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dSPACE Implementation of the Third Harmonic Insertion based Modulation on the Three Phase Power Inverter

This paper shows the implementation of real-time modulation based on the third order harmonic insertion in three-phase power inverter. Two methods of implementation have been proposed. As a working methodology the mathematical model of the duty cycles of the three-phase power inverter have been designed and implemented in Matlab/Simulink®. By an adequate design the appropriate ControlDesk interface send the adequate signals to power inverter and collect all the necessay data to be viewed. Harmonic analysis has been performed. The advantages of using this type of modulation are highlighted.

Keywords: power inverter, Matlab Simulink, dSpace, third harmonic insertion

1. Introduction

Modern energy conversion systems are based on power converters [1]-[3]. The efficiency of the power converters can be improved by using adequate modulation techniques [1], [2], [4]. The advantages of the third harmonic insertion as modulating signal of power inverters are shown in this paper. The Sinusoidal PWM technique conducts to low DC bus utilization, therefore low efficiency. By adding a triple frequency term the DC link voltage usage increase; in this way boosting the drive efficiency.

Two methods of third harmonic insertion have been developed [2], [5] by deducting the maximum amplitude of the signal. Taking into account the limit of the modulating signal, the feasible solution has been selected.

2. First approach

By inserting the third–harmonic PWM the modulating waveform becomes:

$$y(t) = \sin\theta + K\sin 3\theta \tag{1}$$

where: θ-the phase, K- the unknown parameter, has to maintain the limits of the $y(t)$ signal up to 1.

Through the optimization process the K parameters will be found. By derivating the signal $y(t)$ respect to angle θ and equating to zero, the maximum amplitude of the $y(t)$ signal can be found.

$$\begin{aligned} \frac{dy(t)}{d\theta} &= \cos\theta + 3K\cos 3\theta \\ \frac{dy(t)}{d\theta} &= 0 \end{aligned} \tag{2}$$

To develop the $\cos 3\theta$ in terms of $\cos\theta$, it could be considerate:

$$\cos 3\theta = \cos(2\theta + \theta), \tag{3}$$

and taking into account that

$$\begin{aligned} \cos 2\theta &= 2\cos^2(x) - 1 \\ \sin 2\theta &= 2\sin\theta\cos\theta \end{aligned}, \tag{4}$$

the following useful expression can be found:

$$\cos 3\theta = 4\cos^3\theta - 3\cos\theta \tag{5}$$

By introducing (5) in (2) and equating to zero, after some elementary calculus the following expression should be found:

$$\cos\theta\left[1 - 3K\left(4\cos^2\theta - 3\right)\right] = 0 \tag{6}$$

or in the final form:

$$\cos\theta\left[12K\cos^2\theta - (9K - 1)\right] = 0 \tag{7}$$

The above deducted equation (7) has two solutions:

$$\cos\theta = 0 \tag{7a}$$

$$12K\cos^{2\,-}-(9K-1)=0 \text{ or } \cos^{-}=\sqrt{\frac{9K-1}{12K}} \tag{8}$$

In order to find the solutions in terms of $\sin^{-}$, the following equation has to be considered:

$$\sin^{-}=\sqrt{1-\cos^{2\,-}}\ . \tag{9}$$

In this way, two conditions in $\sin^{-}$ expressions could be found:

$$\sin^{-}=1 \tag{10}$$

$$\sin^{-}=\sqrt{\frac{1+3K}{12K}}\ . \tag{11}$$

In the same manner with eq. 5:

$$\sin 3^{-}=\sin^{-}\left(3-4\sin^{2\,-}\right)\ . \tag{12}$$

From eq. (1), by introducing (5) results:

$$\sin^{-}+3K\sin^{-}\left(3-4\sin^{2\,-}\right)=y(t) \tag{13}$$

or in the form

$$\sin^{-}(1+3K)-4K\sin^{3\,-}=y(t) \tag{14}$$

According to the first solution (10), $\sin^{-}=1$, by replacing it into (14), the maximum value of the signal y(t) is obtained for

$$\hat{y}=1-K \tag{15}$$

By using the second solution (11), the maximum value of the y signal (14) could be

$$\hat{y}(t)=8K\sqrt[3]{\frac{1+3K}{12K}} \tag{16}$$

In order to find the optimum value of the K parameter, the first derivative of the maximum value of the $\hat{y}$ (t) signal is computed:

$$\frac{d\hat{y}(t)}{dK}=0 \tag{17}$$

i.e.

$$\left(\frac{1+3K}{12K}\right)^{\frac{1}{2}}\left(2-\frac{1}{3K}\right)=0\,. \tag{18}$$

The first solution

$$K=-\frac{1}{3} \tag{19}$$

conduct to the maximum amplitude signal,

$$\hat{y}(t)>1. \tag{20}$$

Therefore, only the second solution

$$K=\frac{1}{6} \tag{21}$$

will maintain the maximum amplitude of the signal $\hat{y}(t)<1$, i.e.

$$y(t)=\sin{}^{-}+\frac{1}{6}\sin 3^{-}\,. \tag{22}$$

By replacing (21) in (8), the following result is obtained:

$$\cos{}^{-}=\frac{1}{2} \text{ or } {}^{-}=n\frac{\text{®}}{3},\ n=\overline{1,\infty}\,. \tag{22a}$$

Introducing ${}^{-}=n\frac{\text{®}}{3}$ in (22), the maximum value of the $\hat{y}(t)$ amplitude is found:

$$\hat{y}(t)=\pm\frac{\sqrt{3}}{2}\,. \tag{23}$$

According to (23) the maximum value of the modulating waveform decreased by $\frac{\sqrt{3}}{2}$, while the amplitude of the fundamental is unity.

In order to increase the efficiency of the power inverter, the utilization of the DC link voltage can be increased:

$$y(t)=R\left(\sin{}^{-}+\frac{1}{6}\sin 3^{-}\right), \tag{24}$$

where R has to be determined.

The amplitude of the modulating signal is increased at unity by introducing the condition:

$$\hat{y}(t)=1, \tag{25}$$

which means ${}^{-}=n\frac{\text{®}}{3}$.

Considering n=1 and combining the above mentioned conditions (25), from eq. 24 becomes the value of the R parameter can be found:

$$1=\mathrm{R}\frac{\sqrt{3}}{2} \text{ or } R=\frac{2}{\sqrt{3}} \tag{26}$$

By introducing the third harmonic, the obtained three phase modulating signals are as follows:

$$\begin{aligned} u_A^*(t) &= \frac{2}{\sqrt{3}}\left(\sin{}^{-} + \frac{1}{6}\sin 3^{-}\right) \\ u_B^*(t) &= \frac{2}{\sqrt{3}}\left(\sin\left({}^{-} - 2\frac{\text{®}}{3}\right) + \frac{1}{6}\sin 3^{-}\right) \\ u_C^*(t) &= \frac{2}{\sqrt{3}}\left(\sin\left({}^{-} - 4\frac{\text{®}}{3}\right) + \frac{1}{6}\sin 3^{-}\right) \end{aligned} \tag{27}$$

The advantages of using the three phase modulating signals (27) are: increased DC link voltage utilization and the increased amplitude of the modulating signals while the amplitude of the fundamental is increased by 15,5 %.

3. Second approach

In the Fig. 1 the basic power inverter schematic, supplying a three-phase load, is shown. It consists of six power switching devices (IGBTs), S1, S3, S5 makes the upper bridge, and S4, S6, S2 the lower bridge. There are three arms, the power semiconductor devices on one arms cannot conduct simultaneously.

The most common modulation used method is sinusoidal pulse width modulation (PWM). The PWM method introduces an important advantage: generates the high order harmonics, therefore the lower filter inductance is obtained in order to compensate them.

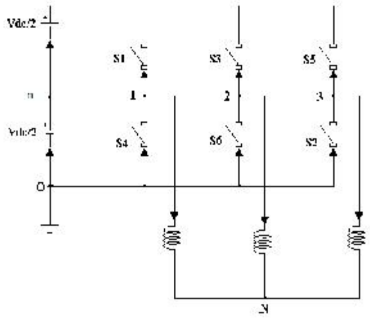

Figure 1. Three-phase power inverter schematic.

Taking into account the insertion of the third order harmonic, according to Fig. 1 the following equations are obtained:

$$v_{s,10}^{*} = \frac{V_{dc}}{2} + v_{s,1n} - \frac{1}{2}\left[\max\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right) + \min\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right)\right] \quad (28)$$

$$v_{s,20}^{*} = \frac{V_{dc}}{2} + v_{s,2n} - \frac{1}{2}\left[\max\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right) + \min\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right)\right] \quad (29)$$

$$v_{s,30}^{*} = \frac{V_{dc}}{2} + v_{s,3n} - \frac{1}{2}\left[\max\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right) + \min\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right)\right] \quad (30)$$

Considering phase 1, during on one sampling period T_c , the DC voltage, V_{dc}, is applied when S1 switch is ON, during $t_{on} = t^{+}$, and a zero voltage is applied during $t_{off} = t^{-}$, S4 being ON, such that

$$V_{dc} t^{+} + 0 t^{-} = v_{s,10}^{*} T_c \quad (31)$$

By taking into consideration the voltage symmetry:

$$v_{s,1n} + v_{s,2n} + v_{s,3n} = 0 \quad (32)$$

From the eq. (31) the adequate duty factor on phase 1 is obtained:

$$d_1^{*} = \frac{1}{2} + \frac{v_{s,1n}}{V_{dc}} - \frac{1}{2V_{dc}}\left[\max\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right) + \min\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right)\right] \quad (33)$$

Similarly, the duty factors for the other two phases are obtained:

$$d_2^{*} = \frac{1}{2} + \frac{v_{s,2n}}{V_{dc}} - \frac{1}{2V_{dc}}\left[\max\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right) + \min\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right)\right] \quad (34)$$

$$d_3^{*} = \frac{1}{2} + \frac{v_{s,3n}}{V_{dc}} - \frac{1}{2V_{dc}}\left[\max\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right) + \min\left(v_{s,1n}, v_{s,2n}, v_{s,3n}\right)\right] \quad (35)$$

4. Simulation results

Initial data: DC-link voltage V_{dc}=310V; sample time t_A=0.0001s; commutation cycle T_c=2*tA; PWM frequecy f_{PWM}=1/(2*tA); inductive load L_s=0.03 H; R_s=50 Ω; R_f=10Ω.

Simulink implementation

By using the first implementation method described in this paper, the adequate command signals have been obtained (Fig.2).

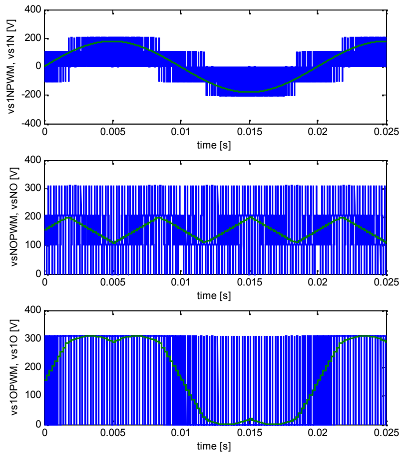

Figure 2. The output phase voltage of the three-phase power inverter and the fundamental signal, insertion of the third harmonic order based on the eq.22. and the modulating signal

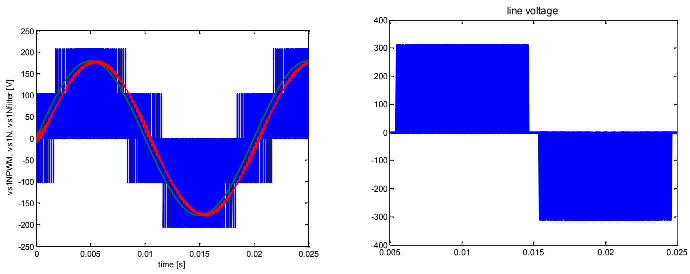

Figure 3. Phase output voltage and the fundamental and the line output voltage

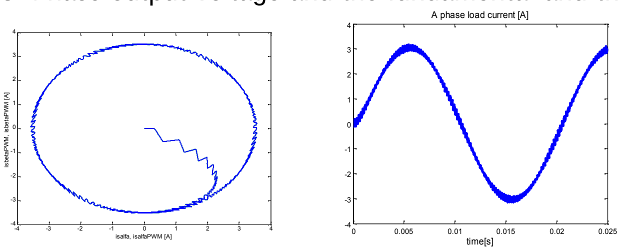

Figure 4. The locci locus of the alpha beta voltage components and the phase load current

The second method has been implemented based on Matlab/Simulink and the following results have been obtained:

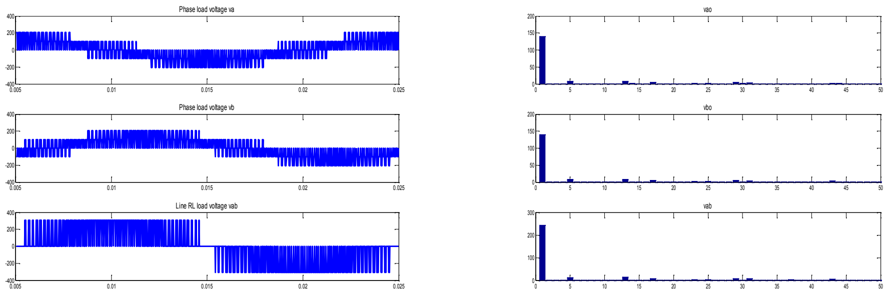

Figure 5. Three phase output modulated voltage and the harmonic spectrum of the three phase load current

5. Implementation on the dSPACE platform

In the Fig. 3 the imposed duty cycle for generating PWM waveform is shown. According to Fig.4, the imposed duty cycle for generating PWM waveform with third order harmonic insertion is shown

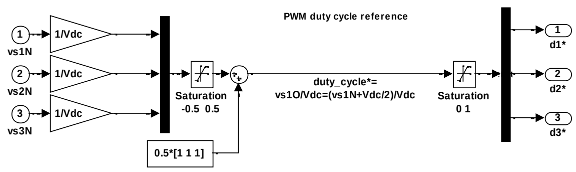

Figure.6 PWM implementation by using the imposed duty-cycle d^*_1, d^*_2, d^*_3

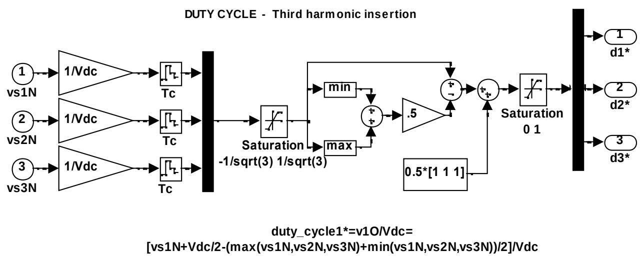

Figure.7 Third harmonic insertion by using the imposed duty-cycle d^*_1, d^*_2, d^*_3

Taking into consideration a DC link voltage V_{dc}= 10V, RL load with L_s=0.03H; R_s=50Ω; filter R_f=10Ω and a sample time of 0.1ms, based on the Fig.3 an adequate ControlDesk interface has been constructed (Fig.8).

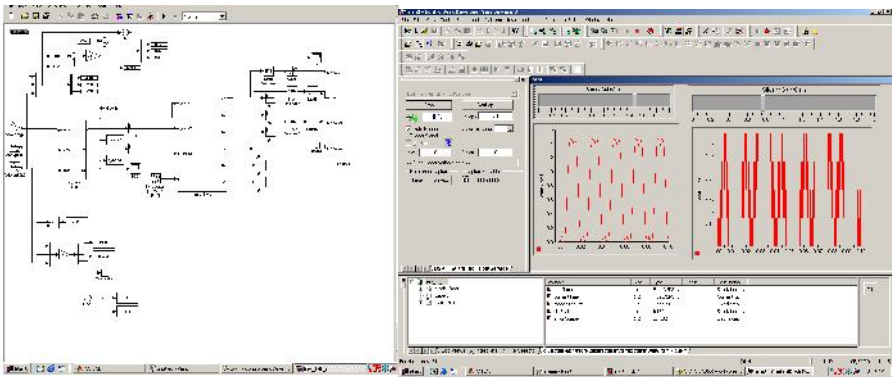

Figure 8. ControlDesk interface for the third harmonic implementation

Adequate harmonic analysis of the load current reveals the influence on the phase and line voltages (Fig.5). The most important harmonics are 5th, 13th and 17th. Therefore a low size RL filter should be designed in order to decrease the harmonics content.

6. Conclusions

The third harmonic insertion increases the power converter efficiency by increasing the DC link voltage utilization and the amplitude of the fundamental is increased by 15,5 %.

Two implementation methods of the third harmonic insertion have been considerate.

By using the dSpace platform, the adequate duty cycle has been implemented through the ControlDesk.

Acknowledgment

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