Noise and vibration characteristics of sub-fractional horsepower single-phase BLDC drives

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Abstract Single-phase brushless DC (BLDC) drives are a cost-effective alternative for three-phase sub-fractional horsepower drives in automotive auxiliary applications. Inherent features of single-phase permanent magnet machines, such as high cogging torque and torque ripple, can, however, make them more audible than their three-phase counterparts. As some of these auxiliary drives are close to the passengers, where even a small amount of noise can be disturbing, the investigation into noise sources is essential to further address this challenge. In this paper, the dominant noise and vibration characteristics of single-phase BLDC machines are investigated for two different stator structures, i.e., salient-pole and claw-pole, and compared. Magnetic force density waves and finite element (FE) analyses are performed to analyze the electromagnetic forces resulting from the open-circuit condition as well as different switching strategies in the load condition. Structural analyses show that due to the mechanical structure’s lower stiffness and natural frequencies in the audible range, the example case machine with the claw-pole stator develops higher structure- and air-borne noise than the machine with the salient-pole stator.

Keywords Noise and vibration · Single-phase BLDC drives · Sub-fractional horsepower · Automotive auxiliary drives · Fan drives

Geräusch- und Schwingungscharakteristika von einphasigen bürstenlosen Gleichstromkleinantrieben

Zusammenfassung Einphasige bürstenlose Gleichstromantriebe (BLDC) sind als Hilfsantriebe für Fahrzeuge eine kostengünstige Alternative zu dreiphasigen Antrieben mit kleiner Leistung. Inhärente Merkmale von Einphasen-Permanentmagnetmaschinen, wie hohes Rastmoment und hohe Drehmomentwelligkeit, führen jedoch zu einer größeren Geräuschemission, als dies für die dreiphasigen Gegenstücke der Fall ist. Da sich einige dieser Hilfsantriebe in der Nähe der Fahrgäste befinden, wo bereits geringe Geräusche störend wirken können, ist die Untersuchung von Geräuschquellen unabdingbar, um dieser Herausforderung weiter zu begegnen. In diesem Beitrag werden die vorherrschenden Geräusch- und Schwingungscharakteristika von einphasigen BLDC-Maschinen für zwei verschiedene Topologien, Schenkelpolständer- und Klauenpoltopologie, untersucht und verglichen. Magnetische Kraftdichtewellen und Finite-Elemente-Analysen werden durchgeführt, um die elektromagnetischen Kräfte, die im Leerlaufzustand vorliegen, sowie verschiedene Schaltstrategien zu analysieren. Ergebnisse von Strukturanalysen zeigen, dass die Beispiel-Maschine mit Klauenpoltopologie aufgrund der geringeren Steifigkeit der mechanischen Struktur und der Eigenfrequenzen im hörbaren Bereich einen höheren Körper- und Luftschall aufweist als die Maschine mit Schenkelpolständer.

Schlüsselwörter Geräusche und Vibrationen · Einphasige BLDC-Motoren · Kleinantriebe · Hilfsantriebe für Fahrzeuge · Lüfterantriebe
1 Introduction

Compared to the main drive system in EV applications, small electric drives are barely audible, but as they are installed close to the passengers, e.g., for seat ventilation and sensor blowers, their vibration and noise limitations according to the industrial standards are significantly lower than those for large drives [1]. This motivates studying the characteristics of noise and vibration of these drives in order to investigate the main roots of electromagnetic induced noise and vibration. In this study, two main structures of outer-rotor single-phase BLDC machines used in automotive applications [2, 3], which are illustrated in Fig. 1, are analyzed. The salient-pole stator is manufactured by laminated steel sheets; the claw-pole stator is manufactured by punching and deep-drawing solid steel. The claw-pole stator is designed to decrease the manufacturing cost, and its application is limited to low power range drives because of the eddy current losses. The principles of the operation of this machine are explained in [3]. The detailed information about the example case drives is shown in Table 1.

In this paper, the two small example case single-phase drives are referred to as sub-fractional horsepower drives. Although sub-fractional horsepower is not a strictly defined technical term, in this paper, it refers to a power range below 10 W. Also, to distinguish between the two example case machines, the machine with the conventional slotted stator is referred to as single-phase machine with the salient-pole stator.

Table 1 Parameters of the example case drives

| Parameter               | Value       |
|-------------------------|-------------|
| DC link voltage ($U_{DC}$) | 8–16 V     |
| Nominal speed ($\omega_{nom}$) | 5000 min$^{-1}$ |
| Rated torque ($T_{r}$)     | 1.54 mN/m   |
| Pole-pair number ($p$)     | 2           |
| Number of slots ($Q_s$)    | 4           |
| Stator’s outer diameter ($D_{so}$) | 23 mm     |
| Rotor’s outer diameter ($D_{ro}$) | 27 mm     |

This paper utilizes an extensively experimentally validated 3D FE model to analyze the magnetic forces of the two example case drives [2–4] implemented in JMAG® [5], shown in Fig. 2.

In Sect. 2, the main magnetic noise and vibration sources in single-phase BLDC machines are investigated. Sect. 3 covers the effect of magnetic forces related to the current injection by comparing two common switching strategies in sub-fractional horsepower drives. In Sect. 4, the modal analysis of the two example case drives is presented, and their noise and vibration performance is compared with structure- and air-borne noise simulations.

2 Magnetic Force Analysis of Single-Phase Permanent Magnet Machines

2.1 Cogging Torque and Torque Ripple

Inherently, single-phase permanent magnet (PM) machines suffer from high cogging torque and torque ripple due to their special magnetic structure and commutation pattern. This can lead to noise and vibration depending on the mechanical boundary conditions [6]. Basically, single-phase BLDC machines have the same number of slots and poles. In this case, all the rotor poles are aligned with stator tooth-tips, while in three-phase PM machines, only some of the slots and magnet poles are aligned at the same time; therefore, single-phase PM machines have higher cogging torque per nominal electromagnetic torque compared to three-phase machines. Furthermore, as single-phase BLDC motors cannot start autonomously, owing to their alternating stator magnetic field, most of the approaches which are typically implemented to facilitate the starting, increase the cogging torque, e.g., tapered air-gap, although, there are several innovative air-gap profiles to decrease this effect [7–10]. It has been shown that cogging torque reduction in single-machine BLDC machines can decrease both structure- and air-borne noise [7, 8].

A tapered air-gap is usually implemented by moving the center of the tooth-tip’s arc [8], as shown in
Fig. 3a. The effect of this movement on the cogging torque of the example case machine with the salient-pole stator is shown in Fig. 3b, where \( x \) represents this displacement. As shown in Fig. 3b, a tapered air-gap provides starting torque at the dead point where electromagnetic torque is zero (see Fig. 5, when \( \theta < \theta_{\text{on}} \)). A similar behavior has been observed for the machine with the claw-pole stator [3]. On the other hand, the tapered air-gap profile increases the positive and negative peaks of the cogging torque; hence, a trade-off between starting torque and cogging torque is usually made to choose the value of \( x \). Besides, increasing air-gap asymmetry decreases the fundamental component of the induced voltage.

A comparison of simulated cogging torque waveform of the example case single-phase machine with the salient-pole stator with tapered air-gap profile with a three-phase machine with the salient-pole stator (4-pole and 6-slot) using the same rotor and average air-gap length is shown in Fig. 4. It shows that the cogging torque of the single-phase case is much higher than that of the three-phase counterpart.

The electromagnetic torque produced by a single-phase BLDC machine has an inherently pulsating waveform, shown in Fig. 5, which compares the ideal torque waveform of single- and three-phase BLDC machines. Turn-on and -off angles of the switches, \( \theta_{\text{on}} \) and \( \theta_{\text{off}} \), are usually implemented to prevent high current peaks and also breaking torque in single-phase machines. As torque ripple can potentially lead to noise and vibration, different techniques have been suggested to decrease the output torque ripple of these machines, and it has been shown that torque ripple reduction can improve noise and vibration behavior [11–13]. The effect of the torque ripple resulting from different switching strategies on structure- and air-borne noise is investigated in more detail in Sects. 3 and 4.

2.2 Radial and Tangential Force Densities

The Maxwell stress tensor is mainly used to investigate the magnetic forces produced by the magnetic field in the middle of the air-gap which can excite the mechanical structure and lead to noise and vibration. The local radial and tangential magnetic force densities, \( \sigma_r(t, \phi) \) and \( \sigma_t(t, \phi) \), vary with respect to \( t \) and \( \phi \) which denote time and the azimuthal angle in the stator reference frame, respectively. These force densities can be determined from the corresponding air-gap flux density components, \( B_r(t, \phi) \) and \( B_t(t, \phi) \), at
In a case of a tapered asymmetric air-gap, the air-gap length along the circumferential direction is distributed as follows:

\[ g(\phi) = g_{\text{sym}} \left( 1 - \epsilon \cos(N_s \phi) \right) \]  

(4)

where \( g_{\text{sym}}, \epsilon, \) and \( N_s \) are the air-gap length in symmetric air-gap case, i.e., when the air-gap length distribution is uniform along the circumference, the relative movement of the center of the tooth-tip of the tapered air-gap relative to \( g_{\text{sym}} \), and number of slots, respectively. Neglecting the nonlinear property of the iron parts, the permeance function of the motor is

\[ P(\phi) = \frac{1}{g(\phi)} = \frac{1}{g_{\text{sym}}} \lambda(\phi), \]

(5)

where \( \lambda(\phi) \) is a relative asymmetric function. This function can be expressed by the summation of the Fourier series as follows:

\[ \lambda(\phi) = \sum_{j=0}^{\infty} \lambda_j \cos(j N_s \phi). \]  

(6)

Also, the slot permeance function of the machine can be defined as [15]

\[ \Lambda(\phi) = \sum_{i=0}^{\infty} \Lambda_i \cos(i N_s \phi). \]  

(7)

The slot permeance function affected by the asymmetry of the air-gap can be expressed by the multiplication of (6) and (7) as follows:

\[ \Lambda_{\text{asy}}(\phi) = \Lambda(\phi) \lambda(\phi). \]  

(8)

As single-phase PM machines have the same number of poles and slots, the absolute value of the flux density along the circumference is the same for each pole pitch in an ideal machine without manufacturing imperfections. Therefore, the magneto-motive force (MMF) of the ideally magnetized PM will be a half-wave symmetric function, and it only has the odd coefficients of the pole-pair harmonics. Therefore, the MMF function can be expressed by a Fourier series as

\[ F(t, \phi) = \sum_{k=1}^{\infty} F_{f_k} \cos \left( p(2k+1)(\phi - \omega t) \right), \]  

(9)

where \( f_k \) and \( p \) are the Fourier coefficients of the MMF function and the number of pole-pairs, respectively.

The air-gap flux density can be represented by the multiplication of (8) and (9). By considering the number of slots, \( Q_s \), and pole number, \( 2p \), the same, the air-gap flux density is
where both coefficients of $\varphi$ and $t$ are odd coefficients of the pole-pair number. The radial force density function can be derived from (1) by neglecting the tangential magnetic flux density as follows:

$$\sigma_r(t, \varphi) = \frac{B_r^2(t, \varphi)}{2\mu_0} = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \sigma_{i,j,k} \cos(2(i \pm j \pm k)p \varphi)$$  \hspace{1em} (11)

where only the coefficients of $2\rho$ appear for both spatial and temporal harmonic orders. The similar equation can be derived for tangential magnetic force density.

By defining $m$ as the number of slots, $Q_s$, and pole number, $2p$, as

$$Q_s = 2p \equiv m,$$  \hspace{1em} (12)

$\sigma_r$ in (11) can be rewritten as

$$\sigma(t, \varphi) = \sum_{n,r} \sum_{f,r} \sigma_{f,r} = \sum_{k_1=0}^{\infty} \sum_{k_2=-\infty}^{\infty} (k_1 m f_r, k_2 m).$$  \hspace{1em} (13)

Due to (13), both spatial and temporal orders are multiples of $m$, and both the dominant radial and tangential force density waves are either $(m f_r, m)$ or $(m f_r, -m)$ depending on the direction of rotation.

The result of the 2D-FFT analysis of both the salient- and the claw-pole single-phase BLDC machines are illustrated in Fig. 6, where all multiples of $m = 4$, due to the number of slots and poles, appear in both spatial and temporal orders, and the dominant force density is $(4f_r, -4)$. Both contours are similar concerning the spatial and temporal orders and the amplitudes, even though the amplitudes of the main waves in the machine with the salient-pole stator are slightly higher than in the machine with the claw-pole stator. It is important to mention that magnetic force density waves with $0^{th}$ harmonic order, i.e., $(0, r)$, are static waves and do not contribute to the vibration in the stationary frame.

All magnetic force density waves can affect the stator, as it is stationary, but in the case of the rotor, the relative speed of each wave should be considered. Based on (13), the angular frequency of each traveling wave with respect to its temporal and spatial orders is

$$\omega_{f,r} = \frac{2\pi f_r}{r} = \frac{k_1}{k_2} \omega_r.$$  \hspace{1em} (14)

![Fig. 7 2D-FFT analysis of open-circuit radial magnetic force density in the rotor frame of the example case single-phase BLDC machines: a salient-pole stator and b claw-pole stator](image)

As both $k_1$ and $k_2$ of the dominant force density wave in single-phase BLDC machines are equal to $m$, the angular frequency of the traveling wave is equal to the rotor’s angular frequency; therefore, this force density wave does not rotate in the rotor frame, i.e., the relative speed is zero. Furthermore, it affects the rotor like a static wave which does not lead to the vibration. The result of the 2D-FFT analysis of radial magnetic force density in the rotor frame for both example case machines is illustrated in Fig 7. It shows that most dominant force density waves in the stationary frame are not sensed by the rotor as a traveling wave; in turn, other waves in the CCW direction, i.e., against the rotation of the rotor, are dominant in the rotor’s frame. The amplitudes of these traveling waves are significantly lower than the stationary frame, e.g., the dominant dynamic wave in the rotor frame is one-fourth of the dominant dynamic wave in the stationary frame; however, since the rotor’s stiffness due to its thin ring-like structure is usually lower than that of the stator, even a small force density wave can be disturbing.

2.3 Unbalanced Magnetic Forces

Unbalanced magnetic forces (UMF) are one of the dominant sources of noise and vibration in small electric machines, and their different roots have been investigated in the literature [16, 17]. Manufacturing imperfections which are one of the main sources of UMF are relatively common in small machines due to the small dimensions and low-cost production process. Most of the manufacturing imperfections, i.e.,
non-uniform magnetization and dynamic eccentricity, may generate significant unbalanced radial, tangential [18], and axial magnetic forces [19]. The effect of the manufacturing imperfections on the unbalanced magnetic forces for single-phase BLDC machines with the salient- and claw-pole stators have been investigated in [16, 17], respectively.

One of the main applications of single-phase BLDC machines is fan applications, like the two example cases in this paper, in which electrical motors often need a retention magnetic force in the axial direction against the fan propulsion to prevent the rotor shaft from dropping out of the slide bearing or to prevent excessive stress on a ball bearing when in operation [20]. Generally, a misalignment between the PM and the stator refers to the upward axial displacement, called the magnet offset here, is applied to satisfy this requirement. Also, usually, there is an asymmetry in the rotor design which can generate unbalanced axial forces, called magnet overhang, to facilitate an accurate position detection by Hall sensors. Both of these asymmetries, which can inherently lead to vibration and noise, are shown in Fig. 8a.

As shown in Fig. 8b, the simulation results indicate that although a magnet offset can overcome fan propulsion, it generates a fluctuating unbalanced axial magnetic force, which can excite the mechanical structure. Furthermore, it shows that only close to 10% of this force ripple is related to the PM overhang, while most of it is related to the magnet offset.

3 Magnetic Force Induced by Current Injection

Although the topology of an electric machine and its magnetic circuit have a remarkable effect on noise and vibration, the magnetic forces induced or amplified by the injected current harmonics can play a key role in determining the noise behavior. This section investigates the effect of two common switching strategies in single-phase BLDC machines, pulse width modulation (PWM) and angle modulated switching strategy (AMSS) [21], on the structure- and air-borne noise of the example case single-phase BLDC machine with the salient-pole stator.

Fig. 9 shows the electronic circuit necessary for the commutation of the phase current in a single-phase PM machine with the bifilar winding, including two sub-phase monofilar windings wound in different directions to provide a 180 electrical degree phase difference between the sub-phases. The circuit comprises the following: a constant supply voltage $U_{DC}$, a diode $D$ which prevents breaking energy from flowing back into the source; a DC link capacitance $C$; and the commutation switches $S_A$ and $S_B$. Also, in the equivalent circuit of the machine, $R$ is the sub-phase resistance and $L_m$ and $L_o$ are the main and leakage inductances, respectively.

Different commutation strategies have been proposed for single-phase BLDC machines based on delaying the turn-on angle and advancing turn-off angles to enhance the machine performance. Thereby, braking torque can be eliminated, and current peaks can be reduced, which increases the efficiency [22, 23]. In this paper, the optimized turn-on and -off angles for 5000 revolutions per minute to maximize the efficiency calculated in [23] are used for the PWM strategy.

![Inverter circuit of the single-phase BLDC motor with bifilar stator winding](image-url)
3.1 PWM

PWM is a common switching strategy to control the average power of the loads. It switches between the maximum and minimum voltage due to the duty cycle, with a constant frequency. The current waveform resulting from PWM is depicted in Fig. 10a. Fig. 11a depicts the results of the 2D-FFT analysis of the magnetic force density waves for the example case drive with the salient-pole stator, under current injection with PWM switching strategy with $f_{\text{PWM}} = 20$ kHz. The results show that the current injection increases most of the magnetic force density waves with a temporal order higher than four, compared to the open-circuit condition in Fig. 6a, and the 4th harmonic order waves are slightly decreased.

3.2 Angle Modulated Switching Strategy

AMSS is mainly designed to reduce the switching frequency to its minimum, namely the electrical frequency, to decrease the radiated electromagnetic emissions [21]. AMSS controls the mean value of the voltage $U$ applied to the winding by adjusting the turn-on and -off angles, which determines the speed of the BLDC machine. In contrast to a fixed switching period with a varying duty cycle, the conduction angle, in this case, is adjustable, resulting in a speed-dependent switching period. The conduction angle is defined as

\[ \alpha = \frac{U}{U_{\text{DC}}} \cdot 180^\circ. \]  

The current waveform and 2D-FFT analysis of the magnetic force density waves for the example case drive with the salient-pole stator resulting from AMSS are shown in Figs. 10b and 11b, respectively. AMSS leads to significantly higher current peaks than PWM, and the amplitudes of the main harmonics are higher than that of the conventional PWM strategy. Quantitatively speaking, the same observation is made for the claw-pole motor.

4 Structural Analysis of Single-Phase Topologies

The magnetic force densities calculated in the previous sections affect the mechanical structure of the rotor and stator and produce structure- and air-borne noise. In this section, structural analysis is performed in JMAG® [5] on both example case machines to investigate their noise and vibration behavior.
4.1 Modal Analysis

One of the critical issues of electromagnetic systems is the resonance of the mechanical structure with the magnetic forces. Modal analysis of the electric machines is usually performed in order to estimate the natural frequencies and evaluate possible modifications to prevent the resonance. For instance, in [25, 26], the resonances between the mechanical structure and the torque fluctuations are detected, and a notch design is implemented to change the frequencies of the cogging torque and the torque ripple to avoid the resonance with a identified natural frequency.

The salient-pole stator topology has several vibration modes in all radial, tangential, and also axial directions. Two of them are shown in Fig. 12 for a single tooth of the machine. Due to the small dimension of the stator, all the natural frequencies are beyond audible range, i.e., over 20 kHz.

Although the claw-pole stator topology has the same stator outer diameter as the salient-pole topology, because of the thinner stator sheet, its natural frequencies are lower, as shown in Fig. 13. The stator thickness and axial length of the claws significantly affect the natural frequencies.

\[ f_n \propto \sqrt{\frac{I}{L_{cp}}}, \]  
(16)

where \( I \) and \( L_{cp} \) are the inertia and the axial length of the claws, respectively [27]. Also, the inertia of the claw is

\[ I \propto W_{cp} \cdot t_{steel}^3, \]  
(17)

where \( W_{cp} \) and \( t_{steel} \) are width and thickness of the claws, respectively [28].

Based on (16) and (17), the thinner and the longer the claws, the lower the natural frequencies. As the thickness of the stator steel sheet is limited to prevent high eddy current losses in the stator, the natural frequencies of the claws should be analyzed during the design process.

In both simulations, stators are assumed to have a solid body, however the example case machine with the salient-pole stator has a laminated stator. It has been shown that the vibration modes of the laminated stator cores have lower resonant frequencies relative to the non-laminated stator cores of the same geometry [29]. However, in this case, this effect has not been considered due to the high-frequency vibration modes.

The structural analysis of the rotor of the two example case machines (the rotors of both example case machines have the same dimensions) is shown in Fig. 14. The machine’s first natural frequency has a mode-2 shape with an elliptical deflection shape with a frequency of 16055 Hz, and all other natural frequencies are above the audible range. As shown in (13), the magnetic force harmonics with the second spatial order are not generated in the example case machines under ideal conditions; therefore, a severe resonance between the elliptical deflection mode and dominant electromagnetic forces is improbable.

4.2 Noise Analysis of Example Case Drives

The results of far-field air-borne noise simulations, i.e., 1-meter distance from the source of noise, of both example case drives are shown in Fig. 15. Two natural
frequencies of the machine with the claw-pole stator depicted in Fig. 13 are visible in the sound pressure level (SPL) spectrum of this machine; in addition, another resonance appears close to 20 kHz which is related to the third natural frequency of the claw-pole stator. On the other hand, there is no significant peak in the SPL of the machine with the salient-pole stator as all natural frequencies of this structure are above 20 kHz. This figure also shows that the dominant electromagnetic forces in the 0–3 kHz frequency range do not produce considerable air-borne noise, as they still generate negative SPL in the dB range. However, the SPL related to these forces in the case of the machine with the claw-pole stator is higher than that of the machine with the salient-pole stator, which could be related to the lower stiffness of the claw due to their small thickness compared to thicker tooth-tips of the machine with the salient-pole stator.

As a result, due to the small dimension and stiff mechanical structure of the machine with the salient-pole stator, which leads to high natural frequencies, its air-borne noise related to electromagnetic forces is barely audible. However, in the machine with the claw-pole stator, the air-borne noise in resonance frequencies could be disturbing.

Structure-borne noise, which appears as vibrations, can excite adjacent construction elements, especially in noise-sensitive environments like car interior auxiliary applications. The results of the structure-borne noise analysis of the example case machines are illustrated in Fig. 16 by acceleration contours at 333.33 Hz, which is the frequency of the dominant magnetic force density wave. Similar to the air-borne noise results, the generated acceleration of the machine with the claw-pole stator is significantly higher than that of the salient-pole one. However, the amplitudes of their magnetic force densities shown in Fig. 6 were close to each other. Thus, this difference in acceleration which is visible for all other frequencies in Fig. 17 is related to the mechanical structure’s lower stiffness.

4.3 Noise Analysis of Different Switching Strategies

The 2D-FFT analysis of two different switching strategies, i.e., PWM and AMSS, is performed in Sect. 3 and reveals that the AMSS generates magnetic force density waves with higher amplitudes compared to PWM. The result of the structure-borne noise analysis of these switching strategies in the example case drive with the salient-pole stator is shown in Fig. 18. As expected, the acceleration excited by AMSS is higher...
than the one excited by PWM in the depicted frequency range.

The experimental results comparing the noise generated by AMSS and frequency hopping PWM (FHPWM) presented in [21] prove that AMSS produces higher structure-borne noise than FHPWM, however, it does not affect air-borne noise significantly as this is dominated by the fan’s aerodynamic noise.

5 Summary

This paper studies the noise and vibration characteristics of single-phase BLDC machines in sub-fractional horsepower applications by comparing salient-pole and claw-pole stator topologies. The magnetic forces are analyzed by means of the 2D-FFT analysis in order to determine the main magnetic force density waves related to the topology or current injected harmonics resulting from different switching strategies. Furthermore, structural analyses, including modal analysis as well as sound pressure level and acceleration analyses, are performed to compare the example case drives.

The results show that although both topologies generate the same magnetic force waves with similar amplitude, the machine with the claw-pole stator produces higher acceleration harmonics than the machine with the salient-pole stator because of the mechanical structure with lower stiffness related to the thin claws. Moreover, due to the claw’s natural frequencies in the audible range and its stiffness, the sound pressure level of the machine with the claw-pole stator is higher than that of the machine with the salient-pole stator. Also, it is shown that the switching strategy can have a significant effect on the noise and vibration behavior of these machines, as AMSS generates significantly higher acceleration harmonics than PWM.

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