Abstract: Steadily increasing power demands are linked with the ongoing process of electrifying the powertrain for dominant and pure electric vehicles. Fulfilling those requirements can be achieved by a multiphase approach which is implemented with a six-phase machine with buried permanent magnets. Besides the new modelling aspects, new control possibilities arise such as controlling the current harmonics individually using vector space decomposition (VSD) methods. Here, this method is used to influence the noise, vibration and harshness (NVH) maintaining the working point in torque and speed. A reduction up to 22 dB of the main acoustic order in the significant speed range was achieved.

1 Introduction

Continuously requesting solutions for more powerful electric motors within the same space limitations in the automotive sector led to various concepts. One approach is to keep the voltage at a tried and tested level and increases the current density in the machine by applying parallel or multiphase current sharing in the machine. Different multiphase solutions are possible which led to plenty of research attention [1–4].

The dual three-phase concept with 30° electrically shifted winding sets, known as asymmetrical six phase machine, is one solution for the above-mentioned request, schematically shown in Fig. 1. This concept is favourable due to the possibility of using certified power electronic modules and an inherent opportunity to maintain operation in a limited scale in case that one of the two three-phase inverters or machine windings fail. Greater attention is required considering possible low current harmonics in an asymmetrical six-phase machine. Only small impedances are limiting the occurrence of the harmonics. These effects can be handled by using control methods like vector space decomposition (VSD) spanning three decoupled subspaces where the electric values can be mapped into [5]. This control possibility is mostly used to eliminate the current harmonics in order to reduce copper losses. Acoustical comfort is a major aspect in automotive drives. Here, the use of current harmonics is examined to improve the noise characteristics while evaluating the loss in efficiency.

Improving the sound quality without hardware design changes only by software measures is a promising advantage of the six-phase control options. Various concepts beginning with manipulating the carrier frequency [6] up to influencing the excitation current in a wound rotor synchronous machine [7] can be found in literature. The influence of current harmonics regarding the NVH characteristics in a three-phase machine is mentioned multiple times [8–11]. The potential drawback in this case is the small amount of current that needs to be controlled and its direct impact on the main harmonic stator flux distribution resulting in potentially unwanted torque pulsations. This is not the case in a dual three-phase machine due to fact that many combinations of current excitation and air-gap flux distribution are short-circuited [12].

This effect will be used in the proposed control method and is explained in more detail in the following sections.

Subsequent to this introduction, the fundamentals of poly-phase systems and their air-gap flux distribution, especially their harmonic magnetomotive force (MMF) behaviour, are reviewed. Section 3 considers the electromagnetic forces especially those responsible for audible noise excited by low-order current harmonics. In Section 4, the control method is presented. The test bench setup and measurements are outlined and discussed in Section 5 closing with a conclusion in Section 6.

2 Fundamentals

A review over the current harmonic control opportunities is given by starting with an analytical description of the stator MMF waves. Knowledge of the MMF harmonics is necessary to calculate the radial forces responsible for audible noise.

Electrical quantities $X$, such as current or voltage in a dual three-phase machine, can be described in various ways. Here, the concept from Dorell et al. using complex Fourier notation, where $o_\omega$ is the fundamental frequency, is used. The first set of three-phase systems is described as [12].
where $a = e^{j2\pi/3}$ stands for a regular 120° phase shift within a three-phase system. For the second system, $b = e^{j\pi/3}$ is introduced representing the 30° electrical phase shift between the two winding sets.

$$X_{\text{Phase } ax}(t) = \text{Re} \left\{ \sum_{k=1}^{\infty} X_e e^{jka\gamma} e^{-jk\omega t} \right\} \quad (1)$$

$$X_{\text{Phase } bx}(t) = \text{Re} \left\{ \sum_{k=1}^{\infty} X_e e^{jkb\gamma} e^{-jk\omega t} \right\} \quad (4)$$

$$X_{\text{Phase } cx}(t) = \text{Re} \left\{ \sum_{k=1}^{\infty} X_e e^{jkc\gamma} e^{-jk\omega t} \right\} \quad (6)$$

Following this description of the time-dependent electrical quantities measurable at the terminals, the spatial distribution within the machine is described with the help of winding functions denoted as:

$$n^\text{Phase } ax_m(x) = N_m \cos(m\gamma) = \frac{N_m}{2} (e^{jm\gamma} + e^{-jm\gamma})$$

$$n^\text{Phase } bx_m(x) = N_m \cos(m\gamma - \frac{2\pi}{3}) = a^m \frac{N_m}{2} (e^{jm\gamma} + e^{-jm\gamma})$$

$$n^\text{Phase } cx_m(x) = N_m \cos(m\gamma + \frac{2\pi}{3}) = a^{-m} \frac{N_m}{2} (e^{jm\gamma} + e^{-jm\gamma})$$

where $\gamma$ is the angular position in the air gap and $N_m$ the winding coefficient. Consequently, the winding functions for the second three-phase system are given by:

$$n^\text{Phase } ax_m(x) = \text{Re} \left\{ \sum_{k=1}^{\infty} X_e e^{jka\gamma} e^{-jk\omega t} \right\} \quad (1)$$

Multiplying each current with its corresponding winding function leads to the MMF waves

$$\text{MMF}(f,t) = \sum_{m=1}^{\infty} n^\text{Phase } (f) \text{e}^j\text{Phase } (t) \quad (13)$$

and to the magnetic flux density

$$B(f,t) = \Lambda_g(\text{MMF}(f,t)) \quad (14)$$

where $\Lambda_g$ is the relative permeance of the air-gap modelling the slot opening, eccentricity or saturation effects. It becomes evident that only a limited variety of combination of current time harmonics and spatial flux harmonics can exist, whereas some are short-circuited (s/c) (see (15)), and Table 1.

Exciting the system with a 5th and 7th current harmonics will not lead – in comparison with a three-phase machine – to a magnetic flux distribution in the main spatial harmonic, as shown in Fig. 1. Therefore, no major torque impact is expected. A visualisation of the effect can be observed by the stator flux distributions with different current excitations is presented in Fig. 2 showing the stator flux with a reduced rotor model.

Following these fundamentals, the electromagnetic forces are expressed by the Maxwell force vector $F_{\text{Maxwell}}$ in cylindrical coordinates [9] (see (16)). The normal and tangential component of the magnetic flux density $B_n$ and $B_t$ can be extracted from a 2D finite element analysis (2D-FEA). The tooth forces are calculated by integration along the integration surface $S_i$ of the $i$th tooth, as indicated in Fig. 3. Further on, the radial component of the Maxwell force vector $F_{\text{Maxwell},r}$ will be focused on due to the higher capability to influence the noise characteristics of an electrical machine [10].

These discrete tooth forces can be used as excitation inputs to a structural analysis, which is beyond the scope of this work. The tooth forces themselves are now representing a discrete force distribution along the air gap which can be further decomposed into time and spatial harmonic content using 2D discrete Fourier transformation (2D-DFT) techniques. Thereby, the average spatial component $F_{\text{Maxwell},s}$ is mainly focused on representing a uniformly distributed pressure acting on the teeth expanding and contracting the stator lamination. This force component is strongly responsible for exciting the structural eigen mode 0, also called breathing mode of the electrical machine. This mode is acoustically one of the most critical for many permanent magnet synchronous machines [10].

### 3 NVH influence of current harmonics

Although there is nearly no usable torque produced by applying 5th and 7th current harmonics, the resulting stator magnetic flux density suggests an influence on the tooth forces, see the integration paths (black lines) in Fig. 3. A radially acting magnetic flux distribution is distinctly noticeable close to the tooth tips which will as a consequence contribute to the Maxwell force and, therefore, result in different tooth forces.

To study the impact capability of the 5th and 7th current harmonics, a sensitivity analysis was performed using Latin Hypercube Sampling setting up a design of experiment by varying amplitude and phase. Dynardo OptiSlang™ is used in this case due to the following reasons:

(i). Managing parallel simulations and performing stochastic analysis

(ii). To overcome the analytic modelling impediment for synchronous machines with buried magnets

$$\text{MMF}(f,t) = \sum_{m=1}^{\infty} n^\text{Phase } (f) \text{e}^j\text{Phase } (t) \quad (15)$$
The current harmonic combinations are applied to FEA simulations with Matlab™ and the tooth force result was stored for further spatial and time decomposition. Fig. 4 shows a typical outcome of a sensitivity analysis generating a Meta model of optimal prognosis approximating the behaviour of the 5th current harmonic subspace. Each dot represents a tooth force result which was decomposed in Table 1 into VSD projecting the main and low current harmonics into distribution oscillating in time with a harmonic order of 48 times the 48th harmonic oscillation of the force shape 0.

4 Control method and application

In this section, the control of low current harmonics is outlined which were presumed to be available up to this point. Asymmetrical six-phase machines offer the opportunity to apply VSD projecting the main and low current harmonics into decoupled subspaces. The basic idea behind VSD is to extend and rearrange the well-known Park transformation projecting the electrical quantities to a rotor position dependent reference frame aligned with the magnetising d-axis and a perpendicular q-axis. By rearranging

$$ T_{\text{park}}(\theta) = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} $$

(17)

to

$$ T_{\text{dual}}^{\text{sub}}(\theta) = \frac{2}{3} \begin{bmatrix} T_{\text{park}}(\theta) & O^{2\times3} \\ O^{2\times3} & T_{\text{park}}(\theta + \frac{\pi}{6}) \end{bmatrix} $$

(18)

$$ T_{\text{dual}}^{\text{sub}}(\theta) $$ can further be multiplied by $$ T_2^{*\times*} $$ [13]

$$ T_2^{*\times*} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ -1 & 0 & 1 & 0 \end{bmatrix} $$

(19)

eventually getting

$$ T_{\text{dual}} = \frac{1}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & 0 & -\frac{\sqrt{3}}{2} \\ 0 & \sqrt{3} & -\frac{\sqrt{3}}{2} & 1 & 1 & -\frac{1}{2} \\ 0 & \sqrt{3} & 1 & -1 & 1 & \frac{1}{2} \\ -1 & 1 & 1 & \frac{\sqrt{3}}{2} & 0 & \frac{\sqrt{3}}{2} \end{bmatrix} $$

(20)

$$ T_{\text{dual}} $$ transforms the six-phase current input for 30° electrically shifted winding sets into two decoupled subspaces: the fundamental component and the (12k ± 1)th harmonics with $$ k \in \mathbb{N}_0 $$ are mapped into one subspace, further called H01-subspace, and the (12k − 6 ± 1)th harmonics are mapped into a second subspace, called the H57-subspace.

The principle of the control structure is separated into three parts performing in the following sequence:

(i). The working point in torque and speed defines the main harmonic components $$ i_{\text{H}01} $$, $$ i_{\text{H}57} $$ originating from previous calculated maximum torque per amphere and maximum torque per flux set points

(ii). Synchronising the main current harmonic content

(iii). 5th and 7th NVH-optimised current harmonic controls

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Six phase synchronous speeds for time and space harmonics of the stator flux distribution [12]</th>
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<tr>
<td>Time harm. $$ k $$</td>
<td>1</td>
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<tr>
<td></td>
<td>$$ \pm 1 $$</td>
</tr>
<tr>
<td>1</td>
<td>$$ \frac{a_1}{p} $$</td>
</tr>
<tr>
<td>5</td>
<td>s/c</td>
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<tr>
<td>7</td>
<td>s/c</td>
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<tr>
<td>11</td>
<td>$$ -\frac{11a_{11}}{p} $$</td>
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<tr>
<td>13</td>
<td>$$ \frac{13a_{13}}{p} $$</td>
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Fig. 2 | Stator flux distribution in a dual three phase machine with 30° electrically shifted winding sets (excl. PM) |
(a) Purely fundamental current applied, (b) 5th and 7th current harmonics applied

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The two three-phase windings have to be as symmetrical as possible. Even small differences between the two systems can lead to unbalanced currents so that VSD has to be extended with a current controller synchronising the main current harmonic content between the two systems. Subsequently when the main current harmonic symmetry is achieved, the NVH control can be initiated. Therefore, previously calculated set points for \( i_{d,H05}, i_{q,H05}, i_{d,H107}, i_{q,H107} \) minimising the oscillation of the force 0 shape – see Section 3 – can be chosen. Further optimisation is achieved by applying multiple voltage variations in \( u_{d,H05}, u_{q,H05}, u_{d,H107}, u_{q,H107} \) at the test bench maintaining the working point in torque and speed. Within a subsequent post-processing step, the optimum set point can finally be detected and stored. As long the machine is not considerably affected by any ageing, the stored voltage for the optimum set point can be applied. Hence, the electrical machine will give an instantaneous and stable response with the optimum current set point. Otherwise, if the current response differs too much from the previously stored optimised current set point i.e. applying the above-mentioned approach to find an optimal set point for \( i_{d,H05}, i_{q,H05}, i_{d,H107}, i_{q,H107} \), minimising the force 0 shape oscillation.

To control the 5th and 7th current harmonics is time-consuming because of very slow parametrised PI controller. This is necessary due to the circumstance that the 5th and 7th current harmonics are mapped into the same subspace. Consequently, additional filtering is needed to extract the mean values after applying rotation matrices \( T_{rot}(−5\theta) \) and \( T_{rot}(7\theta) \).

### 5 Test bench verification

Numerous tests were performed to verify previous studies which were predominantly based on simulated results, namely

(i). Voltage variations in \( u_{d,H05}, u_{q,H05}, u_{d,H107}, u_{q,H107} \)

(ii). Instant turn on of an optimal NVH current set point with an additional power analyser connected to the test bench

(iii). Various speed ramps including an optimised current excitation

The noise mitigation control was applied at around 6000 rpm close to the breathing Eigen mode of the test bench device previously identified as a psychoacoustically critical working point. At this speed, the 48th order is at a frequency of 4.8 kHz, where the human noise perception is very sensitive [14]. The measurements were performed on an acoustical E-machine component test rig in a room according to standard DIN EN ISO 3744 (semi-anechoic chamber). The housing structure and integration of the electromagnetically active components is as close to a vehicle setup as possible on a component test bench. As the power electronics are not mounted in the test chamber, only the sound radiation of the machine can be evaluated without interferences of vibrations of the inverter housing. The microphone setup is cubically arranged which can be seen in Fig. 5.

For the evaluation of the air-borne noise measurements, the root mean squared value of all the sound pressures is taken. Out of this measurement, the Fourier spectrum for the relevant 48th order – multiples of the frequency of the rotational speed – are taken using a high resolution speed signal. In Fig. 6, a sequence from the voltage variation test run is shown. At each vertical dotted line, a current response is taken from the measurement and fed back to the FEA recalculating the tooth forces. A correlation between the sound pressure and the tooth forces is visible and confirms the above-mentioned approach to find an optimal set point for \( d, H05, q, H05, d, H107, q, H107 \), minimising the force 0 shape oscillation.

Instantaneously turning on the NVH control i.e. applying a previously stored optimised current set point i.e. applying the corresponding voltage leads to a 22 dB reduction of the root mean-
The current excitation is optimised at a specific rotational speed e.g. 5900 rpm. In addition, the impact of this voltage harmonic content at nearby rotational speeds is investigated. Therefore, speed runs were performed and their results are shown in Fig. 8. To achieve the optimal current harmonics, voltage harmonics are applied. A purely sinusoidal current is not the acoustical optimum. Run up measurement outlines a reduced sound pressure at the neighboring rotational speeds offering an opportunity to reduce the efforts in the time-consuming optimum current set point generation.

6 Conclusion

Here, a control approach improving the noise vibration and harshness characteristics of a dual three-phase synchronous machine with buried permanent magnets and 30° electrically shifted winding sets is presented. The device under test here was controlled by a 10 kHz switching frequency double three-phase 2-level inverter and the optimisation took place at around 400 Hz fundamental frequency. The control method can arbitrarily be activated in an acoustically critical working point, while maintaining torque and speed. This is done by applying a 5th and 7th current harmonics which can previously be obtained by FEA or through test bench characterisation. A sound pressure reduction of the noticeable slot harmonic order of about 22 dB was achieved at 5900 rpm and 50 Nm by a concomitant efficiency reduction from DC to mechanical power of about 4%. This efficiency reduction will be further investigated. Due to the higher demand of current and voltage, the shown control strategy cannot be applied in the full operational range. Nevertheless for acoustically relevant working points (e.g. part load or constant speed drive), the current harmonic injection is a feasible approach to improve sound quality.

7 References


Fig. 7 Activation of proposed control
(a) RMS Sound pressure of order 48, (b) Pre-activation: H01 control, (c) Post-activation: H01 + H57 control, (d) AC Power analysis

Fig. 8 RMS value of microphones for 50 Nm speed ramps at various voltage excitations

squared sound pressure at the 48th harmonic order, as shown in Fig. 7a. In addition, a power analyser (DEWE-800) was connected logging the transient current signals in Figs. 7b and c and analysing the AC power, see Fig. 7d. The activation of the proposed control leads to higher current amount and thus increases the apparent power. Most of the apparent power is reactive power that is needed to establish the stator flux distribution described in Section 3. It becomes evident that this is not an energy optimised working point any more mainly due to reduced efficiency in the power electronics and the additional copper losses.