial pressure at 21 kHz will not cause resonance and the noise of the studied SynRM will not be influenced by supplying current harmonics to minimize torque ripple.

On the other hand, if it is supposed that \( l \) is an integer at 21 kHz which means the resonance occurs, the rotor speed can be calculated by (23) and is 17500rpm. This speed is too high for the studied machine. Therefore, the resonance will also not appear for the lower speed even if \( l \) is an integer.

4.2. Computation with Manatee

To verify the result, the vibro-acoustic software, Manatee, is applied to simulate the vibration and noise of the studied machine without compensation of torque ripple and with compensation of torque ripple. This software has been proved as an effective tool to test and evaluate the vibration and noise \([29]\). The stator model of the studied SynRM in Manatee is presented in Fig. 10. In order to save the effort, the flux density without torque ripple reduction and with torque ripple reduction obtained in Flux 2D are imported into Manatee directly.

Then the noise level can be calculated by Manatee. The noise without torque ripple reduction and with torque ripple reduction are presented in Fig. 11 and Fig. 12. It can be concluded by comparing these two figures that the noise is 29.5 dB and is not affected by reducing torque ripple. Therefore, the conclusion introduced by the proposed method is validated.
APPENDIX

The theoretical acoustic equation is rewritten

\[ L_w = 10 \log_{10} \left( \frac{P_s}{P_{sref}} \right) \]  (A1)

Where \( P_s \) is the sound power caused by radial force; \( P_{sref} \) is the reference sound power (10^{-12} W).

The sound power \( P_s \) can be calculated

\[ P_s = 4 \sigma_{ref} \rho_s c \pi^2 f_{exc}^2 x^2 R_{out} L_s \]  (A2)

\[ \sigma_{ref} = \frac{k^2}{1+2k^2} k^2 = 2 \pi R_{out} f_{exc} / c \]  (A3)

Where \( R_{out} \) is the outer radius of the stator yoke; \( \rho_s \) is the density of air; \( c \) is the speed of sound in air and \( f_{exc} \) is the frequency of each radial magnetic pressure harmonic.

The frequency of radial magnetic pressure is a multiple of the rotor rotational frequency

\[ f_{exc} = \frac{N_{p} n_{r}}{60} \quad k = 0,1,2,3 \ldots \]  (A4)

The static displacements for different order \( m \) are presented [15]

\[ x^s_{m} = P_{ma} \frac{R_{2} R_{1}}{E_{hy}} m = 0 \]  (A5)

\[ x^s_{m} = P_{ma} \frac{12 R_{h} R_{1}}{E_{hy}(m^2 - 1)^2} \quad m > 1 \]  (A6)

Where \( P_{ma} \) is the harmonics of radial magnetic pressure.

The dynamic displacement is

\[ x^d_{m} = x^s_{m} \left( \frac{1}{(1-f_{exc}^2/f_m^2)^2 + 4f_{h}^2 f_m^2 f_{exc}^2/f_m^2} \right) \]  (A7)

Where the empirical equation of the modal damping ratio is [18]

\[ \xi_m = \frac{1}{2\pi} \left( 2.76 \times 10^{-5} f_m + 0.062 \right) \]  (A8)

For our machine which has been manufactured, the parameters of geometry are fixed. And the mode frequency is also constant. What’s more, the speed of rotor, namely the frequency of radial magnetic pressure, for two situations: compensated torque and uncompensated torque, is also unchanged. When the torque ripple is decreased, the currents of stator are changed and therefore the flux density of air gap is changed. It means that the only variable parameter in the above expressions is the radial magnetic pressure. Therefore, the static displacements (A5) (A6) and dynamic displacements (A7) can be expressed by different radial magnetic pressure

\[ x^s_{m} = P_{ma} k_{sp} \]  (A9)

\[ k_{sp} = \begin{cases} \frac{R_{2} R_{1}}{E_{hy}} & m = 0 \\ \frac{12 R_{h} R_{1}}{E_{hy}(m^2 - 1)^2} & m > 1 \end{cases} \]  (A11)

\[ x^d_{m} = k_{ds} x^s_{m} \]  (A12)

\[ k_{ds} = \frac{1}{\sqrt{(1-f_{exc}^2/f_{h})^2 + 4f_{h}^2 f_{exc}^2/f_{h}^2}} \]  (A13)
Where $k_{sp}$ represents the relation between static displacements and radial magnetic pressure; $k_{ds}$ represents the relation between dynamic displacements and static displacements.

Besides, the acoustic power (A2) can be rewritten as

$$P_a = k_d x_m^2$$  \hspace{1cm} (A14)

$$k_d = 4\sigma_{ref} \rho_a \varepsilon \pi f_{cut}^2 R_{out} L_s$$  \hspace{1cm} (A15)

Where $k_d$ is the function between acoustic density and dynamic displacement.

To evaluate the variation of acoustic noise resulted by minimizing torque ripple, the sound power ($A14$) can be rewritten as

$$P_a = k_d x_m^2 = k_d (k_{ds} x_m^2) = k_d (k_{ds} P_{mu_ksp})^2 = k_p P_{mu}^2$$  \hspace{1cm} (A16)

$$k_p = k_d (k_{ds} k_{sp})^2$$  \hspace{1cm} (A17)

Where $k_p$ is the parameter which defines the relation between sound power and radial magnetic pressure. At each harmonic of radial magnetic pressure, $k_p$ is constant for the same machine at the same speed.

As a result, the variation of acoustic noise can be introduced

$$\Delta L_w = 10 \log_{10} \left( \frac{P_{a_{sin}}}{P_{a_{ref}}} \right) - 10 \log_{10} \left( \frac{P_{a_{opt}}}{P_{a_{ref}}} \right)$$

$$= 10 \log_{10} \left( \frac{P_{a_{sin}}}{P_{a_{opt}}} \right)$$

$$= 10 \log_{10} \left( \frac{k_p^2 P_{mu_{sin}}^2}{k_p^2 P_{mu_{opt}}^2} \right)$$

$$= 10 \log_{10} \left( \frac{P_{mu_{sin}}^2}{P_{mu_{opt}}^2} \right)$$

$$= 20 \log_{10} \left( \frac{FFT2D(P_{a_{sin}})}{FFT2D(P_{a_{opt}})} \right)$$

$$= 20 \log_{10} \left( \frac{FFT2D(K_{as}(t)T_{ext}(t))}{FFT2D(K_{as}(t)T_{ext}(t))} \right)$$  \hspace{1cm} (A18)

Where FFT2D represents the two dimension fast Fourier transform; $P_{a_{sin}}$ and $P_{a_{opt}}$ are the radial magnetic pressures with uncompensated torque $T_{esin(t)}$ and compensated torque $T_{esopt(t)}$ respectively.

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