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An Improved Switching Period Optimization Space Vector PWM Strategy

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Abstract: In order to improve the performance of space vector PWM (pulse width modulation), the optimization is widely used. The switching period optimization space vector PWM can reduce both total harmonic distortion and spectrum peaks, so it has important application prospects and has been widely discussed among several types of optimization strategies. Aiming at the characteristic of uncontrollable switching frequency, the study proposes an improved optimization method that can be used in both steady and non-steady states. The method uses a time window with adaptive width to control the average switching period and divides the value range of reference voltage vectors into two kinds of regions: R and Q based on period coefficients. Switching periods are dependent in the same time window, while independent in different windows. The total extra time between specified periods and optimal periods in region R can be made full use of in region Q. A simulation platform was built in software MATLAB/Simulink. The simulation result verifies excellent performance on harmonic distortion and amplitude peak reduction. The improved strategy has widespread applications in electric vehicles, industry automation and drives, household appliances and so on.

Key words: Space vector PWM, switching period optimization, period coefficient, time window, switching frequency

INTRODUCTION

Space Vector Pulse Width Modulation (SVPWM) has gained wide applications because it can make full use of DC voltage, improve harmonic performance and be implemented in many digital chips, such as TMS320F2812 and Infineon TriCore 1797/1767 (Hava, 1998). SVPWM can be divided into deterministic SVPWM and random SVPWM. Due to the principle of PWM, the output voltage harmonics focus on or around the switching frequency and its integer multiple ones in many deterministic SVPWM strategies with fixed switching frequency, fixed zero vector distribution and fixed pulse position method (Holmes, 1995; Holmes and Lipo, 2003). The optimization method has been used to eliminate selective harmonics or improve modulation performance (Bruckner and Holmes, 2005; Dehbonei *et al.*, 2002; Hao *et al.*, 2010; Holtz and Beyer, 1994; Laczynski *et al.*, 2008; Lee *et al.*, 2009; Wu *et al.*, 2005; Yuan *et al.*, 2009). The randomization method has been used to reduce harmonic spectrum amplitude peaks through uniformly spreading harmonic spectrum on frequency axes, so many random SVPWM strategies have been proposed and discussed (Carlosena *et al.*, 2007; Chen *et al.*, 2012a, b, c; Chen *et al.*, 2013). Three fundamental RSVPWM strategies include random zero vector distribution PWM (RZDPWM), Random Pulse Position PWM (RPPPWM) and Random Switching Frequency PWM (RSFPWM) (Kirlin *et al.*, 2002, 1994; Ma *et al.*, 2007a, b, 2008; Na *et al.*, 2002; Oh *et al.*, 2009; Wang and Wang, 2007). Aiming at switching frequency that is a key parameter in SVPWM, randomization and optimization methods have been discussed. RSFPWM has the most excellent performance in the three fundamental random strategies. Randomization may increase harmonic distortion. Holtz and Beyer (1994) presented an optimal SVPWM method that considered switching subcycles as optimization variables and given a prediction method. Chen *et al.* (2013) discussed the numerical solution of switching cycle duration/period optimization RSVPWM based on infinite cycles in a fundamental. The optimal SVPWM method can get excellent performance and the average switching frequency is controllable if the motor control system works in a steady state, while uncontrollable in a non-steady state. The uncontrollable frequency may damage power switches, so the study proposes an improved optimization method that can be used in both steady and non-steady states.

SWITCHING PERIOD OPTIMIZATION SVPWM

The switching state of the classic two-level three-phase inverter forms eight basic space voltage vectors, as shown in Fig. 1 (Holmes and Lipo, 2003). The eight vectors include six active voltage vectors $\vec{U}_1, \vec{U}_2, \vec{U}_3, \vec{U}_4, \vec{U}_5, \vec{U}_6$ and two zero vectors $\vec{U}_0, \vec{U}_7$.

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An arbitrary voltage vector $\vec{U}_s$ with amplitude U_0 and phase angle θ iside the hexagon region shown in Fig. 1 can be generated by zero vector and two active vectors that are starting and ending boundaries of the sector.

Aiming at harmonic current Root-Mean-Square (RMS) value minimization. Holtz and Beyer (1994) drew the conclusion that the total harmonic distortion reaches minimum when all harmonic current RMS values of all cycles/subcysles/periods are made equal. Based on the above conclusion, Chen *et al.* (2013) discussed computing formulas and numerical computing algorithms for formulas of optimal period Random Space Vector Pulse Width Modulation (RSVPWM) based on infinite cycles in a fundamental. The optimal cycle durations/periods can be computed using the following equation (Holmes and Lipo, 2003).

$$\begin{cases} \varepsilon_k = \dfrac{T_k}{T} = \dfrac{I_{h,min}}{I_{h,k_0}} \\ I_{h,min} = \dfrac{N}{\sum\limits_{k=1}^{N} \dfrac{1}{I_{h,k_0}}} \end{cases} \tag{1}$$

where, ε_k is the kth switching cycle (subcysle)/period coefficient, T_0 is the fixed cycle duration, T_k is the kth optimal cycle duration, $I_{h,min}$ is the same harmonic current RMS value of all subcycles, I_{h,k_0} is the harmonic current RMS value of the kth cycle and N is the number of cycles.

So:

$$Z(M) = \frac{1}{I_{h,min}} = \frac{\sum\limits_{k=1}^{N} \frac{1}{I_{h,k_0}}}{N} = \frac{1}{\frac{\pi}{3}} \frac{\frac{\pi}{3}\sum\limits_{k=1}^{N} \frac{1}{I_{h,k_0}}}{N} = \frac{3}{\pi}\sum_{k=1}^{N}\left(\frac{1}{I_{h,k_0}} \frac{\frac{\pi}{3}}{N}\right) \tag{2}$$

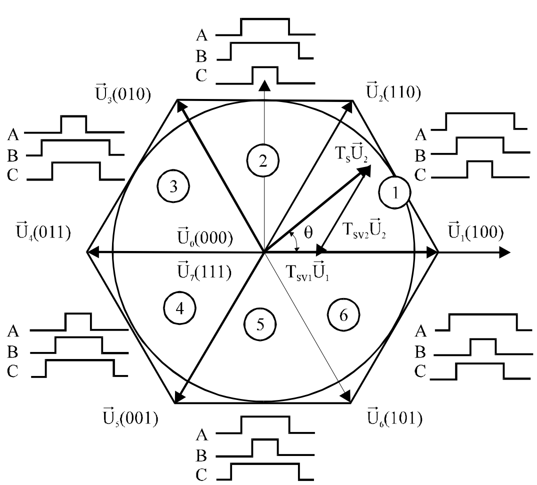

Fig. 1: Voltage vectors, vector summation method and PWM waveforms

Let:

$$d\theta = \frac{\pi/3}{N} \tag{3}$$

For $N \rightarrow +\infty$, I_{h,k_0} becomes a function of the modulation index M and phase angle θ, that is to say, I_{h,k_0} becomes $I_h(M, \theta)$. Then, Eq. 2 can be expressed as:

$$Z(M) = \frac{3}{\pi}\sum_{k=1}^{N}\left(\frac{1}{I_h(M,\theta)}d\theta\right) = \frac{3}{\pi}\int_0^{\frac{\pi}{3}} \frac{1}{I_h(M,\theta)}d\theta = \frac{3}{\pi}\int_0^{\frac{\pi}{3}} \frac{1}{\sqrt{Cf(M,\theta)}}d\theta \tag{4}$$

where, $I_h(M, \theta)$ is RMS value of current ripple to specified modulation index M and phase angle θ, f (M, θ) is the corresponding micro Harmonic Distortion Factor (HDF) and C is the constant factor difference between mean-square value and RMS value.

So, ε_k becomes a function of M and θ and can be expressed as ε (M, θ). Optimal T_k/T_0 for the traditional SVPWM (TSVPWM) and RZDPWM can be computed and shown in Fig. 2.

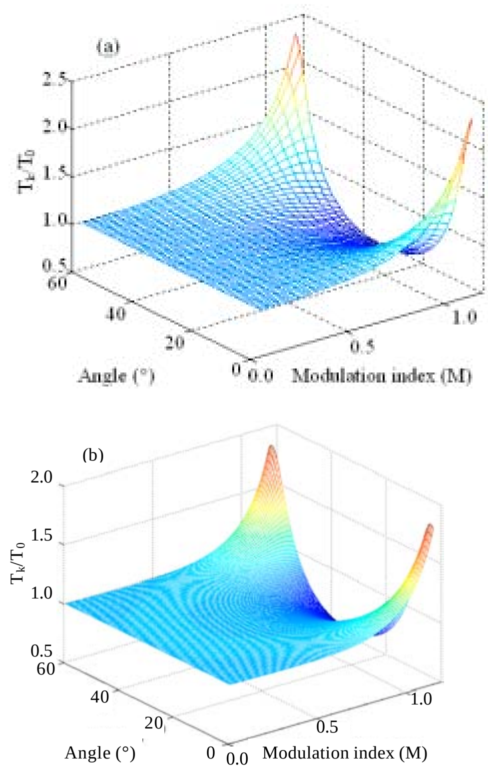

Fig. 2(a-b): Optimal switching period coefficient T_k/T_0 between fixed cycle duration T_0 and optimal cycle duration T_k in the first sector for (a) TSVPWM and (b) RZDPWM

IMPROVED OPTIMIZATION METHOD

The hexagon region shown in Fig. 1 can be divided into two kinds of regions: R and Q as shown in Fig. 3. Region R includes six sub regions: R1, R2, R3, R4, R5 and R6, while region Q includes Q1, Q2, Q3, Q4, Q5 and Q6. The region division method is as follows:

$$\begin{cases} \text{Region R (including R1, R2, R3, R4, R5, R6):} & \varepsilon(M,\theta) > 1 \\ \text{Region Q (including Q1, Q2, Q3, Q4, Q5, Q6):} & \varepsilon(M,\theta) < 1 \\ \text{Boundaries between R and Q regions:} & \varepsilon(M,\theta) = 1 \end{cases} \quad (5)$$

The improved switching period optimization method is shown in Fig. 4 and can be described as follows:

- **S1:** The optimization method begins to work. Whether the reference voltage vector $\vec{U}_s$ cuts across the boundary between R and Q from region Q to region R is analyzed based on the rotation direction and current value of $\vec{U}_s$. If yes, a time window begins to work and the count variable k and the timing variable T_1 are set to 0: $0\rightarrow k$, $0\rightarrow T_1$; else, the switching period is set to a constant value T_0, that is to say, $T_s = T_0$ and go to S7
- **S2:** If the return-to-zero condition is satisfied, the count variable k and the timing variable T_1 are set to 0: $0\rightarrow k$, $0\rightarrow T_1$, then go to S3; else, go to S3 directly. The return-to-zero condition is (1) $\vec{U}_s$ cuts across the boundary from region Q to region R or from one sub regions of R to another sub region of R and (2) $T_1 \geq T_{set}$, where T_{set} is the setting value for timing window width
- **S3:** $k+1\rightarrow k$. Switching period coefficient ε is computed based on the amplitude and phase angle of $\vec{U}_s$. The switching period T_s is set to εT_0: $T_s \leftarrow \varepsilon T_0$. Go to S4
- **S4:** The region where $\vec{U}_s$ locates is analyzed based on current $\vec{U}_s$. If $\vec{U}_s$ locates in region R or the boundary, go to S6; else, go to S5
- **S5:** If $kT_0 \leq T_1+T_s$, go to S6; else, let $T_s \leftarrow T_0$ and go to S6
- **S6:** $T_1+T_s\rightarrow T_1$ and go to S7
- **S7:** The duration time of basic voltages is computed firstly, rising edge time and trailing edge time are computed based on dead time and modulation strategy secondly and corresponding resisters are set finally. The 6 switching signals are automatically generated by the controller

In order to be realized easily in the digital control system, switching period coefficient ε is computed, discretized as a two-dimension lookup table off-line and stored in read-only memory (ROM). The modulating index M and phase angle θ are discretized with step δ_M and δ_θ, respectively and only εs on the grids are stored. If

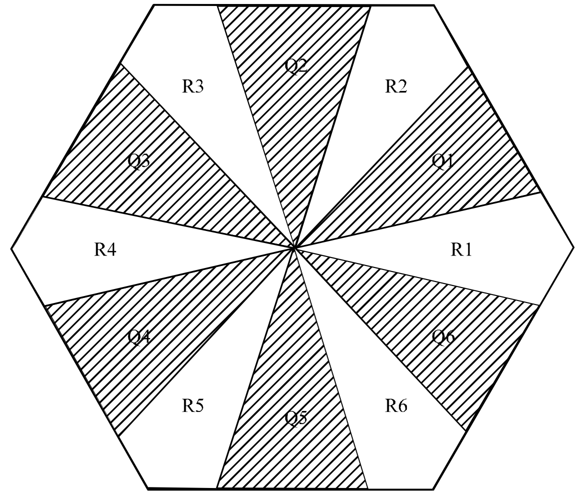

Fig. 3: Region division method of R and Q based on the switching period coefficient ε (M, θ) value and ε (M, θ)>1 in R, ε(M, θ)<1 in Q, ε (M, θ) = 1on boundaries between R and Q

pairs of (M, θ) is on the grid point, the corresponding coefficient ε can be got from the ROM table directly. If not, the interpolation can be utilized.

The classical bilinear interpolation has more excellent performance with less computation and the principle can explained in Fig. 5. $A(M_1, \theta_1)$, $B(M_2, \theta_1)$, $C(M_1, \theta_2)$ and $D(M_2, \theta_2)$ are the four nearest neighbors of $F(M, \theta)$, then $\varepsilon(M, \theta)$ can be got as:

$$\varepsilon(M, \theta) = (\theta-\theta_1)[\varepsilon(F)-\varepsilon(E)]+\varepsilon(E) \quad (6)$$

where, $\varepsilon(E) = (M-M_1)[\varepsilon(B)-\varepsilon(A)]+\varepsilon(A)$ and $\varepsilon(F) = (M-M_1)[\varepsilon(D)-\varepsilon(C)]+\varepsilon(C)$.

The nearest neighbor interpolation is a very simple method that can be used. As shown in Fig. 5, C is the nearest neighbor of F, so ε(C) can also be used as the approximate value of ε(F).

SIMULATION RESULTS AND DISCUSSION

A simulation platform was built in MATLAB/Simulink. The simulation results are shown in Fig. 6-9, with parameters of fundamental frequency 30 Hz, switching frequency 10000 Hz and modulation index 0.9. The Fast Fourier Transform (FFT) algorithm is employed to analyze phase voltage spectra. From the figures, some phenomena can be found as follows:

- The improved optimization method, as well as the traditional optimization method, can significantly reduce harmonic distortion and harmonic amplitude peaks, which can be seen from Fig. 6 and 7

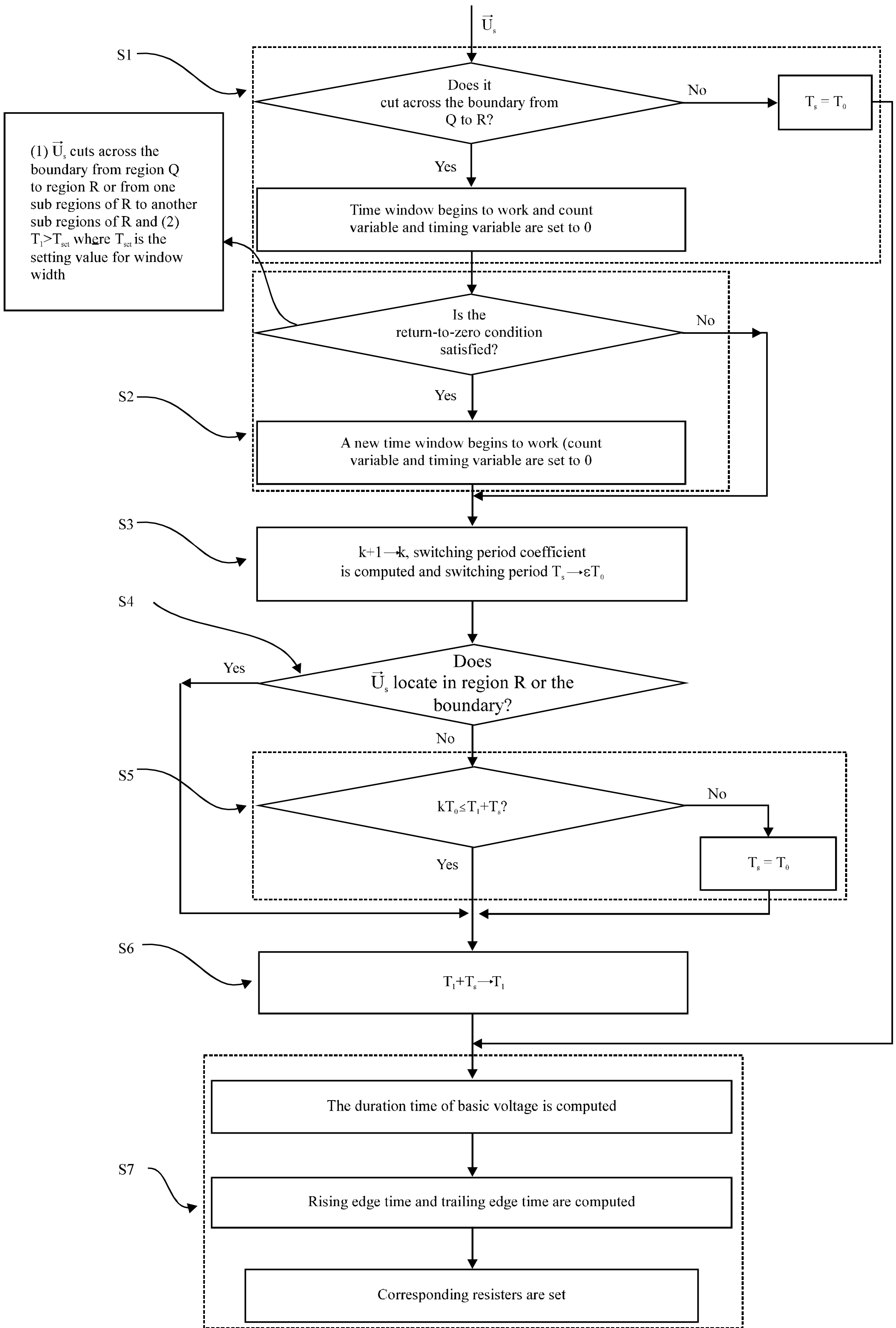

Fig. 4: Flowchart of the improved optimization method

- In the same time window, switching periods are dependent. That is to say, the kth period is determined by corresponding period coefficient and past k-1 switching periods. From Fig. 4 and 8, the switching period can be computed using the corresponding coefficient ε if $\vec{U}_s$ locates in region R, because ε is more than 1 and the corresponding period more than the specified period T_0 that certainly does not make the switching frequency more than the specified one. If $\vec{U}_s$ keeps locating in region Q for a long time, the switching frequency will be more than the specified one. The switching periods in region Q and R are comprehensively considered in the same time window. The total extra

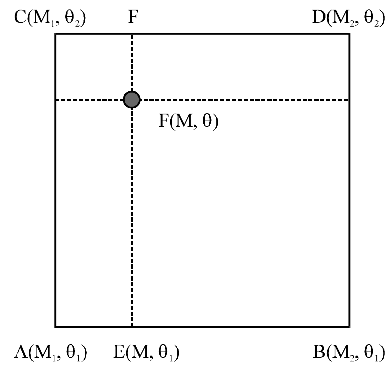

Fig. 5: Bilinear interpolation algorithm to compute F(M, θ) value using four nearest neighbors

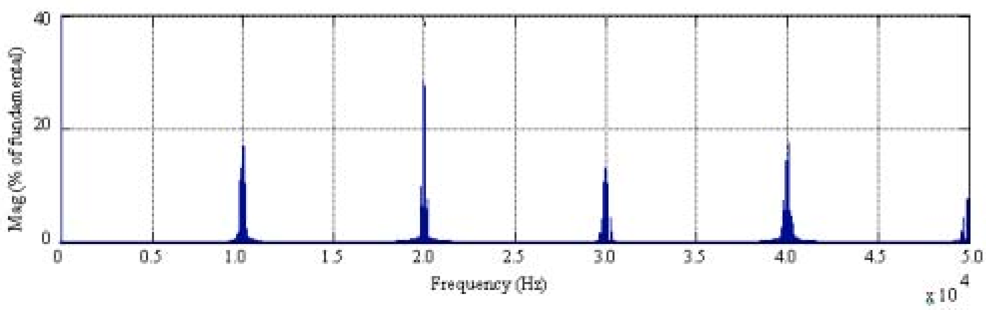

Fig. 6: Phase voltage spectrum of TSVPWM

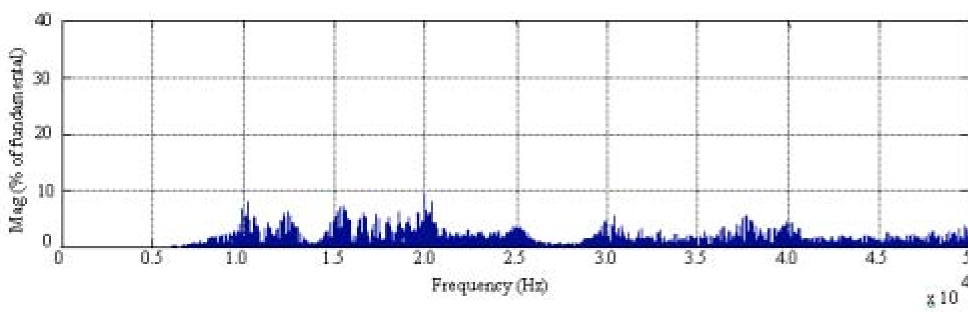

Fig. 7: Phase voltage spectrum of proposed optimization method for TSVPWM

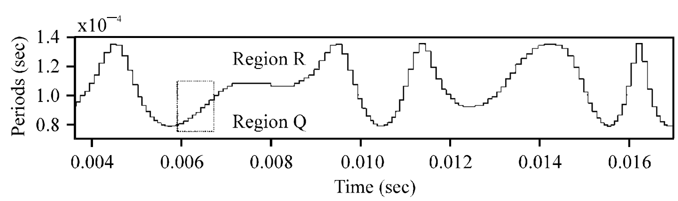

Fig. 8: Switching period of traditional optimization method for TSVPWM

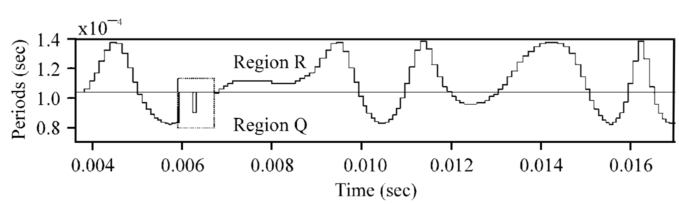

Fig. 9: Switching period of proposed optimization method for TSVPWM

time between specified period T_0 and optimal period T_s in region R can be made full use of in region Q. If the extra time in R is used up in Q, the following period in Q is set to the specified one T_0, as can be seen from Fig. 8 and 9

CONCLUSION

In this study an improved switching period optimization SVPWM strategy is proposed. The strategy uses a time window with adaptive width to control the average switching period and divides the value range of $\vec{U}_s$ into two kinds of regions: R and Q based on period coefficients. Switching periods are dependent in the same time window, while independent in different widows. The total extra time between specified period T_0 and optimal period T_s in region R can be made full use of in region Q. If current width of the time window is more than the specified value and $\vec{U}_s$ cuts across the boundary from Q to R or from one sub regions of R to another sub region of R, the window is returned to zero and a new window begins. A simulation platform was built in MATLAB/Simulink. The simulation result verifies excellent performance on harmonic distortion and amplitude peak reduction.

The improved strategy has widespread applications in electric vehicles, industry automation and drives, household appliances and so on.

It is variable and optimal period that reduces harmonic distortion and spectrum peaks. The combination of switching period optimization and randomization can get more excellent performance. But randomization makes it complicated to realize in digital control units. In the future, the study will focus on how to realize the optimization method and control algorithm in one chip, for example Field-Programmable Gate Array (FPGA).

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