Letters

An Online Compensation Method of VSI Nonlinearity for Dual Three-Phase PMSM Drives Using Current Injection

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***Abstract*—Compensation of voltage-source-inverter (VSI) nonlinearity is of great importance in parameter identification and position sensorless control method for motor drives. In this letter, a simple online compensation method has been proposed for the dual three-phase permanent-magnet synchronous motor (PMSM) drives. The key is to observe the change of voltage references contained VSI nonlinearity after injecting currents in z1z2-axis purposely. Compared with the existing estimation methods for VSI nonlinearity, the proposed method not only can avoid the tedious and time-consuming offline test for modeling inverter but also can achieve real-time estimation without machine parameters. Moreover, the current injection on z1z2 subspace has a slight influence on the *dq* subspace (the torque subspace) thanks to the multiple decoupling subspaces of dual three-phase PMSM. The experiments have been given to verify the validity of the proposed method.**

***Index Terms*—Current injection, dual three-phase permanent-magnet synchronous motor (PMSM) drive, online compensation, voltage-source-inverter (VSI) nonlinearity.**

I. INTRODUCTION

VOLTAGE-SOURCE-INVERTER (VSI) nonlinearity will result in the error voltages between the reference voltages and the output actual voltages [1]. Thus, it brings the degraded performance of state estimation for some control schemes of motor drives, e.g., position sensorless control, where the reference voltages are used to estimate the position considering the inconvenient measurement of the actual output PWM waveform. Moreover, the low-order harmonic components such as the fifth and the seventh order harmonics will be excited due to the VSI nonlinearity. This distortion will, in turn, lead to torque pulsations and the degradation of machine performance especially at a low-speed region. Therefore, it is of great importance to investigate the compensation method of VSI nonlinearity.

In the past few decades, a lot of research work have been carried out for compensation of VSI nonlinearity in three-phase motor drives. The existing methods are mainly categorized into two types: offline test methods and online estimation methods. The offline method can construct the detailed model of VSI nonlinearity by considering its nonideal characteristic such as the dead time, rise/fall time, voltage drop of semiconductors [2], and parasitic capacitors [3]. Recently, the variations of dc-link voltage and carrier frequency have been further taken into account for the accurate model in [4]. The inverter-model-based offline method can offer better compensation performance. However, it is also accused of the tedious operation and time-consuming by acquiring sufficient data of the entire operating conditions.

In order to guarantee the performance of the compensation, the online methods have been investigated based on the system model or identification algorithm. Regarding the VSI nonlinearity as the equivalent disturbance, many system-model-based observers have been presented in [5] and [6]. These online observers are expected to achieve satisfactory performance but they are limited by the accuracy of the employed machine parameters. Moreover, the model reference adaptive system has been employed for the online estimation of the amplitude of error voltages in [7], where the resistance and flux linkage uncertainty can be suppressed. However, the variation of inductance has not been discussed. In general, the performances of the online method usually rely on the accuracy of machine parameters. To the best of the authors' knowledge, all the work of compensation of VSI nonlinearity are for three-phase motor drives, and the related investigation for dual three-phase motor drives is still absent.

As reported in [1] and [4], the error voltages are expressed as the function of signs of phase currents in the stationary reference frame. In order to obtain their more compact form and simplify the compensation method, the model of VSI nonlinearity has to be rewritten as the function of rotor angle and the current angle in the rotating synchronous reference frame. Although the error voltages of each phase between the three-phase drive and dual three-phase drive are identical, it is difficult to directly derive the concise analytical solution about the error voltages of dual three-phase PSMM drives due to the increasing number of phase and subspace. On the other hand, the features of multiple subspaces can provide more control freedoms for the dual three-phase drive

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to utilize the current injection method for compensating VSI nonlinearity.

Striking the balance between simplicity and accuracy, a simple online compensation method has been proposed for dual three-phase permanent-magnet synchronous motor (PMSM) drives in this letter. Different from existing methods, the amplitude of error voltages caused by VSI nonlinearity is calculated from the voltage differences using current injection. Thanks to the multiple decoupling subspaces of dual three-phase PMSM, the proposed method does not need the prior knowledge of machine parameters and has a slight influence on the system operation. The experiments have been carried out to validate the proposed method.

II. MODEL OF VSI NONLINEARITY FOR DUAL THREE-PHASE PMSM DRIVES

A. Model of Dual Three-Phase PMSM

The stator windings of the dual three-phase PMSM can be considered as two sets of three-phase stator windings (named ABC and DEF windings) with a phase shift of 30 electrical degree. Using the vector space decomposition (VSD), the current and voltage vectors of dual three-phase PMSM can be mapped into three orthogonal subspaces [8]. As for the dual three-phase phase PMSM with isolated neutral points, the components of zero-sequence subspace are zero. Hence, the dynamic model of other two subspaces for dual three-phase PMSM drive can be expressed in rotating synchronous reference frame as [9]

$$\begin{aligned} u_d &= R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \\ u_q &= R_s i_q + L_q \frac{di_q}{dt} + \omega (L_d i_d + \psi_m) \\ u_{z1} &= R_s i_{z1} + L_{z1} \frac{di_{z1}}{dt} + \omega L_{z2} i_{z2} \\ u_{z2} &= R_s i_{z2} + L_{z2} \frac{di_{z2}}{dt} - \omega L_{z1} i_{z1} \end{aligned} \tag{1}$$

where L_{dq} and L_{z1z2} are the *dq*-axis inductance and z1z2-axis inductance, respectively. R_s is the stator resistance and ψ_m denotes the rotor flux linkage. *u* and *i* stand for the voltage and current, respectively. The subscripts "*dq*" and "z1z2" denote the *dq* reference frame and the z1z2 reference frame, respectively.

On the other hand, the double *dq* model is widely used in the analysis and control of dual three-phase PMSM drives. And it is necessary to demonstrate the relationship between the VSD model and the double *dq* model as given by [9]

$$\begin{aligned} \boldsymbol{F}_{dq} &= 0.5(\boldsymbol{F}_{d1q1} + \boldsymbol{F}_{d2q2}) \\ \boldsymbol{F}_{z1z2} &= 0.5(\boldsymbol{F}_{d1q1} - \boldsymbol{F}_{d2q2})^* \end{aligned} \tag{2}$$

where the vector $\boldsymbol{F}$ stands for the voltage and current. The subscript "$*$" stands for the complex conjugate of the variable. The subscript "$d1q1$" and "$d2q2$" denote the rotating synchronous reference frame of the first set of three-phase winding and the second set of three-phase winding, respectively.

B. Model of VSI Nonlinearity for Dual Three-Phase Drives

According to the conclusion in [10], the error voltages caused by VSI nonlinearity for dual three-phase drives can be expressed as

$$\begin{bmatrix} \Delta\, u_d \\ \Delta\, u_q \\ \Delta u_{z1} \\ \Delta u_{z2} \end{bmatrix} = \frac{2A_p}{3} \times \begin{bmatrix} \cos(\theta_e - \text{S1} \times \frac{\pi}{3}) + \cos(\theta_e - \frac{\pi}{6} - \text{S2} \times \frac{\pi}{3}) \\ -\sin(\theta_e - \text{S1} \times \frac{\pi}{3}) - \sin(\theta_e - \frac{\pi}{6} - \text{S2} \times \frac{\pi}{3}) \\ \cos(\theta_e - \text{S1} \times \frac{\pi}{3}) - \cos(\theta_e - \frac{\pi}{6} - \text{S2} \times \frac{\pi}{3}) \\ \sin(\theta_e - \text{S1} \times \frac{\pi}{3}) - \sin(\theta_e - \frac{\pi}{6} - \text{S2} \times \frac{\pi}{3}) \end{bmatrix} \tag{3}$$

where θ_e is the electrical angle of the rotor. γ_1 and γ_2 are the shifted angles of current vectors of the first set of three-phase stator windings and the second set of three-phase stator windings against the *d*-axis, respectively. A_p is the amplitude of error voltage in the single phase, which can be calculated by the inverter parameters in [7]. S1 and S2 are the integer determined by the rotor angle and current angle

$$\begin{aligned} \text{S1} &= \text{int}(6 \times \text{mod}((\theta_e + \gamma_1 + \pi/6), 2\pi)/2\pi) \\ \text{S2} &= \text{int}(6 \times \text{mod}((\theta_e + \gamma_2), 2\pi)/2\pi) \end{aligned} \tag{4}$$

where the function of "mod" returns the remainder result and the function of "int" returns the integer result.

III. PROPOSED ESTIMATION AND COMPENSATION OF VSI NONLINEARITY

A. Proposed Estimation Method of VSI Nonlinearity

Considering the VSI nonlinearity, the steady-state model of dual three-phase PMSM drives using the voltage references can be rewritten as

$$\begin{aligned} u_d^{ref} &= R_s i_d - \omega L_q i_q + \Delta u_d \\ u_q^{ref} &= R_s i_q + \omega (L_d i_d + \psi_m) + \Delta u_q \\ u_{z1}^{ref} &= R_s i_{z1} + \omega L_{z2} i_{z2} + \Delta u_{z1} \\ u_{z2}^{ref} &= R_s i_{z2} - \omega L_{z1} i_{z1} + \Delta u_{z2} \end{aligned} \tag{5}$$

where the superscript "ref" denotes the reference value.

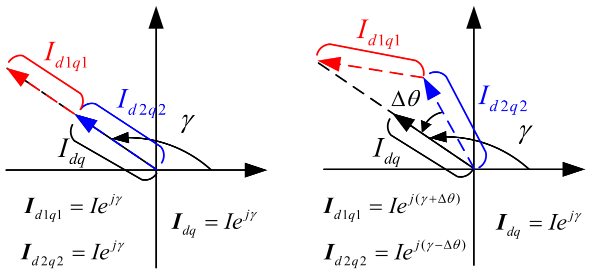
Considering the components in the synchronous reference frame are mainly dc values, the average of both sides of the voltage references of *dq* subspace in (5) are taken, which yields

$$\begin{aligned} \bar{u}_d^{ref} &= R_s \bar{i}_d - \omega L_q \bar{i}_q + \Delta \bar{u}_d \\ \bar{u}_q^{ref} &= R_s \bar{i}_q + \omega (L_d \bar{i}_d + \psi_m) + \Delta \bar{u}_q. \end{aligned} \tag{6}$$

Furthermore, the average of error voltages in (3) can be derived as

$$\begin{aligned} \Delta \bar{u}_d &= 2A_p(cos\gamma_1 + cos\gamma_2)/\pi \\ \Delta \bar{u}_q &= 2A_p(\sin\gamma_1 + \sin\gamma_2)/\pi. \end{aligned} \tag{7}$$

From another point of view, the voltage references of *dq* subspace in (6) are comprised of two parts as illustrated in (8).



(a) (b)

Fig. 1. Different current settings of dual three-phase PMSM drives with the same *dq*-axis currents in *dq* subspace. (a) Current setting I: $\boldsymbol{I}_{z1z2} = 0$. (b) Current setting II: $\boldsymbol{I}_{z1z2} = -j\tan(\Delta\theta)\boldsymbol{I}_{dq}^*$.

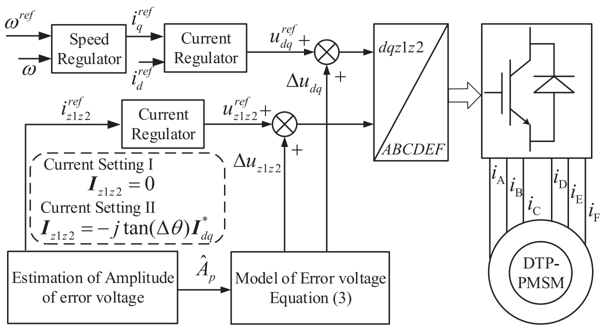


Fig. 2. Proposed online estimation and compensation method of VSI nonlinearity for the dual three-phase PMSM drives.

The first part is the machine voltage, which is related to the machine parameters and the *dq*-axis currents. The second part is the error voltage, which is determined by the inverter parameters, the *dq*-axis currents, and the z1z2-axis currents

$$\bar{u}_d^{\text{ref}} = f_d(\xi_{\text{machine}}, \bar{i}_{dq}) + g_d(\xi_{\text{inverter}}, \bar{i}_{dq}, \bar{i}_{z1z2})$$
$$\bar{u}_q^{\text{ref}} = f_q(\xi_{\text{machine}}, \bar{i}_{dq}) + g_q(\xi_{\text{inverter}}, \bar{i}_{dq}, \bar{i}_{z1z2}). \quad (8)$$

In (8), ξ_{machine} and ξ_{inverter} are the machine parameters and the inverter parameters, respectively. The details of functions in (8) are given as

$$f_d(\xi_{\text{machine}}, \bar{i}_{dq}) = R_s\bar{i}_d - \omega L_q\bar{i}_q$$
$$f_q(\xi_{\text{machine}}, \bar{i}_{dq}) = R_s\bar{i}_q + \omega(L_d\bar{i}_d + \psi_m)$$
$$g_d(\xi_{\text{inverter}}, \bar{i}_{dq}, \bar{i}_{z1z2}) = \Delta\bar{u}_d, g_q(\xi_{\text{inverter}}, i_{dq}, i_{z1z2}) = \Delta\bar{u}_q. \quad (9)$$

Based on the relationship in (2), the current vector in *dq* subspace is half of the sum of the current vector of the first set of three-phase windings in $d1q1$ reference frame and the current vector of the second set of three-phase windings in $d2q2$ reference frame. Assuming that the amplitudes of two sets of three-phase windings are identical, Fig. 1 gives the different current settings of dual three-phase PMSM drives with the same *dq*-axis currents in *dq* subspace.

It should be noted that the components in *dq* subspace are related to the conversation between the electrical energy and mechanical energy, while the components in z1z2 subspace have not contribution to generation of torque. Therefore, the z1z2-axis currents are usually set to be zero for the system efficiency. In this letter, the current injection on z1z2 subspace has been utilized purposely for the online estimation of VSI nonlinearity.

According to Fig. 1(a), substituting the complex vectors of two sets of three-phase wingdings into (2), the currents in z1z2 subspace can be derived as

$$\boldsymbol{I}_{z1z2} = 0.5(\boldsymbol{I}_{d1q1} - \boldsymbol{I}_{d2q2})^* = 0.5(Ie^{j\gamma} - Ie^{j\gamma})^* = 0. \quad (10a)$$

As shown in Fig. 1(a), the current angles of two sets of three-phase wingdings are same, i.e., $\gamma_1 = \gamma_2 = \gamma$. Combining with (7), the voltage references in (8) can be updated as

$$\bar{u}_d^{ref}(\boldsymbol{I}_{z1z2} = 0) = f_d(\xi_{\text{machine}}, \bar{i}_{dq}) + 4A_p cos\gamma/\pi$$
$$\bar{u}_q^{ref}(\boldsymbol{I}_{z1z2} = 0) = f_q(\xi_{\text{machine}}, \bar{i}_{dq}) + 4A_p\sin\gamma/\pi. \quad (10b)$$

Similarly, substituting the complex vectors of two sets of three-phase wingdings in Fig. 1(b) into (2), then the currents in z1z2 subspace can be derived as

$$\boldsymbol{I}_{z1z2} = 0.5(Ie^{j(\gamma+\Delta\theta)} - Ie^{j(\gamma-\Delta\theta)})^*/\cos(\Delta\theta)$$
$$= -jIe^{-j\gamma}\tan(\Delta\theta) = -j\tan(\Delta\theta)\boldsymbol{I}_{dq}^*. \quad (10c)$$

As shown in Fig. 1(b), the current angles of two sets of three-phase wingdings are $\gamma_1 + \Delta\theta$ and $\gamma_1 - \Delta\theta$. Combining with (7), the voltage references in (8) can be updated as

$$\bar{u}_d^{\text{ref}}(\boldsymbol{I}_{z1z2} = -j\tan(\Delta\theta)\boldsymbol{I}_{dq}^*)$$
$$= f_d(\xi_{\text{machine}}, \bar{i}_{dq}) + 4A_p cos\gamma\cos(\Delta\theta)/\pi$$
$$\bar{u}_q^{\text{ref}}(\boldsymbol{I}_{z1z2} = -j\tan(\Delta\theta)\boldsymbol{I}_{dq}^*)$$
$$= f_q(\xi_{\text{machine}}, \bar{i}_{dq}) + 4A_p\sin\gamma\cos(\Delta\theta)/\pi. \quad (10d)$$

From (10b) and (10d), it can be inferred that the amplitude of error voltages can be derived from the variation of average voltage references in *dq*-axis when the z1z2-axis currents are injected during the stable operation of the electrical machine. Thus, the amplitude of error voltage is given by

$$\hat{A}_p = \pi\frac{\bar{u}_q^{\text{ref}}(\boldsymbol{I}_{z1z2} = 0) - \bar{u}_q^{\text{ref}}(\boldsymbol{I}_{z1z2} = -j\tan(\Delta\theta)\boldsymbol{I}_{dq}^*)}{4\sin\gamma(1 - \cos(\Delta\theta))}. \quad (11)$$

As can be seen from (11), the amplitude of error voltages can be calculated without prior knowledge of machine parameter, when the currents of the z1z2-axis are injected. Moreover, the current injection has no influence on the torque due to the constant *dq*-axis currents in the torque subspace regardless of different speed ranges.

B. *Choose of Angle for Current Injection*

As shown in Fig. 1, the current amplitudes of each set of three-phase windings are increased inevitably when the angle for current injection ($\Delta\theta$) is large. On the other hand, the small value of $\Delta\theta$ will results in the slight difference in *q*-axis voltage references, which decreases the signal-to-noise ratio of sampled data. Thus, the angle ($\Delta\theta$) should be chosen by considering

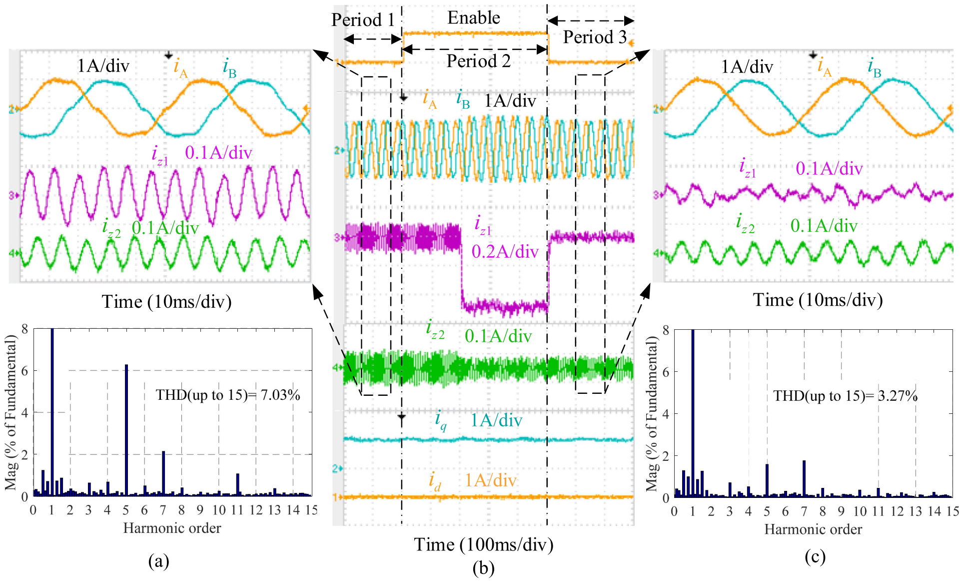


Fig. 3. Experimental results of the proposed compensation method of VSI nonlinearity for the dual three-phase PMSM drives under low speed.

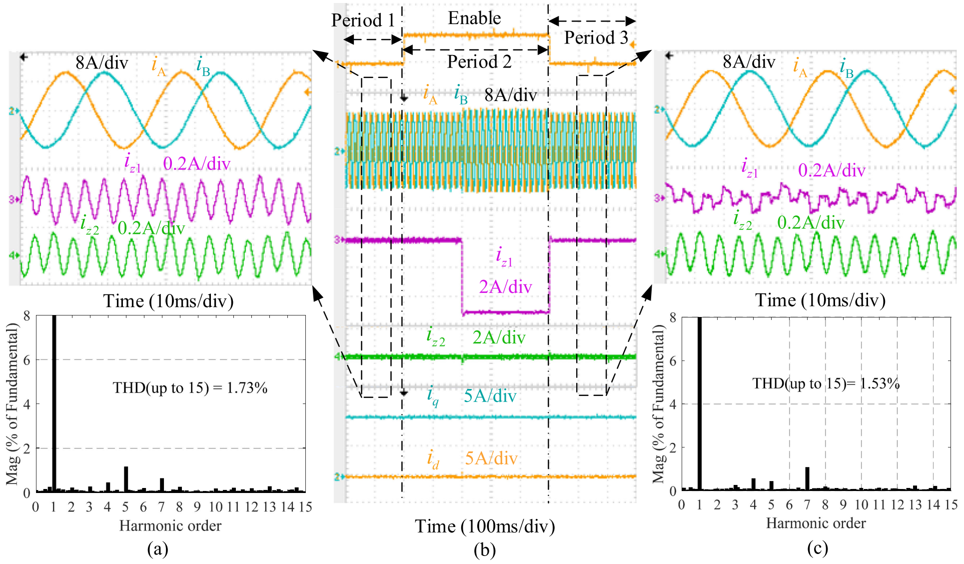


Fig. 4. Experimental results of the proposed compensation method of VSI nonlinearity for the dual three-phase PMSM drives under rated speed.

the variation of current amplitude and the signal-to-noise ratio comprehensively. In this letter, the angle of z1z2-axis current injection ($\Delta\theta$) is set as 25.84°, and the current amplitude will be increased by 10% after injection of the z1z2-axis current.

C. *Compensation Method of VSI Nonlinearity*

Since the amplitude of error voltages caused by VSI nonlinearity has been estimated, the error voltages in (3) can be implemented as the feedforward term in the control method. The proposed online estimation and compensation method of VSI nonlinearity for dual three-phase PMSM drives is illustrated in Fig. 2.

The estimation of VSI nonlinearity under the steady-state has been mainly focused in this letter. It should be noted that the compensation is suitable for both steady-state and transient-state since the model of error voltage is identical under these two states. Furthermore, the proposed estimation method is executed once at regular intervals, and the whole process of the proposed method is short, which takes about 500 ms in this letter.

IV. EXPERIMENTAL VERIFICATION

To verify the effectiveness of the proposed online compensation method, the experiments have been carried out on a laboratory dual three-phase PMSM prototype. The field-oriented control control algorithm is implemented in a Texas Instrument TMS320F28335 digital signal processor for the dual three-phase PMSM drives. For the configuration of digital controller, the control period is 200 μs and the dead-time of PWM signals is 0.8 μs. In order to obtain the average of the q-axis voltage reference in (11), a window with length of 100 is employed to eliminate higher harmonics.

In the experiment, the switching frequency of active switches is chosen to be 5 kHz, and the sampling frequency is same as the switching frequency. The rated current of the inverter is set as 10 A. The pole pair of dual three-phase dual PMSM is 4. The d-axis and q-axis inductances are 10 and 12 mH, respectively. And the value of the resistance and the rotor flux linkage are 0.4 Ω and 0.098 Wb, respectively. The rated speed and the rated load of the dual three-phase PMSM drive are 750 r/min and 10 N·m, respectively.

Fig. 3 presents the experimental waveforms to verify the effectiveness of the proposed online compensation method of VSI nonlinearity. Fig. 3(b) shows the whole process of the dual three-phase PMSM drive, which operates at 300 r/min in a no-load state. Fig. 3(a) shows the enlarged waveform of period 1, where the waveforms of phase currents become distorted owing to the harmonic components caused by VSI nonlinearity. This phenomenon is more distinct especially when the value of phase current is near zero. Meanwhile, the fifth and the seventh harmonic currents are mapped into z1z2 subspace according to the VSD theory. The harmonic amplitude of the z1z2-axis current can also reflect the VSI nonlinearity as shown in Fig. 3(a). In period 2 of Fig. 3(b), the z1-axis currents are injected into the drive to estimate the VSI nonlinearity. During this period, the current amplitude is increased slightly which agrees well with the aforementioned analysis about the choose of $\Delta\theta$. Then, the estimated VSI nonlinearity is compensated in period 3 as shown in Fig. 3(c). By comparison of Fig. 3(a) and (c), it can be observed that the total harmonic distortion (THD) up to 15th order has decreased from 7.03% to 3.27%. Therefore, it is verified that the phase current distorted by the VSI nonlinearity has been compensated by the proposed method effectively.

In order to further verify the proposed method, another experiment under the rated-speed and rated-load condition has been carried out as shown in Fig. 4. The amplitude of harmonic current of the z1-axis has been decreased after the proposed compensation method is enabled. Meanwhile, the THD up to the 15th order has been decreased from 1.73% to 1.53%. Unlike the low-speed and low-load operation, the current waveform seems sinusoidal, and the distortion is hard to be discerned under the rated-speed operation. This is due to the fundamental current component accounts for a relatively large portion under the rated-load conditions, which is much larger than the harmonic current component. It should be pointed out that the remained harmonic components are caused by the harmonic back EMF of the dual three-phase motor.

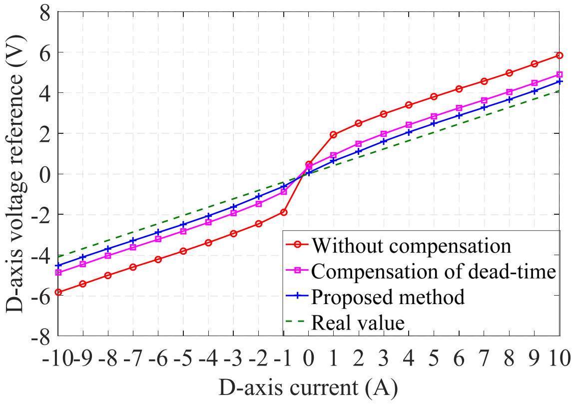


Fig. 5. Experimental results of the d-axis voltage reference with respect to different d-axis currents with different compensation methods.

On the other hand, Fig. 5 gives the measured d-axis voltage reference with respect to different d-axis currents. In the experiment, the dual three-phase PMSM is under stationary state for getting the real value of d-axis voltage reference conveniently. Under this operation state, the voltages induced by the inductance and rotor flux linkage are zero. Therefore, it is reasonable that the d-axis voltage is equal to the voltage drop on the stator resistance. As shown in Fig. 5, owing to the error voltages caused by the VSI nonlinearity, the curve representing d-axis voltages without compensation is far away from the straight line representing the real value with the maximum relative error of 46.3%. The real value is obtained by calculating the voltage drop on the stator resistance theoretically. With the compensation only for dead-time of VSI, the error between the d-axis voltage reference and the real value is smaller with the maximum relative error of 22.5%. With the proposed compensation method, the d-axis voltage reference is further closer to the real value with the maximum relative error of 12.5%. Thus, it can be concluded that the proposed method has a good performance on the compensation of VSI nonlinearity in terms of simplicity and accuracy.

V. CONCLUSION

In this letter, an online estimation and compensation method of VSI nonlinearity has been proposed for the dual three-phase PMSM drives. In the proposed method, the amplitude of error voltages caused by VSI nonlinearity is calculated from the voltage differences after the injection of z1z2-axis current. Thanks to the multiple decoupling subspaces of dual three-phase PMSM, the current injection on z1z2 subspace has a slight influence on the dq subspace (the torque subspace). Moreover, the proposed method does not need the prior knowledge of machine parameters and can estimate the amplitude of error voltages determined by the time-varying inverter parameter online. Since the effect of VSI nonlinearity is obvious at low-speed and light-load conditions, the proposed compensation method can improve the performance of drive system in particular for the low-speed operation region. In conclusion, the proposed method can provide a promising solution to the compensation of VSI nonlinearity for multiphase drives.

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