

Letters

Analysis and Suppression of Negative-Sequence Current in Single-Channel Operation of Dual Three-Phase PMSM With Zero Angle Displacement

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Abstract—In high-power applications, such as wind power generation, dual three-phase permanent-magnet synchronous machines (PMSMs) with two power conversion channels grow in popularity owing to decent fault-tolerant capability. This letter focuses on the current control of dual three-phase PMSMs with zero angle displacement, particularly in scenarios where one channel experiences a malfunction. The influence of asymmetric mutual-inductances on negative-sequence current is investigated. Subsequently, a harmonic control method based on non-integer sliding discrete Fourier transform is proposed to suppress the undesired current harmonics. No additional parameter tuning or digital filters are required, which facilitates engineering implementation and integration. Experimental results on a down-scaled drive system validate the effectiveness of the proposed method.

Index Terms—Dual three-phase permanent-magnet synchronous machine (PMSM), negative-sequence current suppression, sliding discrete Fourier transform (SDFT).

I. INTRODUCTION

MULTIPHASE permanent-magnet synchronous machines (PMSMs) have found extensive application in industrial fields, including electric propulsion and wind power generation owing to high torque density, high power rating, and decent fault-tolerant capability [1], [2]. The dual three-phase (DTP) PMSM is one of the popular multiphase PMSM configurations, as it can utilize commercial three-phase inverters [3], [4], [5]. Notably, harmonic current suppression is vital for DTP PMSMs, drawing extensive attention from both academia and industry.

According to the angle displacement between the two sets of three-phase windings, the DTP machine can be categorized as asymmetric (30° angle displacement) and symmetrical (0° or 60° angle displacement) DTP machine. For the former, the fifth and seventh harmonic components can be decomposed through

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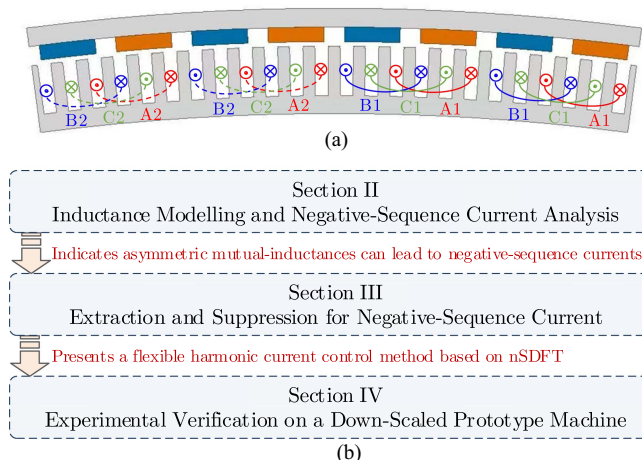


Fig. 1. DTP PMSM with zero angle displacement and associated research contents. (a) Partial model of an external-rotor DTP PM wind power generator. (b) Arrangement of the rest part of this letter.

vector space decomposition (VSD) [6]. Since the conventional proportional–integral (PI) regulator cannot well handle the harmonic disturbance, several methods were proposed on the basis of VSD scheme to further reduce current harmonics. In [7], the undesired current harmonics were suppressed by using resonant controllers in parallel with PI regulators. However, the parameter tuning of resonant controller is slightly complicated and the interference between the different frequencies needs to be eliminated. In [8], the fifth and seventh harmonic currents were regulated by PI controller based on multiple synchronous reference frames (SRFs). The harmonics can be converted into dc components within corresponding SRFs by corresponding order synchronous coordinate transformation, and then be detected by low-pass filters. Nevertheless, the used digital filters can cause significant delay in the control loop, and careful design of cutoff frequency parameters is crucial for optimal performance. Moreover, the previous researches are mainly focused on asymmetric DTP machines, and the current harmonic issues in symmetrical ones are rarely investigated.

The symmetrical DTP PMSMs, especially those with 0° angle displacement (hereafter referred to as zero angle displacement), can increase the system interchangeability and redundancy. This is achievable because the hardware and software can be identical

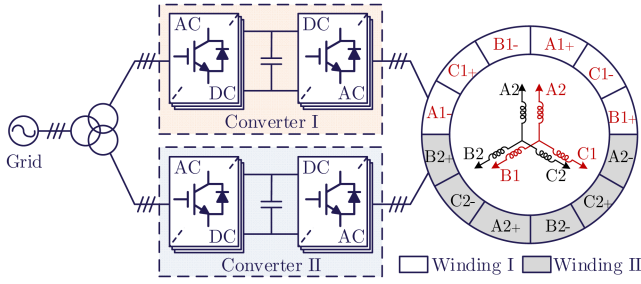


Fig. 2. DTP PMSM drive system with two power conversion channels.

for controlling both sets of windings. Moreover, DTP PMSMs with zero angle displacement are suitable for modular manufacturing [9]. Hence, this type of PMSM could be a solution for megawatt-level drive systems, such as electric ship propulsion and wind turbine generator. For instance, Fig. 1(a) shows a partial model of a 576-slot/192-pole DTP PM wind power generator with zero angle displacement, which is composed of multiple 24-slot/8-pole base machines and featuring modular stator sectors. Furthermore, it was reported that for 12-slot/10-pole DTP PMSMs, the winding configuration with zero angle displacement can decrease the short-circuit current during fault operations [10]. Noted that for high-power applications, such as wind power generation, paralleling power conversion channels can be employed to increase the power level and fault-tolerant capability [11]. Specifically, the system can still operate even if the power converter or machine windings of one power conversion line malfunctions. The fault channel can be directly removed, and another set of windings of the DTP machine can operate independently to tolerate faults conveniently. Under this specific operating condition, additional stator current harmonics may arise. Yet, few studies attempt to carry out in-depth analysis and research on current harmonics in DTP PMSMs with zero angle displacement, especially for conditions where one three-phase channel malfunctions and becomes disconnected.

The rest of this letter follows the structure outlined in Fig. 1(b). This study reveals that in DTP PMSMs with zero angle displacement, asymmetric mutual-inductances can cause the pulsating impedance, which can lead to negative-sequence current when one power channel is cutoff. A harmonic control method based on the improved sliding discrete Fourier transform (SDFT) is proposed to suppress the negative-sequence current. Through accurate and real-time sliding spectrum analysis, the control scheme can extract undesired current harmonics and then transform them to corresponding SRFs for regulation. Experimental results are provided to demonstrate the efficacy of the presented analysis and proposed method.

II. MODELING OF DTP PMSM WITH ZERO ANGLE DISPLACEMENT

Paralleling power conversion lines are commonly used to improve the power level and fault-tolerant capability of large-capacity wind energy conversion systems [11]. The diagram of DTP PMSM drives with two power conversion channels, as shown in Fig. 2. In terms of fault-tolerant operation of such

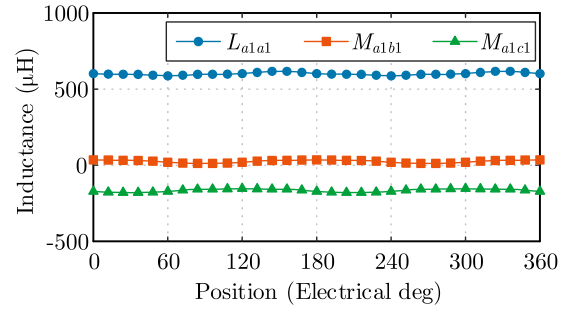


Fig. 3. Inductance waveforms from finite-element analysis.

multiunit systems, the most direct approach involves isolating the faulty three-phase set [12]. This method eliminates the need for a custom postfault algorithm, particularly when each set operates independently regulated, simplifying implementation, and enhancing practicality for industrial applications. In the case of DTP PMSM with zero angle displacement, when one three-phase channel malfunctions and is disconnected, the system can operate like a standard three-phase drive system. However, due to the asymmetric relative position within one set of three-phase windings, the mutual inductance between each phase is not the same. This issue is often overlooked, and this section will provide a detailed analysis.

Ignoring the magnetic saturation, mutual leakage inductance, and core losses, the voltage and flux models in stationary frame can be represented as

$$\begin{cases} U_s = R_s I_s + p\psi_s \\ \psi_s = L_s I_s + \psi_r \end{cases} \quad (1)$$

where p is the derivative operator, U_s is the stator voltage, R_s is the stator resistance, I_s is the stator current, L_s is the winding inductance, ψ_s is the stator flux, and ψ_r is the PM flux. Specifically, L_s can be expressed as

$$L_s = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix}_{6 \times 6} \quad (2)$$

where L_{11} and L_{22} represent the inductance matrix of the first and second winding set, respectively, L_{12} and L_{21} represent mutual inductances between two winding sets. All four matrices are 3×3 dimensional matrices, and it is a common practice to assume that $L_{11} = L_{22}$ and $L_{12} = L_{21}$.

Moreover, the inductance waveforms of the machine depicted in Fig. 1(a), obtained from finite-element analysis, are presented in Fig. 3. The inductance matrix L_{11} at this time can be expressed as

$$L_{11} = \begin{bmatrix} L_{a1a1} & M_{a1b1} & M_{a1c1} \\ M_{b1a1} & L_{b1b1} & M_{b1c1} \\ M_{c1a1} & M_{c1b1} & L_{c1c1} \end{bmatrix} = \begin{bmatrix} L_1 & M_1 & M_2 \\ M_1 & L_1 & M_2 \\ M_2 & M_2 & L_1 \end{bmatrix} \quad (3)$$

where L_{a1a1} , L_{b1b1} , and L_{c1c1} represent self-inductances, M_{a1b1} , M_{a1c1} , M_{b1a1} , M_{b1c1} , M_{c1a1} , and M_{c1b1} represent mutual-inductances, and $M_1 \neq M_2$. This phenomenon is caused by asymmetric relative position within one set of three-phase windings. While the analysis is based on an external-rotor machine, the asymmetric mutual-inductance phenomenon occurs in both external-rotor and internal-rotor machines.

For better representation, the matrix \mathbf{L}_p is introduced to represent the inductance matrix of a standard three-phase machine equivalent to two sets of windings connected in parallel [13], which can be expressed as

$$\mathbf{L}_p = \begin{bmatrix} L_0 & M_0 & M_0 \\ M_0 & L_0 & M_0 \\ M_0 & M_0 & L_0 \end{bmatrix}. \quad (4)$$

Then, (2) can be rewritten as (5) shown at the bottom of this page.

Using synchronous coordinate transformation, the inductance matrix of one set three-phase winding in SRF can be represented as

$$\mathbf{L}_{11dq} = \begin{bmatrix} L_{ave} + \frac{2}{3}M_{asy} \cos \beta & -\frac{2}{3}M_{asy} \sin \beta \\ -\frac{2}{3}M_{asy} \sin \beta & L_{ave} - \frac{2}{3}M_{asy} \cos \beta \end{bmatrix} \quad (6)$$

where L_{ave} represents the average component, M_{asy} represents the asymmetric component of mutual-inductances, and β represents the phase information. They can be expressed as

$$L_{ave} = L_1 - \frac{1}{3}M_1 - \frac{2}{3}M_2, M_{asy} = M_1 - M_2, \beta = 2\theta_e - \frac{2}{3}\pi \quad (7)$$

where θ_e is the electrical position. It can be noted that the non-diagonal elements of the inductance matrix in (6) are not zero due to asymmetric mutual-inductances.

Moreover, the voltage equation of one set three-phase winding in the SRF (taking winding I as an example) can be expressed as

$$\begin{aligned} \begin{bmatrix} u_{d1} \\ u_{q1} \end{bmatrix} &= R_s \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} \\ &+ \omega_e \begin{bmatrix} \frac{2}{3}M_{asy} \sin \beta & -L_{ave} + \frac{2}{3}M_{asy} \cos \beta \\ L_{ave} + \frac{2}{3}M_{asy} \cos \beta & -\frac{2}{3}M_{asy} \sin \beta \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} \\ &+ \omega_e \begin{bmatrix} -\frac{2}{3}M_{asy} \sin \beta & L_{ave} - \frac{2}{3}M_{asy} \cos \beta \\ -L_{ave} - \frac{2}{3}M_{asy} \cos \beta & \frac{2}{3}M_{asy} \sin \beta \end{bmatrix} \begin{bmatrix} i_{d2} \\ i_{q2} \end{bmatrix} \\ &+ 2(L_0 - M_0) \begin{bmatrix} p & -\omega_e \\ \omega_e & p \end{bmatrix} \begin{bmatrix} i_{d2} \\ i_{q2} \end{bmatrix} + \omega_e \begin{bmatrix} 0 \\ \psi_f \end{bmatrix} \\ &+ \begin{bmatrix} L_{ave} + \frac{2}{3}M_{asy} \cos \beta & -\frac{2}{3}M_{asy} \sin \beta \\ -\frac{2}{3}M_{asy} \sin \beta & L_{ave} - \frac{2}{3}M_{asy} \cos \beta \end{bmatrix} p \begin{bmatrix} i_{d1} - i_{d2} \\ i_{q1} - i_{q2} \end{bmatrix} \end{aligned} \quad (8)$$

where R_s is phase resistance, ω_e is rotor angular velocity, u_{d1} and u_{q1} represent dq -axes stator voltage of winding I, i_{d1} and i_{q1} represent dq -axes stator current of winding I, i_{d2} and i_{q2}

represent dq -axes stator current of winding II, and ψ_f represents the amplitude of PM flux linkage.

In accordance with (3)–(8), asymmetric mutual-inductances can induce the pulsating impedance in the d - q frame, which can degrade the control performance. During dual-channel operation with identical loads on both windings, where $i_{d1} = i_{d2}$ and $i_{q1} = i_{q2}$, the impact of the asymmetrical mutual-inductance on the voltage equations of one winding set can be canceled out. Conversely, in single-channel operation, the pulsating impedance in the d - q frame caused by asymmetric mutual-inductances can lead to harmonic currents. Specifically, when the stator voltages are sinusoidal, i.e., when u_d and u_q are both dc components, i_d and i_q are the combination of dc components and the negative second-order harmonic components, respectively. These harmonics can increase the torque ripple and system losses [14]. Hence, it is critical to minimize current harmonics for working conditions where only one three-phase channel is in operation.

III. PROPOSED CURRENT CONTROL SCHEME

A. SDFT-Based Harmonic Extraction

Generally, discrete Fourier transform (DFT) can transform the input discrete signals into frequency-domain as

$$X^k = \sum_{m=0}^{N-1} x(n)W_N^{-mk} \quad k = 0, 1, \dots, N-1, \quad W_N = e^{j\frac{2\pi}{N}} \quad (9)$$

where X^k represents the k th-bin frequency component of DFT, $x(n)$ represents the input signal obtained by sampling the time-domain signal $x(t)$ with sampling frequency of f_s , m is the time index, and W_N is the complex twiddle factor. Noted that the direct calculations of the DFT using (9) can impose a high computational burden. Furthermore, during the calculation process, no estimate of the current amplitude of the equivalent sine wave is available. Hence, in recent years, the SDFT, which can compute the DFT bins using a recursive scheme, was introduced to reduce the computational burden [15]. The difference equation of traditional SDFT can be expressed as

$$X_n^k = \sum_{m=0}^{N-1} x_{q+m}W_N^{-mk} = W_N^k (X_{n-1}^k - x_{n-N} + x_n) \quad (10)$$

where $q = n-N+1$, X_n^k represents the DFT result for the current window of the sequence $\{x(i), i = q, q+1, q+2, \dots, n\}$, and X_{n-1}^k represents the DFT result for the previous window. That is, the transform window of size N is shifted one sample at a

$$\begin{aligned} \mathbf{L}_s &= \begin{bmatrix} \mathbf{L}_{11} & \mathbf{L}_{12} \\ \mathbf{L}_{21} & \mathbf{L}_{22} \end{bmatrix}_{6 \times 6} = \begin{bmatrix} \mathbf{L}_{11} & 2\mathbf{L}_p - \mathbf{L}_{11} \\ 2\mathbf{L}_p - \mathbf{L}_{11} & \mathbf{L}_{11} \end{bmatrix}_{6 \times 6} \\ &= \begin{bmatrix} L_1 & M_1 & M_2 & 2L_0 - L_1 & 2M_0 - M_1 & 2M_0 - M_2 \\ M_1 & L_1 & M_2 & 2M_0 - M_1 & 2L_0 - L_1 & 2M_0 - M_2 \\ M_2 & M_2 & L_1 & 2M_0 - M_2 & 2M_0 - M_2 & 2L_0 - L_1 \\ 2L_0 - L_1 & 2M_0 - M_1 & 2M_0 - M_2 & L_1 & M_1 & M_2 \\ 2M_0 - M_1 & 2L_0 - L_1 & 2M_0 - M_2 & M_1 & L_1 & M_2 \\ 2M_0 - M_2 & 2M_0 - M_2 & 2L_0 - L_1 & M_2 & M_2 & L_1 \end{bmatrix}. \end{aligned} \quad (5)$$

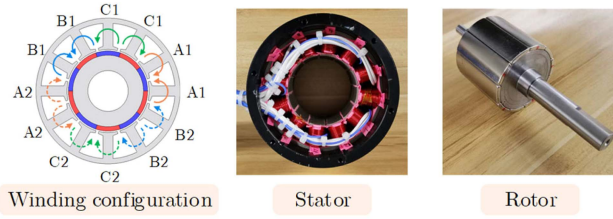


Fig. 7. Down-scaled prototype machine for the experimental verification.

subscript $*$, p , and n represent the reference, positive-sequence, and negative-sequence component, respectively.

The proposed scheme consists of two parts: 1) harmonic current extraction based on nSDFT and 2) harmonic current controller. Due to pulsating impedance, i_{dq} obtained from synchronous coordinate transformation is a combination of dc component and second-order harmonic component. The second-order harmonic current i_{dq_ac} can be obtained by real-time harmonic detection shown as Fig. 4. The dc component i_{dq_dc} of dq -axes currents can be obtained by subtracting i_{dq_ac} from i_{dq} . It is noted that since the proposed harmonic current detection method is based on real-time sliding spectrum analysis, it can accurately extract current harmonics of one or more frequencies without interference from other frequencies. Furthermore, the decomposed current harmonic transformed into negative SRF by the transformation as

$$T_{dq} = \begin{bmatrix} \cos(-2\omega_e t) & \sin(-2\omega_e t) \\ -\sin(-2\omega_e t) & \cos(-2\omega_e t) \end{bmatrix}. \quad (15)$$

Based on the proposed harmonic extraction and conversion process, the harmonic currents can be transformed into dc component i_{dq} . Then, due to the controlled variables in the proposed scheme are all dc components, only the conventional PI controllers are used to regulate the fundamental current and negative-sequence current. This approach implements a current control method using multiple reference frames. The bandwidth of the PI controllers in each reference frame should not exceed that of the harmonic component detection to ensure accurate regulation of harmonic currents to their reference values [18]. The negative-sequence current caused by asymmetric mutual-inductances can be suppressed by setting the references to zero. The input of the modulation strategy, i.e., the reference voltage, consists of the sum of positive-sequence output voltages $u_{\alpha\beta p}^*$ and negative-sequence output voltages $u_{\alpha\beta n}^*$. In the proposed scheme, only simple PI regulators are used, thus avoiding complex controller design and excessive parameter tuning.

IV. EXPERIMENTAL VERIFICATION

The proposed control method is experimentally validated on a down-scaled DTP PMSM as depicted in Fig. 7. An internal-rotor prototype machine with zero angle displacement is manufactured, with each set of three-phase windings distributed in half of the stator as shown in Fig. 2. The inductance waveforms of this machine are presented in Fig. 8, revealing noticeable mutual-inductance asymmetry. The test machine is driven by two three-phase inverters and digitally controlled within a dSPACE

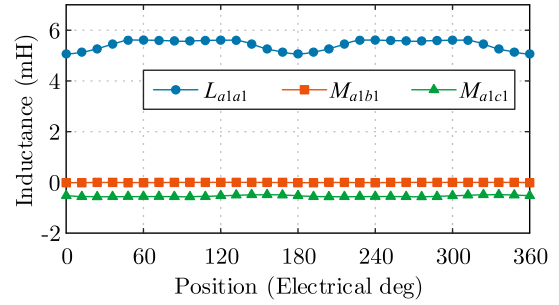


Fig. 8. Inductance waveforms of the down-scaled prototype machine.

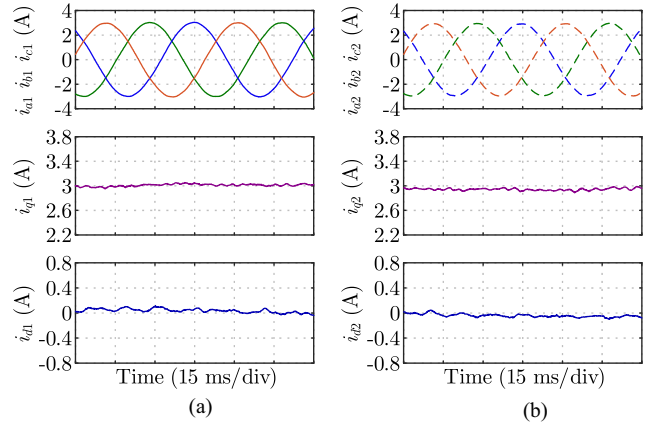


Fig. 9. Experimental results of two-channel operation mode. (a) Winding I. (b) Winding II.

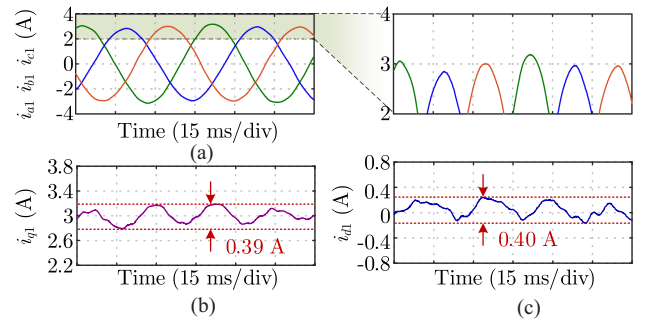


Fig. 10. Experimental results of single-channel operation mode. (a) Phase currents. (b) q -axis current. (c) d -axis current.

system. The sampling frequency is set to be the same as the switching frequency, which is 10 kHz.

Fig. 9 shows the experimental results of the two-channel operation. The reference speed is set as 240 r/min. Due to the coupling effect between the two sets of windings, the three-phase currents of each winding are symmetric and there are no obvious harmonics in dq -axis currents. As a comparison, Fig. 10 presents experimental results of single-channel operation mode. It is noticeable that three-phase currents are unbalanced, and there exist second-order harmonics in dq -axis currents, which can degrade the system performance. This implies that even for a well-designed DTP PMSM with zero angle displacement, unbalanced currents will also exist under single-channel operation, aligning with the presented theoretical analysis.

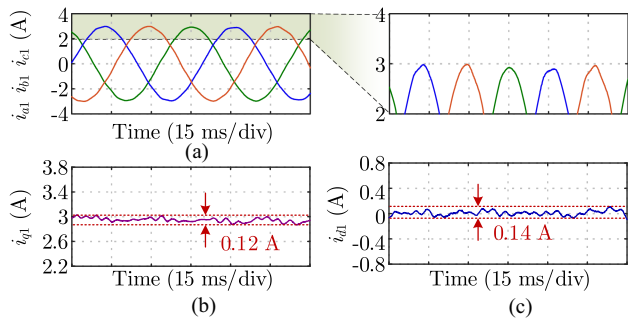


Fig. 11. Experimental results of one channel operation mode with proposed control method. (a) Phase currents. (b) q -axis current. (c) d -axis current.

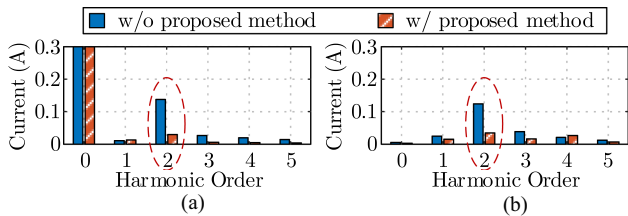


Fig. 12. Harmonic spectrum comparison. (a) q -axis current. (b) d -axis current.

Fig. 11 displays experimental results of the single-channel operation mode with the proposed control method. The fluctuations in q - and d -axis current decrease from 0.39 and 0.40 A to 0.12 and 0.14 A, respectively, indicating that the proposed method has a decent harmonic suppression effect. Moreover, Fig. 12 illustrates a comparison of the harmonic spectrum with and without the proposed method. It is evident that the second-order harmonics caused by asymmetric mutual-inductances can be effectively attenuated through the utilization of the proposed method.

V. CONCLUSION

This letter concentrates on the issue of current harmonics in symmetrical DTP PMSMs, with a specific emphasis on the single-channel operation mode. The research shows that the asymmetric mutual-inductances caused by asymmetric relative position between one set of windings can contribute to negative-sequence currents, a phenomenon that is particularly evident in single-channel operation. In response, a flexible harmonic control method utilizing nSDFT is proposed to mitigate these undesired harmonics. The achievements are outlined as follows.

- 1) Only conventional PI controllers are used, eliminating the need for additional parameter tuning or digital filters.
- 2) The frequency of target harmonic can be flexibly selected, allowing the proposed scheme to be applied for arbitrary current harmonic detection and regulation.

Finally, the effectiveness of the presented analysis and proposed method is verified by laboratory tests. These tests confirm the existence of negative sequence current, and demonstrate that

the proposed scheme effectively suppresses dq -axis harmonic current ripples.

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