

Inverter Dead-Time Compensation up to the Field Weakening Region with Respect to Low Sampling Rates

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ABSTRACT

This report presents a new compensation method for distortions related to dead time, caused by B6-inverters with pulse-width-modulated output voltages. In spite of low sampling rates, the new method of compensation is effective at all ranges of rotation speed up to the field weakening region. No additional hardware is required for its implementation. The effectiveness of the new method has been shown experimentally. A description of the relevant distortions is given first to provide a basis for the development. This considers the field weakening region, and offers an illustrative method of quantifying the distortions. It is also shown that the use of compensation methods that do not take the sampling time into account leads to additional distortions. It is even possible that they exceed the distortions in an equivalent system without compensation.

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INTRODUCTION

The use of electrical drives in modern vehicles offers an enormous potential for saving both fuel and CO₂ emissions. Permanent magnet synchronous motors (PMSM) are increasingly being used as the electric motor. Typically these are powered by voltages generated by an inverter using pulse-width modulation (PWM). In order to avoid short-circuits in the inverter when the voltages are pulse-width-modulated, dead times must be maintained between the switching processes in complementary switches. These dead times distort the PWM, and introduce distortions to the current drawn and to the torque generated by the electrical drive. This puts additional loading on the vehicle power supply, while the irregular torque output generates acoustic noise. In the context of electric mobility it is necessary to apply effective and robust compensations to fulfill the increasingly strict requirements on the vehicle power network and on the noise level.

Publications [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17] describe dead-time distortions and methods for its compensation. However, there are designed for low rotation speeds without field weakening, and assume that the motor controller has a high sampling rate. In the automotive field

high sampling rates often cannot be implemented for reasons of cost, and field weakening is necessary in many applications.

This report describes dead-time distortions over the full operating range, including the field weakening region. An angle ϕ is introduced in order to account for the field weakening. Depending on the angle ϕ , trajectories of the distortions are calculated in dq coordinates, on the basis of which an illustrative method of quantifying the distortions up to the field weakening is given. The distortions are described in accordance with the systematic approach presented in [1].

It is also shown that the use of compensation methods that do not take the sampling time into account gives rise to additional distortions. This increases with the rotation speed and with the field weakening, and can exceed the distortions from an equivalent system without compensation.

A new compensation method is developed with the aid of the distortion description; this effectively and robustly compensates for the dead-time distortions, in spite of low sampling rates. Consideration of the angle ϕ makes the compensation method suitable both for low speeds and for high speeds with field weakening. The compensation method does not require any additional hardware, and can be implemented with few resources. The effectiveness of the

new method of compensation has been experimentally verified.

DESCRIPTION OF DEAD-TIME DISTORTIONS UP TO FIELD WEAKENING

The arrangement illustrated in Figure 1 is taken for the fundamental structure of the electrical drive.

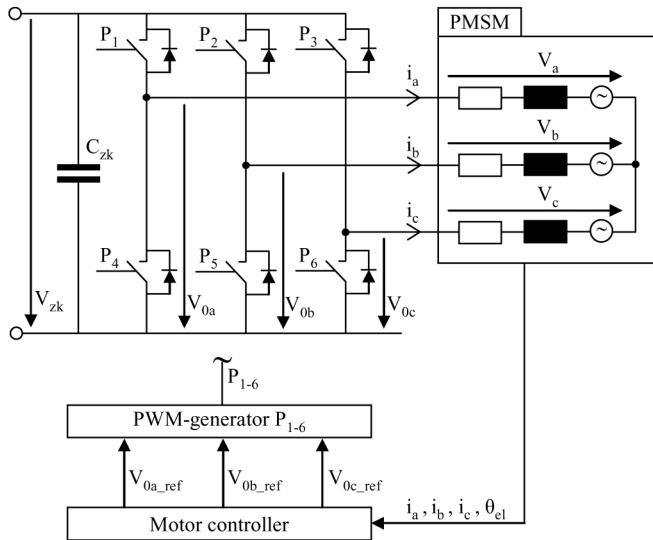


Figure 1. Three-phase inverter with PMSM, the motor controller and the PWM-generator

Typically the motor voltages are controlled by PWM with a constant period time T_{pwm} . Therefore the PWM-generator block converts the voltage reference values V_{0abc_ref} specified by the motor controller into the pulse patterns P_1 to P_6 . According to the pulse patterns the voltages V_{0abc} and further on the phase voltages V_{abc} of the PMSM are generated. The resulting motor currents i_{abc} are approximately sinusoidal, and can be represented through the Clarke-Park transformation as a current vector in the dq coordinate system [18]. An angle φ is enclosed between the current vector and the positive I_d axis. There is no field weakening when the angle φ is $\pi/2$. As the angle φ increases, the field weakening increases accordingly. Figure 2 illustrates the relationship between the dq-current vector, the field weakening, and the angle φ .

With a consideration of the angle φ the currents i_{abc} can be described according to (1), where θ_{el} represents the electrical rotor angle of the PMSM.

$$\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \hat{I} \cdot \begin{pmatrix} \sin(\theta_{el} + \varphi + \pi/2) \\ \sin(\theta_{el} + \varphi + \pi/2 - 2\pi/3) \\ \sin(\theta_{el} + \varphi + \pi/2 - 4\pi/3) \end{pmatrix} \quad (1)$$

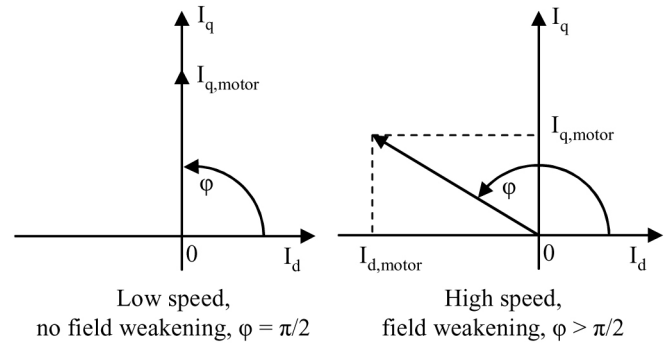


Figure 2. Relationship between the dq-current vector, the field weakening, and the angle φ

In order to avoid short-circuits in the inverter a dead time T_d must be maintained between the current commutation from P_x to P_y and vice versa. During the dead time both switches are non-conducting, and the current flows through one of the free-wheeling diodes D_x or D_y depending on current direction. In the case in which current is flowing from the inverter to the motor, this is the diode D_y , and respective D_x when current flows in the other direction, see Figure 3. In this report, the current direction towards the motor is defined as positive.

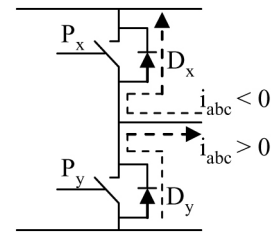


Figure 3. Flow of current through the inverter branch during the dead time

This distorts the pulse width of the PWM. For $i_{abc} > 0$ the pulse width is shortened by the dead time; correspondingly, it is lengthened for $i_{abc} < 0$. The distortions caused in this way in the voltages V_{0abc} can be described with (2), whereby sgn represent the signum function, and V_{0abc_PWM} is the mean value of V_{0abc} over one PWM pulse.

$$V_{0abc_PWM} = V_{0abc_ref} + V_{0abc_err}$$

$$\begin{pmatrix} V_{0a_err} \\ V_{0b_err} \\ V_{0c_err} \end{pmatrix} = \underbrace{\frac{-T_d V_{zk}}{2T_{PWM}}}_{\Delta e} \begin{pmatrix} \text{sgn}(i_a) \\ \text{sgn}(i_b) \\ \text{sgn}(i_c) \end{pmatrix} \quad (2)$$

The voltages V_{0abc_err} can be transformed to the dq coordinate system by the Clark-Park transformation (3).

$$\begin{pmatrix} V_{d_err} \\ V_{q_err} \end{pmatrix} = \frac{4}{3} \Delta e \cdot \begin{pmatrix} \sin(-\varphi + \kappa + \frac{1}{3}\pi) \\ \sin(-\varphi + \kappa + \frac{5}{6}\pi) \end{pmatrix} \quad (3)$$

Here, κ (4) is limited to values between 0 and $\pi/3$ by the modulo function,

$$\kappa = (\theta_{el} + \varphi - \frac{\pi}{2}) \bmod \frac{\pi}{3} \quad (4)$$

Equation (3) represents the dead-time distortions of the motor voltages in the dq coordinate system, taking the field weakening into account. The distortions are not continuous, and demonstrate a jump for $\kappa = 0$. In order to simplify the conversion of the voltage distortions into current distortions, the discontinuities can be eliminated through a Fourier series. The summands of the Fourier series exhibit the 6th, 12th, 18th etc. order harmonics of the electrical rotation frequency, along with a constant component. Frequently, only the sixth order harmonic is interesting, as the amplitudes of higher order harmonics are comparatively small, and the constant component can be balanced out. Equation (5) gives the summands of the sixth order Fourier series.

$$\begin{pmatrix} V_{d_err_6} \\ V_{q_err_6} \end{pmatrix} = \frac{4}{3} \Delta e \cdot \begin{pmatrix} -\frac{6}{35\pi} \cos(\varphi) \cdot \cos(6 \cdot (\theta_{el} + \varphi - \frac{\pi}{2})) \\ -\frac{6}{35\pi} \sin(\varphi) \cdot \cos(6 \cdot (\theta_{el} + \varphi - \frac{\pi}{2})) \\ -\frac{36}{35\pi} \sin(\varphi) \cdot \sin(6 \cdot (\theta_{el} + \varphi - \frac{\pi}{2})) \\ +\frac{36}{35\pi} \cos(\varphi) \cdot \sin(6 \cdot (\theta_{el} + \varphi - \frac{\pi}{2})) \end{pmatrix} \quad (5)$$

In the usual design of the motor controller, its bandwidth is, even at low rotation speeds, no longer adequate to attenuate voltage distortions at a frequency six times greater than the basic rotation speed. In this case, the current distortions exhibit the same characteristics as the voltage distortions, and can be described in a simplified form by an additional proportionality factor Γ and a phase shift γ (6).

$$\begin{pmatrix} i_{d_err_6} \\ i_{q_err_6} \end{pmatrix} = \frac{4}{3} \Delta e \cdot \Gamma \cdot \begin{pmatrix} -\frac{6}{35\pi} \cos(\varphi) \cdot \cos(6 \cdot (\theta_{el} + \varphi - \frac{\pi}{2} + \gamma)) \\ -\frac{6}{35\pi} \sin(\varphi) \cdot \cos(6 \cdot (\theta_{el} + \varphi - \frac{\pi}{2} + \gamma)) \\ -\frac{36}{35\pi} \sin(\varphi) \cdot \sin(6 \cdot (\theta_{el} + \varphi - \frac{\pi}{2} + \gamma)) \\ +\frac{36}{35\pi} \cos(\varphi) \cdot \sin(6 \cdot (\theta_{el} + \varphi - \frac{\pi}{2} + \gamma)) \end{pmatrix} \quad (6)$$

In the dq coordinate system, the trajectory of the current distortions takes the form of an ellipse which repeats itself six

times within one electrical motor rotation. The minor axis of the ellipse encloses an angle φ with the real, positive axis, and is a great deal shorter than the major axis, see Figure 4 (i). The distortions in the vehicle power supply and in the motor torque are primarily due to the distortions in the quadrature current I_q , and can be graphically quantified with the aid of the elliptical shape. At low speeds of rotation without field weakening, the major axis of the ellipse is parallel to the real axis. In this case, the amplitude of the distortions in the quadrature current are small and as consequence the distortions in the vehicle power supply and in the motor torque are small. As the field weakening increases, the major axis turns towards the imaginary axis. In accordance with the field weakening, the distortions in the quadrature current, in the vehicle power supply and in the motor torque increase. Figure 4 (ii) illustrates the amplitude of the dead-time distortions in the motor torque M through a run-up, from stationary to high speeds with field weakening. The curve of the amplitude of the distortions in the vehicle power supply takes a similar form.

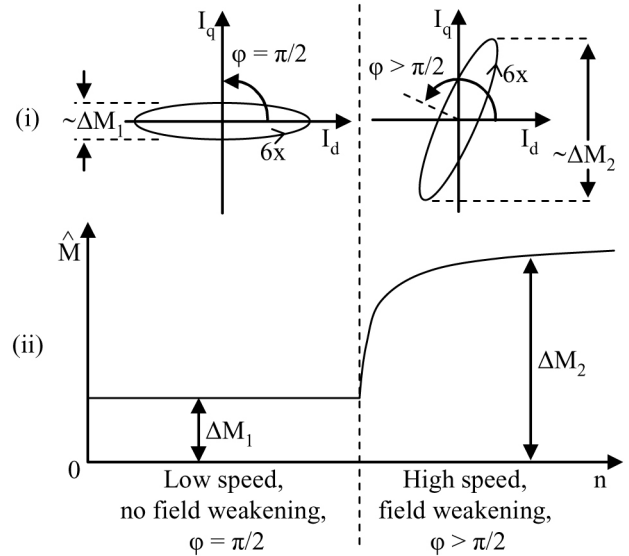


Figure 4. (i) Trajectory of the current distortions; (ii) amplitude of the distortions in the torque

Equations (3) and (6) describe the dead-time distortions up to the field weakening region. The next section provides a new compensation method adequate for systems with low sampling rates.

COMPENSATION OF DEAD-TIME DISTORTIONS UP TO THE FIELD WEAKENING REGION IN SPITE OF LOW SAMPLING RATES

EFFECT OF LOW SAMPLING RATES

Now, the motor controller has a constant sampling rate f_a , and a corresponding constant sampling time T_s . Hence,