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Analysis of the impact of space vector modulation techniques on the operation of ultrahigh speed induction machines

Péter Stumpf [a,*], Rafael K. Járdán [b], István Nagy [b]

[a] *Budapest University of Technology and Economics, Department of Mechatronics, Optics and Engineering Informatics Informatics, Bertalan Lajos utca 2, 1111, Budapest, Hungary*

[b] *Budapest University of Technology and Economics, Department of Automation and Applied Informatics, Group of Electrical Engineering, Magyar tudósok körútja 2, QB108, 1117, Budapest, Hungary*

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Abstract

The paper investigates the impact of different space vector modulation (SVM) techniques on the operation of ultrahigh speed induction machines (USIMs), where the m_f frequency ratio is low owing to the necessarily high fundamental frequency f_1. Three different sampling techniques, the Regular Sampled, Naturally Sampled and the Oversampled are studied by simulation. It is found that the SVM is proned to generate DC current in the stator windings. Furthermore subharmonic flux and current components with considerable amplitudes can also be generated in USIM. In the paper it is revealed that both the DC and the subharmonic components could lead to extremely large additional losses in the USIM enhanced by its special parameters.

Keywords: Space vector modulation; High speed drives; Subharmonics

1. Introduction

In the last decade increasing attention has been given to high speed drives to reduce system size and improve power conversion efficiency [1–3,5,6,10,15,18]. In [2] the main design problems of high speed drives are discussed. In [1] a sensorless *V/f* control of a SPMSM is discussed, while in [5] the optimal design of a PMSM with a nominal speed of 18 krpm and a nominal power of 1.5 MW is presented. In [10] the rotordynamics of an ultra high speed motor with a nominal speed 120 krpm are studied by finite element analysis. Parallel operation of PWM inverters is presented to reduce the current ripple in a high speed motor drive in [6]. In [3] the different factors, which lied behind the speed limitations of high speed PM drives are discussed. In [18] an unmodulated square wave converter supplied by a dc/dc converter is applied for a real ultra-high speed (500 krpm) application.

The basic feature of the SVM controlling the VSC fed USIMs is the low frequency ratio $m_f = f_c/f_r$ ($m_f < 15$) owing to the necessarily high fundamental f_1 or reference f_r frequency and the carrier frequency f_c with limited maximum value leading to stator voltage and current harmonic spectra far more unfavorable as compared to those obtained at low fundamental frequencies. The rated frequency of the USIM in our case is $f_{rn} = 1500$ Hz. The maximum carrier

* Corresponding author.
E-mail addresses: stumpf@get.bme.hu (P. Stumpf), jrk@get.bme.hu (R.K. Járdán), nagy@get.bme.hu (I. Nagy).

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frequency of the converters available on the market is typically $f_{c,max}$ = 12–24 kHz and generally their values can be changed in discrete steps. Selecting f_c = 12 kHz, the frequency ratio is only m_f = 8.

2. Overview of space vector modulation

Many up-to-date converters apply space vector modulation (SVM) technique beside the widely used Carrier Based Subharmonic Modulation (CBSM), which applies a triangular carrier signal to compare against the reference waveform (pure sinusoidal, sinusoidal plus third harmonic component, trapezoidal, etc.) to generate the switching signals. The main benefits of the SVM compared against CBSM applying sinusoidal reference signal are [7,13]: increase in the VDC utilization with 15%, less Total Harmonic Distortion (THD), and reduction in switching loss. Furtermore SVM facilitates the application of field oriented control [12].

The theory of SVM is well covered in the literature [7–9,11,13,14,16]. Here only a short summary is presented to lay the foundation for the next sections. The two level converter applied has six active voltage vectors ($\mathbf{v}_1$,$\mathbf{v}_2$, ..., $\mathbf{v}_6$) and two inactive zero vectors ($\mathbf{v}_0$, $\mathbf{v}_7$), all stationary in the α–β plane, where $\mathbf{v}_k(u_{h+})$, here k = 0, ..., 7; h = a, b, c and + means "positive side" (Fig. 1(a)). The reference space voltage vector $\mathbf{v}_{ref}$ is rotating with angular speed $\omega_1 = 2\pi f_1 = 2\pi/T_1$, where $f_1 = f_r$.

SVM uses the two adjacent active vectors and two zero vectors to approximate $\mathbf{v}_{ref}$ during one carrier period T_c [13,17]:

$$\mathbf{v}_{ref} = \mathbf{v}_- t_- + \mathbf{v}_+ t_+ + \mathbf{v}_0 t_0 + \mathbf{v}_7 t_7 \tag{1}$$

where $\mathbf{v}_0 = \mathbf{v}_7 = 0$ and

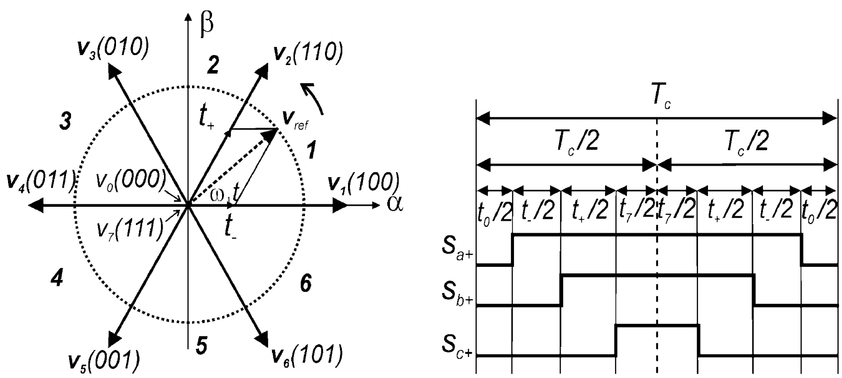
$$\frac{t_-}{T_c} = \frac{\sqrt{3}m_a}{2}\cos\left[\omega_1 t + (15 - 2s)\frac{\pi}{6}\right] \tag{2}$$

$$\frac{t_+}{T_c} = \frac{\sqrt{3}m_a}{2}\cos\left[\omega_1 t + (11 - 2s)\frac{\pi}{6}\right] \tag{3}$$

$$t_0 + t_7 = T_c - t_- - t_+ \tag{4}$$

Here s = 1, 2, ..., 6, the sector number and $T_c = 1/f_c$. Note that t_- belong to the right adjacent voltage vector, t_+ to the left adjacent vector while t_0 and t_7 to the zero vectors. $m_a = 2\hat{V}_{ref}/V_{DC}$ is the modulation index, where $\hat{V}_{ref}$ is the amplitude of the reference phase voltage and V_{DC} is the total dc link voltage. In sector 1, s = 1 and $\mathbf{v}_- = \mathbf{v}_1$; $\mathbf{v}_+ = \mathbf{v}_2$ (Fig. 1(a)).

The order of voltage vectors applied in one carrier period depends on the particular SVM technique. The most commonly used technique is the center aligned pattern, where the sequence of the voltage space vectors are symmetrical to the half carrier period (Fig. 1(b)). In this case the on-time interval of the zero voltage vectors is equal: $t_0 = t_7$. Each



(a) (b)

Fig. 1. Voltage space vectors and decomposition of the reference vector (a). Symmetrical switching pattern in sector 1 (b).