A Study of Harmonics in Pulse Width Modulation Power Inverter as a Motor Drive

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INTRODUCTION

The dc-ac converter also known as an inverter basically converts dc power to ac power. The DC power input of inverter is obtained from the existing power supply network after its rectification. And can be a battery, photovoltaic, wind energy, or other DC sources (B. Ismail 2008). The filter capacitor across the inverter input terminals provide a constant dc link voltage. Therefore the inverter is called a voltage source inverter (VSI) (M. H. Rashid 2005).

The inverter is a specified arrangement of switches that chops DC input voltage under the influence of control signals to give an output at which the current flows only in a single direction. The oldest invented DC-AC inverters are the single pulse width inverters which gives a single positive or negative pulse at half cycle. Probably, this type can be used for low power applications, but it performs badly when it works with high power applications. This type of inverters has some good properties like its’ high fundamental component, but has a bad current spectrum which causes problems for the load.

With the availability of high-speed switching devices, it was discovered that; chopping the DC voltage into uniform or non-uniform pulses in specified manner improves the spectrum of the output waveform and gives the facility of voltage control, this method is known as Pulse Width Modulation (PWM)(M. Samter 2007).

The most famous method of the PWM is the sinusoidal pulse-width modulation (SPWM), where it is compared sine wave signal called the modulating signal with triangular wave at high frequency, called the carrier signal. This is explained in the next section.

The latest methods of the (PWM) used in the present time to control the inverter switching ON/OFF is the Space-Vector Pulse-Width Modulation (SVPWM). This method contains two basic types are continuous SVPWM and discontinuous SVPWM (A. M. Hava 1999, andG. S. Rao 2011).

Discontinuous SVPWM contain many types most famous are DPWMMax, DPWMMin, DPWM0, DPWM1, DPWM2, and DPWM3. The most recent studies focused about these types of PWM.

Methods of Pulse-Width Modulation PWM can be implemented by using two ways direct digital and carrier-based implementation. The carrier-based pulse-width modulation (CB-PWM) is an efficient method used to enhance the performance of the power inverter by reducing the low order harmonics of its output voltage and current. In this paper three types of PWM are studied using CB-PWM method include: Sinusoidal PWM (SPWM), Continuous Space-Vector PWM (CSVPWM), and Discontinuous Space-Vector PWM (DSVPWM). All these types are applied on a 3-phase voltage source inverter (VSI) drive an induction motor. Variable speed control of an induction motor is conceptually very simple. The frequency and amplitude of the drive voltage must be varied to change the motor speed. So that a model is proposed in this paper to stabilize V/f constant ratio for speed variation. The model is derived from the modulation index (M) and the inverter output voltage by the curve fitting method. The results proved that the stabilizing V/f constant ratio is very efficient, resulting in too small error rates (with no more than ±5% tolerance) for all types of PWM mentioned. The study also compared the results with the international standards of total harmonic distortion (THD), it explained that some of the mentioned PWM method are very reliable in AC machine drive application, and some of them should be avoided for this purpose. Furthermore, some of PWM mentioned method may be used for lower frequencies (less than rated frequency). All models in this research are built and simulated in MATLAB 2010a SIMULINK and programming.
(H.W.Broeck, et al. 1988), are studied a space vector concept for deriving the switching instants for pulse-width modulated voltage source inverters and compared it with the commonly used established sinusoidal concept. Based an analytical calculation, the current distortions and torque ripples were evaluated and compared with those of established sinusoidal pulse width modulation.

The two main implementation techniques: Carrier-Based PWM and Direct Digital technique are applied for the Continuous Pulse-Width Modulation (CPWM) and Discontinuous Pulse-Width Modulation (DPWM) (A. M. Hava1999). Output voltage control is an essential feature of adjustable frequency system, and various technique for achieving voltage control within inverter were considered by (P.M. Menghal2003). The Generalized DPWM scheme for 3-phase VSI has been studies by (O. Ojo 2004). Where this study presents analytical techniques for the determination of the expressions for the modulation signals used in the Carrier-Based non-sinusoidal and Generalized DPWM modulation schemes for two-level, three-phase voltage source inverters. (M. B. AbbuSamter 2007), the thesis projects on the Carrier-Based PWM (CB-PWM) with all its common strategies in both triangular intersection and direct digital implementation methods. Detailed analysis about CPWM and DPWM are involved, containing the derivations for mathematical equations to estimated switching periods for inverter in both direct digital as well as triangular intersection.

The pulse width modulation strategy with, space vector modulation (SVM) was analyzed in detail by(A.Jidin2009). Where the principle of the (SVM) strategy was performed using MATLAB/SIMULINK.

(K. S. Gowri 2009), In this study a novel Space-Vector based Generalized DPWM algorithm is presented without angle estimation based on the concept of imaginary switching times. Where the conventional SVPWM method with equal division of zero state vectors V0 and V-is modified. (R. Rajendran, et al. 2010), they were presented the analysis and realization of SVPWM for variable speed control of AC motor drives, employing Xilinx Spartan 3E FPGA device. The selection of zero vectors and space vector sequence are given and the possibilities of realization on FPGA are analyzed in this study. (A. Iqbal, and et al. 2010),in this study focuses on step by step development of MATLAB/SIMULATION model of continuous and discontinuous SVPWM followed by their experimental implementation. (K. V. Kumar, and et al. 2010), In this study first a model for SVPWM is made and simulated using MATLAB/SIMULINK software and then its performance is compared with SPWM.

Simulation with conventional Continuous Space-Vector PWM (CSVPWM) and various Discontinuous Space-Vector PWM (DSVPWM) techniques are presented and compared by, (G. S. Rao, et al. 2011).

In this paper all kinds of PWM mentioned above will be studied in detail as well as how the design of each PWM methods using MATLAB / SIMULINK and MATLAB Programming and then applied each design for the 3-phase inverter drives A 3-phase squirrel cage induction motor. One of the main uses of inverter is to control the speed of induction motors, by changing the frequency of the input power, this method is one of the best methods used to control the speed of induction motors. It is worth mentioning that when the motor speed control by frequency must be maintained on the ratio V/f to be constant i.e. when the value of frequency reduced in turn should reduce the value of the voltage and vice versa. Therefore, in this paper a technique has been proposed to stabilize this ratio by reducing the supply voltage through the modulation index (M_s), and will be mentioned in section IV.

Voltage Control of Inverters:

Some loads, require simultaneous control of voltage and frequency such as induction motor drive. Control output frequency of the inverter motor achieve by controlling the conduction intervals of the inverter switches. Inverter output voltage may be done by any of the following techniques (P. S. Bimabha 2007).

1- Control of input DC voltage.
2- External control of inverter AC output voltage.
3- Internal control of inverter.

The first two methods require the use of extra components whereas the third method requires no extra components and it is the most popular method of voltage control of inverter where the form of inverter output voltage is a pulse width modulated wave, and the controlling this voltage done by controls the width of these pulses. The popular name of internal control method is the Pulse-Width-Modulation (PWM) method. There are two ways to implement the PWM methods: Direct Digital PWM (DPWM) method and Carrier-Based PWM (CB-PWM) method. As mentioned above the CB-PWM is applied in this paper.

Carrier Based Pwm:

A high-frequency carrier wave and a reference (modulating) wave are compared with each other. The intersection of these two signals determines the switching instants (J. R. Espinoza 2001). The frequency of the reference signal represent the inverter output frequency whereas, the carrier frequency represent the number of pulses per cycle.
Sinusoidal Pulse-Width Modulation (SPWM):

In SPWM of three-phase inverter, there are three sinusoidal reference waves \((v_a, v_b, v_c)\) each shifted by 120°. A carrier wave is compared with the reference signal corresponding to a phase to generate the gating signals for that phase as shown in Fig. (1.a) (M. H. Rashid 2005). The intersection of \(v_c\) and \(v_i\) waves determines the switching instants and commutation of the modulated pulse.

The ratio of \(\frac{|v_c|}{|v_i|}\) is called the amplitude modulation index \((M_a)\). The pulse-width and RMS value of voltage depend upon \(M_a\) (Y. R. Manjunatha, et al. 2008). The frequency of the reference wave decides the output frequency \(f_c\). The carrier frequency decides number of pulses per half cycle p. In order to use a single carrier signal and preserve the features of the PWM technique, the normalized carrier frequency \(m_p\) should be an odd multiple of 3.

Continuous Space-Vector Pulse-Width Modulation (CSVPWM):

Space vectors \((v_i, i = 1, 2, \ldots, 8)\) available in VSIs as shown in Fig.(2). The equivalent vector \(V_e\) rotating in the counter clockwise direction. The magnitude of this vector is related to the magnitude of the output voltage and the time of this vector takes to complete one revolution is the same as the fundamental time period of the output voltage (S. Panda, et al. 2009). However, if the modulating signal \(V_c\) is laying between the arbitrary vectors \(V_i\) and \(V_{i+1}\), only the nearest two nonzero vectors \((V_i \text{ and } V_{i+1})\) and one zero SV \((V_c = V_f \text{ or } V_0)\) should be used.

To ensure that the generated voltage in one sampling period \(T_s\) (made up of the voltages provided by the vectors \(V_i, V_{i+1}, \text{ and } V_c\) used during times \(T_i, T_{i+1}, \text{ and } T_c\)) is on average equal to the vector \(V_c\), the following expression should hold:

\[
V_c.T_s = V_i.T_i + V_{i+1}.T_{i+1} + V_c.T_c, \ldots (1)
\]

The solution of the real and imaginary parts of Eq.(1) for a line-load voltage that features an amplitude restricted to \(0 \leq \hat{v}_c \leq 1\) gives bellow

\[
T_i = \frac{\sqrt{3}T_s|V_i|}{V_{dc}} \sin \left(\frac{\pi}{3} - \omega t\right) (2)
\]

\[
T_{i+1} = \frac{\sqrt{3}T_s|V_{i+1}|}{V_{dc}} \sin \left(\omega t - \frac{(i-1)\pi}{3}\right) (3)
\]

\[
T_c = T_s - (T_i + T_{i+1}) (4)
\]

The preceding expressions indicate that the maximum fundamental line-voltage amplitude is unity as \(\frac{(i-1)\pi}{3} \leq \omega t \leq \frac{3\pi}{3}\). This is an advantage over the SPWM technique which achieves a \(\frac{\sqrt{3}}{2}\), maximum fundamental line-voltage amplitude in the linear operating region (P. S. Bimbhra 2007).

For a given dc link voltage \(V_{dc}\), the ratio of the fundamental component magnitude of the line to neutral inverter output voltage \(V_{lin}\) to the fundamental component magnitude of the six-step mode voltage \(V_{1m6step} = \frac{2}{\pi}V_{dc}\) is termed the modulation index \(M_a(4)\).

\[
M_a = \frac{V_{lin}}{V_{1m6step}} (5)
\]

It is found that the normalized sampling frequency \(f_{sn}\) should be an integer multiple of 6 (P. S. Bimbhra 2007). This is due to the fact that in order to produce symmetrical line voltages, all the sectors (a total of 6) should be used equally in one period.

The SVPWM can be implemented by using wither sector selection algorithm (also called direct digital method) or by using a carrier based space vector algorithm (S. Panda, et al. 2009). The Carrier-Based technique is applied in this paper. The technique is based on the duty ratio profiles, which can be produced by adding the zero-sequence signal to the three-phase reference signals. By comparing the duty ratio profile with a higher frequency triangular carrier the pulses can be generated, based on the same arguments as the sinusoidal pulse width modulation.

The zero sequence signal, which generates by employing the minimum magnitude test compares the magnitudes of the three reference signals and selects the signal with minimum magnitude. Scaling this signal with 0.5, the zero sequence signal of SVPWM is found.

Assume \(|v_a^*| < |v_b^*|, |v_c^*|\) then...
\[ v_0 = 0.5 \times v_a^* \]  

(6)

The modulating waveform and the ZSS for this strategy are shown in Fig.(3).

**Dsvpwm:**

In this PWM scheme, one of the three inverter output legs is clamped to either positive or negative DC bus without any switching’s for 120° interval of electrical fundamental period. There are six different schemes are available depending on the variation in the placement of the zero space vectors (A. Iqbal et al 2010).

- **DPWMMMax:**
  The reference signal with the maximum value defines the zero sequence. Assume \( v_b^* \leq v_a^* \leq v_c^* \), then
  \[ v_0 = \frac{v_{dc}}{2} - v_c^* \]  
  (7)

- **DPWMMin:**
  The reference signal with the minimum value defines the zero sequence. Assume \( v_b^* \leq v_a^* \leq v_c^* \), then
  \[ v_0 = \frac{v_{dc}}{2} - v_b^* \]  
  (8)

- **DPWM0:**
  All three reference modulation signals \( v_a^* \), \( v_b^* \), and \( v_c^* \) are phase shifted by 30° (leading), and of the new three signals \( v_{ax}^* \), \( v_{bx}^* \), and \( v_{cx}^* \), the one with the maximum magnitude determines the zero sequence signal. Assume \( |v_{ax}^*| \geq |v_{bx}^*|, |v_{cx}^*| \), then
  \[ v_o = \left( \text{sign}(v_{ax}^*) \right) \times \frac{v_{dc}}{2} - v_a^* \]  
  (9)

- **DPWM1:**
  The reference signal with the maximum magnitude defines the zero sequence signal. Assume \( |v_c^*|, |v_b^*| \leq |v_a^*| \), then:
  \[ v_0 = \left( \text{sign}(v_{ax}^*) \right) \times \frac{v_{dc}}{2} - v_a^* \]  
  (10)

- **DPWM2:**
  All three reference modulation signals \( v_a^* \), \( v_b^* \), and \( v_c^* \) are phase shifted by 30° (lagging), and of the new three signals \( v_{ax}^* \), \( v_{bx}^* \), and \( v_{cx}^* \), the one with the maximum magnitude determines the zero sequence signal. Assume \( |v_{ax}^*|, |v_b^*| \leq |v_c^*| \), then
  \[ v_o = \left( \text{sign}(v_{cx}^*) \right) \times \frac{v_{dc}}{2} - v_a^* \]  
  (11)

- **DPWM3:**
  The reference signal with the intermediate magnitude defines the zero sequence signal. Assume \( |v_b^*| \leq |v_a^*| \leq |v_c^*| \), then
  \[ v_0 = \left( \text{sign}(v_{cx}^*) \right) \times \frac{v_{dc}}{2} - v_a^* \]  
  (12)

**Proposed V/F Constant Ratio:**

Changing the frequency of the supply voltage is an ideal method for induction motor speed control. In order to ensure a correct motor magnetization, it is also necessary to change the amplitude of the voltage according to the following equations. The value of active EMF is:

\[ E = 4.44\Phi_{max} fN \]  

(13)

Where:

E: Electromagnetic Motive Force (Volt).
\[ V = K\Phi f \]  
\[ M_a = a_1 V + a_2 \]  

\[ \Phi: \text{Flux (Weber).} \]
\[ N: \text{Stator windings turn number.} \]
Assuming, that the voltage drop of stator circuit is negligible, the relationship between the voltage and the frequency is written as:

Where:
\[ V: \text{Stator Voltage (Volt).} \]
\[ K: \text{Constant.} \]

Therefore, in order to maintain the motor flux constant, the V/f ratio has to be kept constant. This is known as the constant Volt/Hertz principle. This principle is illustrated in Fig.(5)(S. Panda, et al. 2009). If this ratio is kept constant, the stator flux will remain constant, and so the motor torque will only depend on the slip frequency.

When the stator frequency fails under a given frequency threshold (called the boost frequency), the voltage magnitude must be kept at a given level (called the boost voltage) to keep the rotor flux magnitude constant. At the opposite, when the frequency becomes higher than the rated value, the voltage magnitude is also kept to the rated value, to take the saturation of the inverter into account. The rotor flux is no more constant and the torque decreases.

In this paper, a new technique is proposed to control of the V/f ratio. This method controls the value of V/f and fixed it by changing the value of modulation index (Ma). This method is constructed by connecting the motor loaded with full-load to the Inverter, and builds table consists of several readings, since each value of modulation index (Ma) takes the corresponding voltage of the voltage. Initially feed motor with rated voltage and write the value of M_a and then decrease the value of M_a and record the Inverter output voltage to get the minimum voltage of voltage, which is the value of motor work at 5% of the rated speed. When readings are completed, we take the curve fitting to both rows and thus appear a general equation of M_a can be applied at any value of the voltage. It is worth mentioning that this equation applies to the motor, at any value of load. The readings which are recorded are inserted in table(2).

It is known that the relationship between fundamental r.m.s of inverter output voltage \( V_{m1} \) and \( M_a \), it is close to linear relation so that the polynomial equation will be first order equation and the general shape is:

\[ M_a = a_1 V + a_2 \]  

After finding \( a_1 \) and \( a_2 \), can be design this controller using MATLAB as shown in Fig.(6).

**Results:**

In accordance with international standards stipulate, the value of the THD should be less than equal to 5% (IEEE Standard 519-1992, and R. G. Ellis 1996). So that the criterion which taken in this study to test the acceptability for each mentioned PWM types is the current THD% should be less than 5%.

In the beginning a 3-phase induction motor at no-load condition. The no-load current and spectrum are plotted for each type of PWM. The THDIs calculated for 50 numbers of harmonics.

Then full-load condition of the induction motor (when the motor is loaded by 25.5 N.m torque), the obtained load current waveforms are illustrated and analyzed to obtain the spectrum of each strategy.

Finally similar results for full load are shown with half-load induction motor

**Test Results of Induction Motor at No-Load:**
The histogram in Fig.(7) shows the current THDs when the induction motor at no-load state.

**Test result of Induction Motor at Full-Load:**
The histograms in Fig.s.(8) and (9) show the current THDs% at the carrier frequencies 3.5KHz and 10KHz respectively, when the induction motor at full-load state.

The results in table (2) shows that the current THD% is decreased with increasing the carrier frequency. The increasing in the carrier frequency should not exceed the certain values to avoid some drawbacks such as increasing in the switching losses.

**Test Result of Induction Motor at Half-Load:**
The histograms in Fig.s.(10) and (11) show the current THDs% at the carrier frequencies 3.5KHz and 10KHz respectively, when the induction motor at half-load state.
Fig. 1: Sinusoidal pulse-width modulation (SPWM) for three-phase inverter a) Carrier and modulating signals; b) Switch 1 state; c) Switch 3 state; d) ac output voltage.

Fig. 2: Space vector representation.

Fig. 3: SVPWM Modulating Waveform and its ZSS (M. Samter 2007).

Fig. 4: Discontinuous Space-Vector PWM a) DPWMMax, b) DPWMMin, c) DPWM0, d) DPWM1, e) DPWM2, f) DPWM3.
Fig. 5: Stator Voltage Magnitude Versus the Stator Frequency Deduced from the V/f Principle.

Fig. 6: Proposed model to stabilize V/f ratio for desired speed.

Fig. 7: No-load current THD%.

Fig. 8: Current THD% for 3.5KHz carrier frequency at full load.
Fig. 9: Current THD% for 10KHz carrier frequency at full load.

Fig. 10: Current THD% for 3.5KHz carrier frequency at half load.

Fig. 11: Current THD% for 10KHz carrier frequency at half load.

Modulating and carrier signals of DPWMMax.  (b) Modulating and carrier signals of DPWMMIn.

Fig. 12: The comparing states of DPWMMax and DPWMMIn.
Table 1: Recorded reading of proposed method to control v/f ratio.

<table>
<thead>
<tr>
<th>V</th>
<th>V referred</th>
<th>Vf</th>
<th>Vr</th>
<th>Vf/Vr</th>
<th>Mj</th>
<th>Current THD%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>1387.5</td>
<td>7.7</td>
<td>50</td>
<td>401.8</td>
<td>0.9577</td>
<td>3.05</td>
</tr>
<tr>
<td>1300</td>
<td>1186</td>
<td>8.76</td>
<td>43.333</td>
<td>348.3</td>
<td>0.8321</td>
<td>3.14</td>
</tr>
<tr>
<td>1000</td>
<td>879.6</td>
<td>12.04</td>
<td>33.333</td>
<td>268.0</td>
<td>0.6401</td>
<td>2.819</td>
</tr>
<tr>
<td>500</td>
<td>431</td>
<td>13.8</td>
<td>16.666</td>
<td>134.1</td>
<td>0.3201</td>
<td>3.059</td>
</tr>
</tbody>
</table>

Table 2: Measured values of mentioned PWMs at 3.5KHz carrier frequency and full loaded induction motor.

<table>
<thead>
<tr>
<th>Synchronous Speed(r.p.m)</th>
<th>Rotor Speed(r.p.m)</th>
<th>Slip%</th>
<th>Frequency (Hz)</th>
<th>V_L-L (volt)</th>
<th>V/f ratio</th>
<th>Mj</th>
<th>Current THD%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPWM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1800</td>
<td>1623</td>
<td>9.83</td>
<td>60</td>
<td>401.8</td>
<td>0.9577</td>
<td>0.89</td>
<td>8.99</td>
</tr>
<tr>
<td>1500</td>
<td>1387.5</td>
<td>7.5</td>
<td>50</td>
<td>401.8</td>
<td>0.9577</td>
<td>0.9577</td>
<td>3.724</td>
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<tr>
<td>1300</td>
<td>1186</td>
<td>8.76</td>
<td>43.333</td>
<td>348.3</td>
<td>0.8321</td>
<td>0.8321</td>
<td>3.14</td>
</tr>
<tr>
<td>1000</td>
<td>879.6</td>
<td>12.04</td>
<td>33.333</td>
<td>268.0</td>
<td>0.6401</td>
<td>0.6401</td>
<td>2.819</td>
</tr>
<tr>
<td>500</td>
<td>431</td>
<td>13.8</td>
<td>16.666</td>
<td>134.1</td>
<td>0.3201</td>
<td>0.3201</td>
<td>3.059</td>
</tr>
</tbody>
</table>

Table 3: Suitable and unsuitable states for each PWM mentioned.

<table>
<thead>
<tr>
<th>Induction motor at full-load</th>
<th>Induction motor at half-load</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPWM</td>
<td>Suitable</td>
</tr>
<tr>
<td>T_f = 3.5KHz</td>
<td>Suitable</td>
</tr>
<tr>
<td>T_f = 10KHz</td>
<td>Unsuitable</td>
</tr>
<tr>
<td>SPWM</td>
<td>Suitable</td>
</tr>
<tr>
<td>SVPWM</td>
<td>Suitable</td>
</tr>
<tr>
<td>DPWMMax</td>
<td>Unsuitable</td>
</tr>
<tr>
<td>DPWMMin</td>
<td>Unsuitable</td>
</tr>
<tr>
<td>DPWM0</td>
<td>Suitable</td>
</tr>
<tr>
<td>T_f ≤ 40Hz</td>
<td>Suitable</td>
</tr>
<tr>
<td>DPWM1</td>
<td>Suitable</td>
</tr>
<tr>
<td>T_f ≤ 45Hz</td>
<td>Unsuitable</td>
</tr>
<tr>
<td>DPWM2</td>
<td>Suitable</td>
</tr>
<tr>
<td>T_f ≤ 50Hz</td>
<td>Suitable</td>
</tr>
<tr>
<td>DPWM3</td>
<td>Suitable</td>
</tr>
<tr>
<td>T_f ≤ 60Hz</td>
<td>Suitable</td>
</tr>
</tbody>
</table>
Conclusion:
- Through the result shown in Table (2), it is noted that the proposed method stabilized the $\psi_f$ constant ratio giving us high accuracy results.
- The types SPWM, SVPWM, DPWM3 and DPWM1 can be used for any frequency because the percentage of current THD is less than the values that set forth in international standards (less than 5%). And also note that the SVPWM is better than the other types because it has less current THD.
- Results shown that the two methods DPWMMax and DPWMMIn are not suitable for such uses because the current THD much more than the values stipulated in international standards.
- The DPWM0 technique can be used only when the frequencies less or equal to 40 Hz.
- The DPWM2 technique can be used for frequencies less than or equal to 45 Hz.
- DPWMMax and APWMMin have number of pulses of almost 40% lower than the other types of PWM and this leads to the switching losses will be reduced by the same percentage. Increasing in carrier frequency are not given any improvement of the carrier THD and the reason is that the modulating signal in SPWMMax and DPWMMIn is compared with the carrier signal only in negative part for DPWMMax and the positive part for the DPWMMIn as shown in Fig. (12).
- Table (3) gives the suitable and unsuitable state for each PWM mentioned.

REFERENCES


