The impact of sampling frequency and amplitude modulation index on low order harmonics in a 3-phase SV-PVM voltage source inverter

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Abstract: Nowadays, variable speed AC motors are widely used in industry and there are many speed adjustment techniques available. In the last decade there has been a trend towards the use of space vector PWM–IGBT inverters, due to easier digital realization and better utilization of the DC bus. Every power inverter produces a total harmonic distortion (THD) on its output that causes extra losses in stator of induction motors. By eliminating a number of low order voltage/current harmonics it is possible to reduce harmonic losses (stator losses) and mechanical oscillations in general. This could be achieved by implementing filters in the output of inverters or by applying a modern modulation technique such as space vector pulse width modulation (SV-PWM). The objective of this paper is focused on using general techniques of SV-PWM in 2-level 3-phase voltage source inverters for inductive load tempting to eliminate the low order voltage/current harmonics, by varying sampling frequency and amplitude modulation index, without using filters.

Key words: Space vector pulse width modulation (SV-PWM), THD – total harmonic distortion, amplitude modulation index, switching frequency, harmonic losses

1. Introduction

Control of AC motors’ speed can be accomplished by changing the level of the applied voltage, using variable frequency voltage, variable level voltage, or both, but it cannot be accomplished either directly from 3-phase/multiphase AC electrical networks or with transformers. It can be accomplished with PWM inverters [1,2].

In general, control of variable frequency can be achieved with two methods: the scalar and the vectorial method.

The scalar control method is simple to implement but does not provide high performance. This method is based on varying two parameters simultaneously, the voltage and frequency with ratio V/f = constant. The disadvantage of this control method is sluggish control response because of the inherent coupling effect (both torque and flux are functions of the stator voltage/current and frequency) [3]. Torque is influenced by incremental of slip and flux that tends to decrease. This sluggish nature lengthens the response time and an induction motor can never give a fast transient response [4].

The vectorial method does not control only the effective value of voltage and frequency but it also controls the actual position of voltage vectors, current, and flux. This provides improved dynamic behavior of
the supplied unit, in general. With this technique, it is possible to uncouple the field components. Uncoupling establishes two independent and single controlled currents: the flux-producing current and torque-producing current. Using these currents, the flux and torque can be independently controlled [5].

Advancements in power electronics and semiconductor technology have brought significant improvements in power electronics systems, mainly through IGBT transistors and technology of digital signal processing (DSP).

The driving circuit (not shown) for each of the 6 IGBTs of the three legs of voltage source inverters (VSIs) has direct impact on the harmonic content of the inverter’s output voltages/currents. This paper is focused on the development of a general technique of SV-PWM in 2-level 3-phase VSIs [2], aiming at their utilization for driving variable speed 3-phase induction motors of medium power. One of the major issues faced in power electronic design is the reduction of harmonic content in inverter circuits [6–9].

Switching frequencies are selected as 720 Hz and 1080 Hz (multiples of 60 Hz) and 1.5 kHz, 3 kHz, and 10 kHz (multiples of 50 Hz), but the output frequency of VSI is 50 Hz.

According to the literature review [10–12], there are also the following well-known phenomena:

- At SV-PWM inverters, the THD% of the current phase decreases when the switching frequency increases as a multiple integer of the output frequency \( f \).

- The output voltage magnitude of SV-PWM inverters does not depend on switching frequency \( f_{sw} \) but it depends on amplitude modulation index.

It has been shown that THD% is very low for 2-level 3-phase VSIs working at higher switching frequencies such as 3 kHz and 10 kHz. Our motivation is to research this phenomenon with different settings of switching frequencies and fundamental harmonics to improve performance.

The work presented in this manuscript differs in approach from the other authors, because we used multiples of 50 Hz and 60 Hz switching frequency, while setting the fundamental harmonic at 50 Hz.

We noticed that for higher switching frequency (1500 Hz, multiple of 50 Hz) we obtained much higher THD% than at lower frequencies (720 Hz and 1080 Hz, multiples of 60 Hz).

Our major findings are in two sampling frequencies, \( f_{sw} = 3 \) kHz and \( f_{sw} = 10 \) kHz, by changing the modulation index from \( m_a = 0.85 \) to \( m_a = 1 \), whereas THD% values of phase currents are compared. When \( f_{sw} = 10 \) kHz, we noticed a “jumping” growth phenomenon of the THD% of phase current, which does not occur in the case of \( f_{sw} = 3 \) kHz.

The circuit of a typical model of a 2-level 3-phase VSI is as shown in Figure 1. The output from this inverter is used to drive a 3-phase balanced load (induction motor).

This is a 2-level inverter because it has only two level voltages between any phases (A, B, C) and the negative pole of battery, \( + E_{dc} \) and 0, but line to line voltages of inverter \( (V_{AB}, V_{AC}, V_{CA}) \) have three various values of voltages \( + E_{dc}, 0, \) and \( - E_{dc} \).

During all analyses in this paper, IGBT switches have been considered to be ideal wherein switching losses are zero.
2. Description of SV-PWM control on 2-level VSI

The switching states of the inverter presented in Figure 1 have been indicated by a three-bit switching word \((ABC)\). When one bit is equal to 1 the upper side switch of that leg is ON, and when the particular bit is equal to 0, the switch of the lower side leg is ON. There are eight possible combinations of switching states with the 2-level inverter: \(V_1(100)\), \(V_2(110)\), \(V_3(010)\), \(V_4(011)\), \(V_5(001)\), \(V_6(101)\), \(V_7(111)\), \(V_8(000)\). Six of these switching states are active states, but the switching states \((111)\) and \((000)\) are zero/passive \([2,6–9]\).

The relationship between switching states, line to line output voltages, and their corresponding space vectors are given in Table 1.

Table 1. Space vectors, switching states of IGBT, line to line output voltages of inverters, and the state of switching vectors.

<table>
<thead>
<tr>
<th>Switching vectors</th>
<th>S_1</th>
<th>S_3</th>
<th>S_5</th>
<th>S_6</th>
<th>S_4</th>
<th>S_2</th>
<th>V_{ab}</th>
<th>V_{bc}</th>
<th>V_{ca}</th>
<th>Active/passive vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_1(100))</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>N</td>
<td>Off</td>
<td>On</td>
<td>+ E_{dc}</td>
<td>0</td>
<td>- E_{dc}</td>
<td>Active</td>
</tr>
<tr>
<td>(V_2(110))</td>
<td>On</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
<td>0</td>
<td>+ E_{dc}</td>
<td>- E_{dc}</td>
<td>Active</td>
</tr>
<tr>
<td>(V_3(010))</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
<td>- E_{dc}</td>
<td>0</td>
<td>+ E_{dc}</td>
<td>Active</td>
</tr>
<tr>
<td>(V_4(011))</td>
<td>Off</td>
<td>On</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>- E_{dc}</td>
<td>0</td>
<td>+ E_{dc}</td>
<td>Active</td>
</tr>
<tr>
<td>(V_5(001))</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>0</td>
<td>- E_{dc}</td>
<td>+ E_{dc}</td>
<td>Active</td>
</tr>
<tr>
<td>(V_6(101))</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>+ E_{dc}</td>
<td>- E_{dc}</td>
<td>0</td>
<td>Active</td>
</tr>
<tr>
<td>(V_7(111))</td>
<td>On</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Passive</td>
</tr>
<tr>
<td>(V_8(000))</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>On</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Passive</td>
</tr>
</tbody>
</table>

The six active vectors \((V_1 \text{ to } V_6)\) form a regular hexagon, but zero vectors \((V_7 \text{ and } V_8)\) lie on the center of the hexagon (as shown in Figure 2). None of these vectors move in space and are referred to as stationary vectors \([10,13,14]\).
Figure 2. Space vector hexagon for the two-level inverter.

Figure 2 shows the reference vector ($V_{ref}$) for a particular angular position $\theta$, onto the stationary reference frame $\alpha-\beta$. $V_{ref}$ is the rotating vector in space and can be synthesized by three near-by stationary vectors (two active and one/two zero vectors), depending on which sector it is [2,15,16].

When $V_{ref}$ rotates in the counterclockwise direction it is expected to pass through successive sectors I to VI one by one, and different sets of switches will be switched (on or off).

Duration of active and passive vectors within a sector is represented by sampling period $T_s$. Hence, effective value and frequency of output voltages of the VSI depend on the rotating speed and magnitude of $V_{ref}$, respectively.

For every three-phase balanced inductive load:

$$v_{AN}(t) + v_{BN}(t) + v_{CN}(t) = 0,$$

Where $v_{AN}, v_{BN}, v_{CN}$ are balance load phase voltage.

When we apply the Clark transform [2,10,15–18], we have

$$V_{ref}(t) = \frac{2}{3} [a^0 v_{AN}(t) + a \cdot v_{BN}(t) + a^2 \cdot v_{CN}(t)],$$

where

$$a = e^{j2\pi/3}, \quad a^2 = e^{j4\pi/3}$$

If we analyze Figure 1 for the active switching state (100), respective phase voltages are

$$v_{AN}(t) = \frac{2}{3} E_{dc}, \quad v_{BN}(t) = -\frac{1}{3} E_{dc}, \quad v_{CN}(t) = -\frac{1}{3} E_{dc} \tag{3}$$

By substituting (3) into (2), the corresponding space vector is

$$V_1 = \frac{2}{3} E_{dc} \cdot e^{j0} \tag{4}$$
Continuing the same procedure, for next five active states can be derived

\[ V_k = \frac{2}{3}E_{dc}e^{j\left(k-1\right)\frac{\pi}{6}}, \quad k = 2, 3, \ldots 6 \]  

(5)

The selection algorithm of stationary vectors presents a modulation scheme, while duration of stationary space vectors represents the dwell time or duty-cycle time (on-state or off-state time) of the selected IGBTs during a sampling period \( T_s \).

The modulation algorithm that does not use successive modulation vectors (DSVM- discontinuous space vector modulation) produces higher THD [19]. At the same time it is expected that the harmonic losses will be higher.

In SV-PWM each desired position on the circular locus can be achieved by an average relationship between two neighboring active vectors. Zero state vectors are used to fill up the gap to a constant sampling interval [20].

Rotating vector \( \mathbf{V}_{ref} \) is sampling once within each \( T_s \), and it gives average values of the applied vector on the given sub-cycle.

The dwell time calculation is based on the “volt-second balancing” principle, that is, the product of the reference voltage \( \mathbf{V}_{ref} \) and sampling period \( T_s \) equals the sum of the voltage multiplied by the time interval of the chosen space vectors [2,12].

Assuming that the reference vector falls into sector I as shown in Figure 3, the volt-second balancing integral equation is

\[
\int_0^{T_s} \mathbf{V}_{ref} dt = \int_0^{T_a} \mathbf{V}_1 dt + \int_{T_a}^{T_a+T_b} \mathbf{V}_2 dt + \int_{T_a+T_b}^{T_s} \mathbf{V}_0 dt, \quad (6)
\]

where \( V_0 = 0 \) and \( T_s = 1/f_s \) (switching frequency) sampling period, respectively.

The dwell times \((T_a, T_b, \text{ and } T_0)\) for the vector \( \mathbf{V}_1, \mathbf{V}_2 \) and zero vectors \( \mathbf{V}_7 \) or \( \mathbf{V}_8 \) are obtained.
with integral equation solution (6),

\[ T_a = T_s \cdot m_a \cdot \sin \left( \frac{\pi}{3} - \theta \right) \]
\[ T_b = T_s \cdot m_a \cdot \sin \theta \]
\[ T_0 = T_a - T_a - T_b \]

for \( 0 \leq \theta \leq \pi/3 \),

where \( m_a \) represents amplitude modulation index

\[ m_a = \frac{\sqrt{3} \cdot V_{\text{ref}}}{E_{dc}} \]

The amplitude modulation index for the SV-PWM scheme is in the range of

\[ 0 \leq m_a \leq 1 \]

The amplitude modulation index \( (m_a) \) and switching frequency (sampling frequency \( f_{\text{sw}} = f_{\text{sp}} = 1/T_s \)) have impact on total distortion and losses on symmetrical inductive load in general.

The SV-PWM technique satisfies the requirements for the minimization of switching frequency of the switching VSI elements and low order voltage/current harmonics in comparison with the traditional sine-PWM technique. Using a high switching frequency improves the harmonic spectrum by drifting the harmonics toward higher orders [21].

3. MATLAB/Simulink model

All results in this paper are obtained after building the SV-PWM scheme using the MATLAB/Simulink Powersim Library (Figures 4–6).

Figure 4. Simulink model of three-phase VSI fed induction motor.
The model was run according to the following data: DC link voltage $E_{dc} = 400$ V and 3-phase balanced inductive load ($R = 10$ $\Omega$, $L = 5$ mH).
4. Simulation results and analysis

Simulation results are obtained based on five measurement conditions for these switching (sampling) constant frequencies ($f_{sw1} = 720$ Hz, $f_{sw2} = 1080$ Hz, $f_{sw3} = 1500$ Hz, $f_{sw4} = 3$ kHz and $f_{sw5} = 10$ kHz), by changing the amplitude modulation index from $m_a = 0.6$ to $m_a = 1$ in regular conditions of modulation.

Since the load is 3-phase balanced with inductive character and based on the output voltage and current symmetry of two other phases shifted for $2\pi/3$, the presented measurements (in time domain) stand only for line to line voltage ($V_{AB}$) and phase current – $i_A$. THD of voltages/currents is almost the same; in this case other measurements are not presented. Thus, by applying switching frequencies in operation conditions from 1 to 5, the amplitude modulation index increases by 0.05 between 0.6 and 1, whereas fundamental frequency remains constant of 50 Hz.

In this paper only simulation results for amplitude modulation index of 0.85 are presented, whereas its changes are done in Model properties/Callback.

The magnitude of the fundamental ac output voltage is a function of the amplitude modulation index $m_a$. Setting the amplitude modulation index at $m_a = 0.85$ is important because fundamental line-to-line and phase voltages of the 3-phase inverter get approximate voltage values with respective European 3-phase grid distribution.

Measurements for amplitude modulation indexes within the range 0.6 to 1 and five switching frequencies above are included in Tables 2–6.

Line-to-line voltage and phase current produced by the SV-PWM inverter contain odd and even harmonics.

**Condition 1. Analysis in $f_{sw} = 720$ Hz.**

Line-to-line voltage $V_{AB}$ and phase current $i_A$ (when $m_a = 0.85$) are represented in Figure 7. Table 2 shows the simulation results for various values of amplitude modulation index in this sampling frequency. By increasing the amplitude modulation index from 0.85 to 1 the THD voltage/current decreases.

![Figure 7. Line-to-line voltage $V_{AB}$ and phase current $i_A$ (case when $f_{sw} = 720$ Hz).](image-url)
Table 2. THD-$V_{AB}$ and THD-$i_A$ in function of amplitude modulation index ($m_a$) when sampling frequency is 720 Hz.

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD-$V_{AB}$</td>
<td>45.19%</td>
<td>43.20%</td>
<td>40.20%</td>
<td>36.91%</td>
<td>33.16%</td>
<td>28.79%</td>
<td>25.31%</td>
<td>23.44%</td>
<td>22.38%</td>
</tr>
<tr>
<td>THD-$i_A$</td>
<td>11.18%</td>
<td>11.10%</td>
<td>10.17%</td>
<td>9.17%</td>
<td>8.10%</td>
<td>7.56%</td>
<td>6.56%</td>
<td>6.78%</td>
<td>7.12%</td>
</tr>
</tbody>
</table>

From the obtained results we can see that using this modulation technique THD voltage has high values but it has a reduced THD current. As shown in the simulation results of Figure 8, in this modulation frequency the first 10 harmonics have low values and pretty evident harmonic losses.

![FFT analysis](image1)

**Figure 8.** THD-line-to-line voltage $V_{AB}$ and phase current $i_A$ (case when $f_{sw} = 720$ Hz).

In these operation conditions even though $m_a$ increases, THD of load phase currents has an approximate value of 7%.

**Condition 2. Analysis in $f_{sw} = 1080$ Hz.**

Simulation results in this sampling frequency are given in Figures 9 and 10 and Table 3. In Figure 10 the disappearance of 15 lower order harmonics is obvious, what did not occur in the previous case and harmonic shifting on the right of harmonic order, causing smaller losses compared to the previous case. By increasing $m_a$ from 0.8 to 0.85, the THD- $V_{AB}$ and THD-$i_A$ decrease at the same time. This is a very good compromise by which the SV-PWM modulation technique differs from the traditional technique Sin-PWM [5].

**Condition 3. Analysis in $f_{sw} = 1500$ Hz.**

Simulation results in this sampling frequency are given in Figures 11 and 12 and Table 4. In all used switching frequencies, by changing amplitude modulation index, as a result the reference voltage amplitude ($V_{ref}$) and line-to-line voltage output of the 2-level 3-phase inverter changes too.
Figure 9. Line-to-line voltage $V_{AB}$ and phase current $i_A$ (case when $f_{sw} = 1080$ Hz).

Figure 10. THD-line-to-line voltage $V_{AB}$ and phase current $i_A$ (case when $f_{sw} = 1080$ Hz).

Table 3. THD-$V_{AB}$ and THD-$i_A$ in function of amplitude modulation index ($m_a$) when sampling frequency is 1080 Hz.

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD-$V_{AB}$</td>
<td>45.41%</td>
<td>42.76%</td>
<td>40.12%</td>
<td>36.95%</td>
<td>33.49%</td>
<td>29.45%</td>
<td>26.04%</td>
<td>24.54%</td>
<td>23.56%</td>
</tr>
<tr>
<td>THD-$i_A$</td>
<td>8.02%</td>
<td>7.42%</td>
<td>6.79%</td>
<td>6.12%</td>
<td>5.45%</td>
<td>4.82%</td>
<td>4.52%</td>
<td>4.99%</td>
<td>7.12%</td>
</tr>
</tbody>
</table>
Figure 11. Line-to-line voltage $V_{AB}$ and phase current $i_A$ (case when $f_{sw} = 1500$ Hz).

Figure 12. THD-line-to-line voltage $V_{AB}$ and phase current $i_A$ (case when $f_{sw} = 1500$ Hz).

Table 4. THD-$V_{AB}$ and THD-$i_A$ in function of amplitude modulation index ($m_a$) when sampling frequency is 1500 Hz.

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD-$V_{AB}$</td>
<td>91.46%</td>
<td>83.37%</td>
<td>75.66%</td>
<td>68.57%</td>
<td>61.36%</td>
<td>54.26%</td>
<td>48.72%</td>
<td>45.97%</td>
<td>43.62%</td>
</tr>
<tr>
<td>THD-$i_A$</td>
<td>16.45%</td>
<td>14.80%</td>
<td>13.22%</td>
<td>11.74%</td>
<td>10.39%</td>
<td>9.22%</td>
<td>8.51%</td>
<td>8.44%</td>
<td>8.78%</td>
</tr>
</tbody>
</table>
Condition 4. Analysis in $f_{sw} = 3$ kHz.

Simulation results in this sampling frequency are given in Figures 13 and 14 and Table 5. When modulation index changes from 0.85 to 1 we can see that the 50th low-order harmonics have been reduced (almost to zero) without using any filters, but there is a shift of present harmonics on the right of the 50th harmonic. Moreover, THD\% (of phase currents) values are very low and at a satisfactory level and almost constant (about 5\%). This leads to work stability of the variable speed induction motor.

**Figure 13.** Line-to-line voltage $V_{AB}$ and phase current $i_{A}$ (case when $f_{sw} = 3$ kHz).

**Figure 14.** THD-line-to-line voltage $V_{AB}$ and phase current $i_{A}$ (case when $f_{sw} = 3$ kHz).
Table 5. THD-$V_{AB}$ and THD-$i_A$ in function of amplitude modulation index ($m_a$) when sampling frequency is 3 kHz.

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD-$V_{AB}$</td>
<td>91.63%</td>
<td>83.50%</td>
<td>75.66%</td>
<td>68.67%</td>
<td>61.47%</td>
<td>54.22%</td>
<td>48.84%</td>
<td>45.99%</td>
<td>44.33%</td>
</tr>
<tr>
<td>THD-$i_A$</td>
<td>8.34%</td>
<td>7.48%</td>
<td>6.66%</td>
<td>5.92%</td>
<td>5.22%</td>
<td>4.61%</td>
<td>4.36%</td>
<td>4.88%</td>
<td>5.44%</td>
</tr>
</tbody>
</table>

The SV-PWM strategy in this switching frequency is very favorable because the amplitude of harmonics over 50 is lower too. For example, from Figure 14 we see that the amplitude of the 58th current harmonic is only 2.11% of the fundamental harmonic.

Despite the inherent property of the low pass filter of motor load, the load current is associated with harmonics of orders higher than 50.

This shift of current harmonics towards higher orders results in the reduction of extra losses in the stator windings of the motor.

Thus, by "shifting" the frequency band harmonic (current harmonics of high frequency) to the right, fortunately, the impulsive rotational moments of current harmonics and their effect will be tamed (smoothened) for big inertia moment of the driving system.

**Condition 5. Analysis in $f_{sw} = 10$ kHz.** The obtained results from Figures 7–16 show that by using various switching frequencies a certain number of low order harmonics can be reduced even when continual modulation of space vector strategy is used.

![Line-to-line voltage $V_{AB}$ and phase current $i_A$](image)

Figure 15. Line-to-line voltage $V_{AB}$ and phase current $i_A$ (case when $f_{sw} = 10$ kHz).

In the switching frequency of 1080 Hz, when $m_a$ changes from 0.95 to 1 there is an enhanced increase of THD-$i_A$ from 4.99% to 7.12%.

When comparing the inverter function in $f_{sw} = 1080$ Hz and $f_{sw} = 3000$ Hz, THD-$i_A$ almost overlaps when $m_a$ changes from 0.6 to 0.95, but when $m_a$ increases from 0.95 to 1 THD-$i_A$ increase is much more enhanced.

In this switching frequency, when $m_a$ changes from 0.9 to 1 there is a slightly enhanced increase in THD-$i_A$ (Table 6).
Figure 16. THD-line-to-line voltage $V_{AB}$ and phase current $i_A$ (case when $f_{sw} = 10$ kHz).

Table 6. THD-$V_{AB}$ and THD-$i_A$ in function of amplitude modulation index ($m_a$) when sampling frequency is 10 kHz.

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD-$V_{AB}$</td>
<td>91.32%</td>
<td>83.70%</td>
<td>75.65%</td>
<td>68.61%</td>
<td>61.62%</td>
<td>54.41%</td>
<td>49.04%</td>
<td>46.21%</td>
<td>44.53%</td>
</tr>
<tr>
<td>THD-$i_A$</td>
<td>2.55%</td>
<td>2.36%</td>
<td>2.08%</td>
<td>1.80%</td>
<td>1.61%</td>
<td>1.41%</td>
<td>1.83%</td>
<td>3.12%</td>
<td>4.10%</td>
</tr>
</tbody>
</table>

When $f_{sw}$ increases from 1080 Hz to 1500 Hz, the THD-$V_{AB}$ and THD-$i_A$ do not decrease.

Even though the THD of phase current for $f_{sw} = 3$ kHz is not comparable with the THD of phase current for $f_{sw} = 10$ kHz, it is very important to omit the first 50 low order harmonics as respective impedances of load become very large, causing reduction of losses of harmonic current, without using filters.

5. Comparison of THD% among conditions 1–5

Obtained results from conditions 1 to 5 are shown in Figure 17, representing a comparison of THD-$i_A$ (%) on five various switching frequencies ($f_{sw}$) depending on amplitude modulation index ($m_a$). When we use $f_{sw} = 3$ kHz and change the $m_a$ from 0.85 to 1, the THD% is very low and almost constant, which is in contrast to switching frequencies $f_{sw} = 1080$ Hz and $f_{sw} = 10$ kHz.

6. Conclusion

Hereby, in order to obtain the impact of sampling frequency and amplitude modulation index on low order harmonics, a 3-phase SV-PVM voltage source inverter is built in MATLAB and analyzed for 5 different switching frequencies and 9 amplitude modulation index values.

From all other switching frequencies that are used in this manuscript, we prefer to use $f_{sw} = 3$ kHz, which according to our results is the lowest frequency showing significant improvement of THD%. Our major
findings are obtained by changing the modulation index from $m_a = 0.85$ to $m_a = 1$. The improvement has been noted in this switching frequency, which complies with the requirements for the reduction of lower harmonics, while the THD% of phase current remains within the satisfactory values. The most important fact is the smooth variation of THD% of the phase current, which results in the significant stability of the induction motors during an increase/decrease in speed.

When we used the switching frequency of 10 kHz under conditions with modulating index $m_a = 0.85$ we noticed that the THD of current was reduced in a very satisfying amount, THD-$i_A = 1.41\%$. With this switching frequency, by changing the modulation index from $m_a = 0.85$ to $m_a = 1$ we noticed a "jumping" growth phenomenon of the current phase THD% from 1.41% to 4.10%, which does not occur in the case of the switching frequency $f_{sw} = 3$ kHz. Thus, by increasing the amplitude of the output voltage we obtain a “huge increase” in the THD current, which results in a nonsmooth performance of the induction motor. The motor speed changes with difficulties in response to these impulsive rotational moments. Therefore, at this switching frequency, unwanted resonance of the mechanical system of the device can be caused while regulating the speed.

As future work we plan to use fuzzy logic algorithms to achieve optimal reduction of THD% on the switching frequencies multiple of 60 Hz, while the output of fundamental voltage frequency of VSI is set at 50 Hz.

References


