A Comparative Thermal Study of Two Permanent Magnets Motors Structures with Interior and Exterior Rotor

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1. Introduction

Considering the large variety of electric motors, such as asynchronous motors, synchronous motors with variable reluctances, permanent magnets motors with radial or axial flux, the committed firms try to find the best choice of the motor conceived for electric vehicle field. The electric traction motor is specified by several qualities, such as the flexibility, reliability, cleanliness, facility of maintenance, silence etc. Moreover, it must satisfy several requirements, for example the possession of a high torque and an important efficiency (Zire et al., 2003; Gasc, 2004; Chan., 2004).

In this context, the surface mounted permanent magnets motor (SMPMM) is characterized by a high efficiency, very important torque, and power-to-weight, so it becomes very interesting for electric traction.

In the intension, to ensure the most suitable and judicious choice, we start by an analytical comparative study between two structures of SMPMM which are the permanent magnets synchronous motor with interior rotor (PMSMIR) and the permanent magnets synchronous motor with exterior rotor (PMSMER), then, we implement a methodology of design based on analytical modelling and the electromagnetism laws. Also, in order to understand the thermal behaviour of the motor, we implant a comparative thermal performance of the two structures illustrated with careful attention to the manufacturing techniques used to produce the machine, and the associated thermal resistances and capacitances, to obtain good steady state and transient thermal performance prediction.

2. Modelling of two SMPMM structures

2.1 Structural data

The structures of motors allowing the determination of the studied geometry are based on three relationships.

The ratio $\beta$ is the relationship between the magnet angular width $L_m$ and the pole-pitch $L_p$. This relationship is used to adjust the magnet angular width according to the motor pole-pitch.
(1)

(2)

The ratio $R_{ldla}$ is the relationship between the angular width of a principal tooth and the magnet angular width. This ratio is responsible for the regulation of the principal tooth size which has a strong influence on the electromotive force form.

(3)

The $R_{did}$ ratio is the relationship between the angular width of the principal tooth and the angular width of the inserted tooth $A_{toothi}$. This relationship fixes the inserted tooth size.

(4)

2.2 Geometrical structures of PMSMIR and PMSMER

This part is devoted to an analytical sizing allowing calculation of geometrical sizes of the two SMPMM configurations which are the PMSMER and the PMSMIR.

Figure 1 represents the PMSMER and the PMSMIR with the number of pole pairs is $p=4$ and a number of principal teeth is 6, between two principal teeth, an inserted tooth is added to improve the wave form and to reduce the leakage flux (Ben Hadj, N. et al., 2007). The slots are right and open in order to facilitate the insertion of coils and to reduce the production cost (Magnussen, F. et al., 2005; Bianchi, N. et al., 2003; Libert, F. et al., 2004).

Fig. 1. Permanent magnets motors with exterior rotor and interior rotor
2.3 Analytical sizing of the two SMPMM structures

The analytical study of motor sizing is based on the schedules data conditions parameters (Table 1), the constant characterizing materials (Table 2), the expert data and configurations of the two motors.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric vehicle mass</td>
<td>M</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Angle of starting</td>
<td>(a_d)</td>
<td>3(^\circ)</td>
</tr>
<tr>
<td>Time of starting</td>
<td>(t_d)</td>
<td>4 s</td>
</tr>
<tr>
<td>Outside temperature</td>
<td>(T_{out})</td>
<td>40(^\circ)C</td>
</tr>
<tr>
<td>Maximum motor power</td>
<td>(P_{max})</td>
<td>21,635 kW</td>
</tr>
<tr>
<td>Winding temperature</td>
<td>(T_w)</td>
<td>95(^\circ)C</td>
</tr>
<tr>
<td>Base speed of the vehicle</td>
<td>(V_b)</td>
<td>30 km/h</td>
</tr>
<tr>
<td>Maximum Speed of the vehicle</td>
<td>(V_{max})</td>
<td>100 km/h</td>
</tr>
<tr>
<td>Slots load factor</td>
<td>(k_r)</td>
<td>0.44</td>
</tr>
<tr>
<td>Current density in the slots</td>
<td>(\delta)</td>
<td>7 A/mm(^2)</td>
</tr>
</tbody>
</table>

Table 1. The schedules data conditions

<table>
<thead>
<tr>
<th>Definition</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remanent magnetic induction of the magnets</td>
<td>(B_m)</td>
<td>1,175 T</td>
</tr>
<tr>
<td>Demagnetization Induction</td>
<td>(B_c)</td>
<td>0,383 T</td>
</tr>
<tr>
<td>Magnetic induction in teeth</td>
<td>(B_{tooth})</td>
<td>0.9 T</td>
</tr>
<tr>
<td>Magnets permeability</td>
<td>(\mu_a)</td>
<td>1.05</td>
</tr>
<tr>
<td>Mechanical losses coefficient</td>
<td>(k_m)</td>
<td>1%</td>
</tr>
<tr>
<td>Copper resistivity at 95(^\circ)C</td>
<td>(R_{cu})</td>
<td>17,2 (10^{-9}) Ωm</td>
</tr>
<tr>
<td>The copper resistivity variation coefficient</td>
<td>(\alpha)</td>
<td>0.004</td>
</tr>
<tr>
<td>Density of the electrical sheets</td>
<td>(M_{vt})</td>
<td>7850 kg</td>
</tr>
<tr>
<td>Density of magnets</td>
<td>(M_{va})</td>
<td>7400 kg</td>
</tr>
<tr>
<td>Density of copper</td>
<td>(M_{vc})</td>
<td>8950 kg</td>
</tr>
<tr>
<td>Sheets quality coefficient</td>
<td>(Q)</td>
<td>1,1</td>
</tr>
</tbody>
</table>

Table 2. Specific constants of materials

**Expert data**

The expert data are practically represented by three sizes which are, the magnetic induction in the air gap \(B_w\), the magnetic induction in the stator yoke \(B_{sy}\) and the magnetic induction in the rotor yoke \(B_{ry}\). It should be noted that the zone of variation of these three parameters varies between 0.2 to 1.6T (Ben Hadj et al., 2007).

**Structural data**

For the two configurations, we adopted the same number of pole pairs \(P=4\), with an air gap thickness equivalent to 2mm, with a relationship \(\beta\) equal to 0.667 and \(R_{ldla}\) equal to 1.2.

**Data identified by the finite elements method**

\(k_{fu}\) is the leakage flux coefficient of the PMSMIR which is fixed to 0.95 whereas for the PMSMER, \(k_{fu}\) is equal to 0.98. In this context, we define a ratio \(R_{did}\) equal to 0.2.
2.4 Geometrical sizes

Geometrical parameters of the two structures motors are defined in figure 2. Where:

1. The magnet height, $h_m$
2. The slots height $h_s$ and the tooth height $h_{tooth}$
3. The rotor yoke height, $h_{ry}$
4. The stator yoke height, $h_{sy}$
5. The air gap thickness, $e$

![Fig. 2. PMSMER and PMSMIR parameters](image)

In the stator of the PMSMIR, geometrical sizes are defined by:

The slot average width: $W_s$

$$W_s = D_m + e + h_{tooth} A_s$$

(5)

The principal tooth section: $S_{tooth}$

$$S_{tooth} = \frac{D_m + e}{2} A_{tooth} l_m$$

(6)

Where $l_m$, $D_m$ are the average motor length and the average motor diameter.

The inserted tooth section: $S_{toothi}$

$$S_{toothi} = \frac{D_m + e}{2} A_{toothi} l_m$$

(7)

The slot section: $S_s$

$$S_s = \frac{1}{2} \left[ \frac{2\pi}{N_{tooth}} - A_{tooth} - A_{toothi} \right] \frac{D_m + e}{2} l_m$$

(8)

In the stator of the PMSMER, geometrical sizes are defined by:

The slot average width: $W_s$

$$W_s = \frac{D_m - e - h_{tooth}}{2} A_s$$

(9)

The principal tooth section: $S_{tooth}$
A Comparative Thermal Study of Two Permanent Magnets Motors Structures with Interior and Exterior Rotor

\[ S_{\text{tooth}} = \frac{D_m + e}{2} A_{\text{tooth}} l_m \]  
(10)

The inserted tooth section: \( S_{\text{toothi}} \)

\[ S_{\text{toothi}} = \frac{D_m + e}{2} A_{\text{toothi}} l_m \]  
(11)

The slot section: \( S_s \)

\[ S_s = \frac{1}{2} \left[ 2\pi - A_{\text{tooth}} - A_{\text{toothi}} \right] \frac{D_m - e}{2} l_m \]  
(12)

The teeth height \( h_{\text{tooth}} \) of the PMSMIR and the PMSMER are expressed by equation 13 and 14 where \( N_{\text{sph}} \) is the number of turns per phase, \( I_n \) is the rated current and \( N_{\text{teeth}} \) in the number of teeth.

\[ h_{\text{tooth}} = \frac{N_{\text{sph}} I_n}{N_{\text{teeth}} \delta K_s A_s} + \left( \frac{D_m + e}{2} \right)^2 - \frac{D_m + e}{2} \]  
(13)

\[ h_{\text{toothi}} = \frac{N_{\text{sph}} I_n}{N_{\text{teeth}} \delta K_s A_s} + \left( \frac{D_m - e}{2} \right)^2 - \frac{D_m - e}{2} \]  
(14)

The stator yoke thickness \( h_{\text{sy}} \) is obtained by the application of the flux conservation theorem, where \( B_{\text{tooth}} \) is the magnetic induction in the tooth.

\[ h_{\text{sy}} = \frac{B_{\text{tooth}} S_{\text{tooth}}}{2 l_m B_{\text{sy}}} \]  
(15)

In the rotor of the two structures, geometrical sizes are defined by:

The expression of the magnet height \( h_m \) is the same one in the two structures. It is obtained by the application of the Ampere theorem.

Where \( \mu_a \) is the air permeability and \( k_{ju} \) is the flux leakage coefficient.

\[ h_m = \frac{\mu_a B_e}{M(Ta) - \frac{B_e}{k_{ju}}} \]  
(16)

Where the magnet induction \( M(Ta) \) at \( T_a \)°C is defined by:

\[ M(Ta) = M \left[ 1 + \alpha_m (T_a - 20) \right] \]  
(17)

The rotor yoke thickness \( h_{ry} \) is defined:
2.5 Electrical sizing

The electromotive force in the two SMPMM structures is expressed by:

\[
EMF_i(t) = \frac{8}{\pi} N_{sph} l_m D_m B_e \sin\left(\frac{\pi \beta}{2}\right) \sin\left(\frac{\pi}{2} \beta R_{\text{ldla}}\right) \Omega_m \sin(p \Omega_m t)
\]  

(19)

The motor electric constant : \( K_e \)

\[
K_e = \frac{12}{\pi} N_{sph} l_m D_m B_e \sin\left(\frac{\pi \beta}{2}\right) \sin\left(\frac{\pi}{2} \beta R_{\text{ldla}}\right)
\]  

(20)

The electromagnetic torque : \( T_{em} \)

\[
T_{em}(t) = \frac{1}{\Omega} \sum_{i=1}^{3} EMF_i(t) i_i(t)
\]  

(21)

where \( EMF_i \), \( i_i \), and \( \Omega_m \) represent respectively the electromotive force, the current of the \( i \) phase and the angular speed of the motor.

The motor rated current \( I_n \) is the ratio between the electromagnetic torque and the motor electric constant.

\[
I_n = \frac{T_{em}}{K_e}
\]  

(22)

The phase resistance of the motor : \( R_{ph} \)

\[
R_{ph} = R_{\text{co}}(T_w) \frac{N_{sph} 5L_{sp}}{I_n / \sqrt{2}}
\]  

(23)

where \( R_{\text{co}}(T_w) \) is the copper receptivity at the temperature of winding \( T_w \) and \( L_{sp} \) is the spire average length (Ben Hadj et al., 2007).

3. Comparative thermal study between the two SMPMM

In this study, the comparison between the two SMPMM structures consists on the thermal analysis which is based upon lumped-circuit analysis. It represents the thermal problems by using the thermal networks, analogous to electrical circuits. The thermal circuit in the steady state consists of thermal resistances and heat sources connected between motor component nodes. For transient analysis, the heat/thermal capacitances are used additionally to take into account the change in internal energy of the body with time. The thermal resistances for conduction and convection can be obtained by:

\[
R_{\text{convection}} = \frac{1}{A_k} \left[ K / W \right]
\]  

(24)
A Comparative Thermal Study of Two Permanent Magnets Motors Structures with Interior and Exterior Rotor

\[ R_{\text{conduction}} = \frac{l}{A_c h} [K / W] \]  

(25)

Where \( l \) is the distance between the point masses and \( A \) is the interface area, \( k \) is the heat conductivity, \( A_c \) is the cooling cross section between the two regions and \( h \) is the convection coefficient calculated from proven empirical dimensionless analysis algorithms.

The heat capacitance is defined as follow:

\[ C = V \rho c [Ws / K] \]  

(26)

Where \( V \) is the volume, \( \rho \) is the density and \( c \) is the heat capacity of the material. The simplified stator for the thermal study of the two SMPMM structure are given by figures 3 and 4, also the thermal model for the two structures are implemented in MATLAB simluter where the different radius for the PMSMER dimensions are defined as follow:

\[ R_{\text{carter}} = R_1 = R_f + \frac{e}{2} + h_m + h_{ry} + e_{\text{carter}} \]  

(27)

\[ R_{\text{rotorgake}} = R_2 = R_f + \frac{e}{2} + h_m + h_{ry} \]  

(28)

\[ R_{\text{magnet}} = R_3 = R_f + \frac{e}{2} + h_m \]  

(29)

\[ R_4 = R_f + \frac{e}{2} \]  

(30)

\[ R_{\text{slot}} = R_5 = R_f - \frac{e}{2} \]  

(31)

\[ R_{\text{insulator}} = R_6 = R_5 - h_s \]  

(32)

\[ R_7 = R_5 - h_s - t_{\text{insulator}} \]  

(33)

\[ R_8 = R_7 - h_{sy} \]  

(34)

The thermal resistances are calculated along the radial direction. The \( R_i \) radius are calculated from dimensions of motor, where \( R_f \) is the Bore radius and \( t_{\text{insulator}} \) is the thickness insulator.

The different radius for the PMSMIR dimensions are defined as follow:

\[ R_1 = R_f + \frac{e}{2} \]  

(35)
\[
R_2 = R_f + \frac{e}{2} + h_{tooth} \tag{36}
\]

\[
R_3 = R_f + \frac{e}{2} + h_{tooth} + t_{insulator} \tag{37}
\]

\[
R_4 = R_f + \frac{e}{2} + h_{tooth} + t_{insulator} + h_y \tag{38}
\]

\[
R_5 = R_f + \frac{e}{2} + h_{tooth} + t_{insulator} + h_y + t_{carter} \tag{39}
\]
As described earlier, the thermal resistance values are automatically calculated from motor dimensions and material data. Figure 5 shows the thermal model in transient behaviour of the PMSMIR.

![Thermal model of the PMSMIR in transient behaviour](image)

**Fig. 5.** Thermal model of the PMSMIR in transient behaviour

In this model, the heat sources are respectively the copper losses and iron losses in the stator. The $T_i$ variables are the temperatures in various points of the motor. The expressions of thermal resistances of the PMSMIR result from the resolution of the heat equation at the fields borders.

$R_{coil}$ represents the coil thermal resistance ($K.W^{-1}$).

$$R_{coil} = \frac{1}{4\pi l_n \lambda_{coil}} [1 - 2 \frac{R_1^2}{R_2^2 - R_1^2} \ln \frac{R_2}{R_1}]$$  \hspace{1cm} (40)

$R_{inso}$ represents the isolator thermal resistance ($K.W^{-1}$).

$$R_{inso} = \frac{\ln R_3}{2\pi \lambda_{inso} l_m}$$  \hspace{1cm} (41)

$R_{inso-sy}$ represents the contact thermal resistance between insulator and the stator yoke ($K.W^{-1}$).

$$R_{inso-sy} = \frac{1}{300 \frac{2}{2\pi \lambda_{inso} l_m}}$$  \hspace{1cm} (42)

$R_{jco}$ represents the thermal resistance of stator yoke ($K.W^{-1}$).

$$R_{jco} = \frac{\ln R_4}{2\pi \lambda_{iron} l_m}$$  \hspace{1cm} (43)
\( R_{fco} \) represents the thermal resistance of conduction in the stator yoke (\( K \cdot W^{-1} \)).

\[
R_{fco} = \frac{1}{4\pi l_m A_{iron}} [1 - 2\frac{R_3^2}{R_4^2 - R_5^2} \ln \frac{R_4}{R_3}] \tag{44}
\]

\( R_{sy-ca} \) represents the thermal resistance between stator yoke and the carter (\( K \cdot W^{-1} \)).

\[
R_{sy-ca} = \frac{1}{\frac{1500}{2\pi R_4 l_m}} \tag{45}
\]

\( R_{ca} \) represent the thermal resistance of carter (\( K \cdot W^{-1} \)).

\[
R_{ca} = \frac{\ln R_4}{2\pi R_4 l_m} \tag{46}
\]

\( R_{ext} \) represents the convection thermal resistance between the carter and ambient air (\( K \cdot W^{-1} \)).

\[
R_{ext} = \frac{1}{h S_{ext}} \tag{47}
\]

In the previous expression, \( S_{ext} \) represents the outer surface of the motor and \( h \) is the heat transfer coefficient between the carter and the ambient air. It can be between 20 and 40 \( K \cdot W^{-1} \cdot m^{-2} \) for a motor with natural ventilation, and may exceed 80 \( K \cdot W^{-1} \cdot m^{-2} \) for the motor forced air.

To calculate the outer surface of SMPMM, we considered only the outer surface of the cylinder with radius \( R_5 \) and height \( l_m \) (Gasc, 2004; Chan., 2004).

\[
S_{ext} = 2\pi R_5 l_m \tag{48}
\]

The expressions of heat capacities of the PMSMIR are given by the following equations:

\( C_{coil} \) represents the heat capacity of coil (\( JK^{-1} \)).

\[
C_{coil} = \rho_{coil} V_{coil} C_{th-coil} \tag{49}
\]

\( C_{inso} \) represents the heat capacity of insolator (\( JK^{-1} \)).

\[
C_{inso} = \rho_{inso} V_{inso} C_{th-inso} \tag{50}
\]

\( C_{sy} \) represents the heat capacity of stator yoke (\( JK^{-1} \)).

\[
C_{sy} = \rho_{iron} V_{sy} C_{th-iron} \tag{51}
\]

\( C_{ca} \) represents the capacity of carter (\( JK^{-1} \)).

\[
C_{ca} = \rho_{alu} V_{ca} C_{th-alu} \tag{52}
\]
Figure 6 shows the thermal model in transient behaviour of the PMSMER.

The expressions of the PMSMER thermal resistances obtained from the resolution of the heat equation at the fields borders.

\[ R_{sy} = \frac{1}{4\pi l_m \lambda_{iron}} \left[ 1 - 2 \frac{R_y^2}{R_y^2 - R_y} \ln \frac{R_y}{R_y} \right] \]  \hspace{1cm} (53)

\[ R_{inso} = \frac{1}{4\pi l_m \lambda_{inso}} \left[ 2 \frac{R_{inso}^2}{R_{inso}^2 - R_{inso}} \ln \frac{R_{inso}}{R_{inso}} \right] \]  \hspace{1cm} (54)

\[ R_{coil} = \frac{1}{4\pi l_c \lambda_{coil}} \left[ 1 - 2 \frac{R_{coil}^2}{R_{coil}^2 - R_{coil}} \ln \frac{R_{coil}}{R_{coil}} \right] \]  \hspace{1cm} (55)

\[ R_{mag} = \frac{\ln R_1}{2\pi \lambda_{mag} l_m} \]  \hspace{1cm} (56)

\[ R_{ry} = \frac{\ln R_2}{2\pi \lambda_{iron} l_m} \]  \hspace{1cm} (57)

\[ R_{ca} = \frac{\ln R_1}{2\pi \lambda_{ca} l_m} \]  \hspace{1cm} (58)
To calculate the outer surface of SMPMM, we considered only the cylinder outer surface with radius \( R_1 \) and the height \( l_m \).

\[
S_{\text{ext}} = 2\pi R_1 l_m
\]

(59)

The expressions of heat capacities of the PMSMER are given by the following equations:

\[ C_{\text{mag}} \] represents the heat capacity of magnet (\( J/\text{K} \)).

\[
C_{\text{mag}} = \rho_{\text{mag}} V_{\text{mag}} C_{\text{th-mag}}
\]

(60)

\( C_{\text{ry}} \) represents the heat capacity of rotor yoke (\( J/\text{K} \)).

\[
C_{\text{ry}} = \rho_{\text{iron}} V_{\text{ry}} C_{\text{th-iron}}
\]

(61)

\( C_{\text{coil}} \) represents the heat capacity of coil (\( J/\text{K} \)).

\[
C_{\text{coil}} = \rho_{\text{co}} V_{\text{co}} C_{\text{th-co}}
\]

(62)

\( C_{\text{inso}} \) represents the heat capacity of insolator (\( J/\text{K} \)).

\[
C_{\text{inso}} = \rho_{\text{inso}} V_{\text{inso}} C_{\text{th-inso}}
\]

(63)

\( C_{\text{sy}} \) represents the heat capacity of stator yoke (\( J/\text{K} \)).

\[
C_{\text{sy}} = \rho_{\text{iron}} V_{\text{sy}} C_{\text{th-iron}}
\]

(64)

The below table presents the different thermal conductivities of materials (Jérémí, R., 2003)

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivities (Wm-1K-1)</th>
<th>Mass heat capacity (Jkg-1K-1)</th>
<th>Density (Kgm-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper (Coil)</td>
<td>( \lambda_{\text{co}} = 5 )</td>
<td>( C_{\text{th-co}} = 398 )</td>
<td>( \rho_{\text{co}} = 8953 )</td>
</tr>
<tr>
<td>Insolator</td>
<td>( \lambda_{\text{inso}} = 0.25 )</td>
<td>( C_{\text{th-inso}} = 1250 )</td>
<td>( \rho_{\text{inso}} = 1200 )</td>
</tr>
<tr>
<td>(Iron) Stator Yoke</td>
<td>( \lambda_{\text{iron}} = 25 )</td>
<td>( C_{\text{th-iron}} = 460 )</td>
<td>( \rho_{\text{iron}} = 7650 )</td>
</tr>
<tr>
<td>Magnet</td>
<td>( \lambda_{\text{mag}} = 6.5 )</td>
<td>( C_{\text{th-mag}} = 420 )</td>
<td>( \rho_{\text{mag}} = 7400 )</td>
</tr>
<tr>
<td>aluminium (Carter)</td>
<td>( \lambda_{\text{alu}} = 180 )</td>
<td>( C_{\text{th-alu}} = 883 )</td>
<td>( \rho_{\text{alu}} = 2787 )</td>
</tr>
</tbody>
</table>

Table 3. The thermal conductivities of materials

6. Results and simulations

Simulation results with Matlab software allowed us to obtain the curves of temperatures specific to different materials of the PMSMER and PMSMIR structures. The thermal results at steady and transient state is reached by figures 7, 8.

According to the results, we find that the steady state in the PMSMIR is reached after 4000s. However, the steady state in the PMSMER is achieved after 2000s.

By comparing the results in steady and transient state between the two configurations, we note that temperatures of different parts in PMSMIR are higher than temperatures in PMSMER (especially the coil temperature). That’s why, we choose the PMSMER configuration as the best solution in electric traction field.
Fig. 7. Various temperatures in different parts of the PMSMER in transient state.

Fig. 8. Various temperatures in different parts of the PMSMIR in transient state.
Moreover, we always look to get a permissible values of coil temperature, based on the proper choice of motors geometric parameters in order to ensure a good compromise between geometric dimensioning and thermal modeling motor.

7. Conclusion

In this paper, a thermal model of two SMPMM with interior rotor and exterior rotor was realised, the intention to compare the evolution of the temperatures of different parts of the two motor configurations and especially the modeling of temperature at the coil is made.

8. References

In this book, modeling and simulation of electric vehicles and their components have been emphasized chapter by chapter with valuable contribution of many researchers who work on both technical and regulatory sides of the field. Mathematical models for electrical vehicles and their components were introduced and merged together to make this book a guide for industry, academia and policy makers.

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