Lower Side Switching Modification of SHEPWM for Single H-Bridge Unipolar Inverter

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Abstract. Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) is a famous fundamental frequency method for both single stage H-bridge inverter and cascaded multilevel inverters. The main function of SHEPWM is to eliminate the selective lower order of odd harmonic such as 3rd, 5th, 7th and 9th of the output voltage of the inverter but maintain the fundamental component. In this paper, the 5kHz of the unipolar SHEPWM switching scheme of the inverter is developed and later will be compared to the modified SHEPWM switching scheme. The performance of this inverter is measured through the final total harmonic distortion (THD), the efficiency of the whole system and the natural shape of the output after LC filter.

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1. Introduction
The full bridge inverter is a circuit consists of four units of power semiconductor switches that performs the switching operation between ON and OFF in a dedicated sequence with respect to the switch gate pattern and convert the DC input voltage into a symmetric AC output voltage with desired magnitude and frequency [1]. In the default switching scheme, the first phase of inverter will conduct from $0 - \pi$, while the second phase will be in $\pi - 2\pi$ and both phases are in high switching state. It is noticeable that the switching can be modified by changing the lower side switching of the inverter with a 50 Hz ON-state for both phases. Table 1 shows the desired modification scheme, Figure 1 illustrate the conventional switching strategy and Figure 2 the proposed modified switching scheme.

| Gate Signal | Conventional | Modified |
|-------------|--------------|----------|
|             | $0 - \pi$    | $\pi - 2\pi$ | $0 - \pi$ | $\pi - 2\pi$ |
| S1          | High Frequency | OFF | High Frequency | OFF |
| S2          | High Frequency | OFF | 50 Hz ON-state | OFF |
| S3          | OFF           | High Frequency | OFF | High Frequency |
| S4          | OFF           | High Frequency | OFF | 50 Hz ON-state |
In inverter studies, the measurement of THD and efficiency of the whole system are important. These two criteria can be set and tuned at the switching scheme of the inverter itself. As an example, the higher switching frequency will lead to a bigger switching loss which later could impose to a low efficiency of the inverter. Improper switching angles also will lead to appearance of harmonic at odd
orders resulting the increment percentage of final THD value. As seen in Fig. 2., the switching scheme
is modified by combining the high switching state with a single 50 Hz ON-State at the lower side
MOSFET of the inverter.

By modifying this switching scheme will lead to lesser switching state as can be seen in Fig. 6.
below. By right when the switching state in reduce, the efficiency of the inverter should increase and
also the value of THD will be decreased. This matter will be discussed more in result section below.

2. Formulation for Unipolar SHEPWM
The SHEPWM switching angles are determined by using mathematical formulation. The waveform of
the inverter for unipolar is given by the following Fourier series and the waveform has odd quarter-
wave symmetry.

\[ f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos(n \theta) + b_n \sin(n \theta)) \]  

(1)

\[ a_n, a_n \text{ and } b_n \text{ are constant coefficient} \]

This equation is used to solve the unknown angles that hold the desired harmonics order to be
eliminated. By means this equation can calculate the right angles for not generating the harmonic at
the desired harmonic order to be eliminated with respect following the condition of equation (4) below
[4]. Usually for multilevel inverter, certain harmonic order will be eliminated as the nature shape of
multilevel inverter output voltage is in symmetrical AC wave shape while for unipolar inverter natural
shape before the filter is in square wave shaped. For this project, the \( f_{\text{sw}} \) selected is 5 kHz and the
elimination is made up to 99\textsuperscript{th} harmonic order cancelations by using the following equations:

\[ F = [(\cos \theta_1) - (\cos \theta_2) + (\cos \theta_3) - \ldots + (\cos \theta_n)] \]  

(2)

\[ F = [(\cos \theta_1) - (\cos \theta_2) + (\cos \theta_3) - \ldots + (\cos \theta_99)] \]  

(3)

\[ \theta_1 < \theta_2 < \theta_3 \ldots < \theta_{99} < 90^\circ \]  

(4)

2.1. MATLAB code generation
In order to solve the equation, MATLAB software is used. The equation need a proper initial guess of
triggering angles and it will re-calculate the correct initial guess with MATLAB M-File [2-5].
Equation (5) shows that the transcendental equation and the value of output is set to zero except the
fundamental equation. To solve this equation, Newton-Raphson method is used. MATLAB M-file
code is used as this Newton-Raphson requires heavy computation strain [3-5].

\[ \cos(1 \times t) - \cos(1 \times t) + \ldots + \cos(1 \times t(n - 2)) = \frac{A \pi}{4} \]  

(5)

\[ \cos(3 \times t) - \cos(3 \times t) + \ldots + \cos(3 \times t(n - 2)) = 0 \]  

(6)

\[ \cos(m \times t) - \cos(m \times t) + \ldots + \cos(m \times t(n - 2)) = 0 \]  

(7)

Where,

Odd order: \( t_1, t_3, t_5 = \) Turned ON state
Even order: \( t_2, t_4, t_6 = \) Turned OFF state
\( m = \) harmonic order
\( m = n - 1 \)
\( n = 2 \times \text{number of pulses per quadrant} \)
\( m = (2 \times 25) - 1 = 49 \) harmonic order (harmonic 3\textsuperscript{rd} – 99\textsuperscript{th})
Figure 3. MATLAB code for angle generation

It has 4 major parts in this MATLAB code generation where are to insert the proper initial guess, the iteration of the numerical method, the deviation of the actual answer and the final part is the Jacobian matrix as to differentiated the value of F matrix from the previous section as in equation (8):

\[
J = \begin{bmatrix}
-1 \sin(1 \times t1) & 1 \sin(1 \times t2) & \ldots & 1 \sin(1 \times t50) \\
-3 \sin(3 \times t1) & 3 \sin(3 \times t2) & \ldots & 3 \sin(3 \times t50) \\
\vdots & \vdots & \ddots & \vdots \\
-99 \sin(99 \times t1) & 99 \sin(99 \times t2) & \ldots & 99 \sin(99 \times t50)
\end{bmatrix}
\]  

(8)

The iteration process continued by finding a new angle by using the final equation (9):

\[
t = t + D_t
\]  

(9)

After the iteration process is done, the calculated angles will be presented as follows in the MATLAB workspace as in Table 2. The iteration process usually repeats several times as to get the degree of accuracy [6].

Table 2. Example of calculated angles using MATLAB

| State | Angles | Radian | Degree | Times |
|-------|--------|--------|--------|-------|
| ton   | t1     | 0.0583 | 3.3405 | 185.58|
| toff  | t2     | 0.0619 | 3.5472 | 197.07|
3. Simulation Design using Simulink
At this time, this project is tests with simulation using MATLAB Simulink as to test the performance of the inverter and the THD behaviour using FFT analysis module in the Simulink. The circuits are constructed together with its controller as in Figure 4 and Figure 5. The circuit parameter for this project as shown in Table 3.

| ton  | t3    | 0.1166 | 6.6816 | 371.20 |
|------|-------|--------|--------|--------|
| toff | t4    | 0.1238 | 7.0943 | 394.13 |
| ton  | t5    | 0.1750 | 10.0239| 556.88 |
| toff | t46   | 1.4208 | 81.4087| 4522.70|
| ton  | t47   | 1.4215 | 81.4483| 4524.90|
| toff | t48   | 1.4837 | 85.0071| 4722.62|
| ton  | t49   | 1.4839 | 85.0209| 4723.38|
| toff | t50   | 1.5708 | 89.9990| 4999.95|

![Figure 4. The conventional SHEPWM controller](image1)

![Figure 5. The Modified SHEPWM controller](image2)
Table 3. Example of calculated angles using MATLAB

| Criteria                      | Conventional | Modified |
|-------------------------------|--------------|----------|
| Fundamental frequency, \( F \) | 50 Hz        | 50 Hz    |
| Switching frequency, \( F_{sw} \) | 5 kHz       | 5 kHz    |
| Input Voltage                 | 100 V        | 100 V    |
| Resistive load                | 25 ohm       | 25 ohm   |
| Inductor                      | 2.5 mH       | 2.5 mH   |
| Capacitor                     | 60 uF        | 60 uF    |

As shown above, the same circuit used for both cases, only the controller are different. Conventional SHEPWM share the same signal for both MOSFET 1 and MOSFET 2 while for modified SHEPWM, MOSFET 1 received the high switching state from G1 signal and MOSFET 2 received 50 Hz On-state from G2 signal.

4. Verification

4.1 Simulation results

To verify the results, both conventional and modified SHEPWM inverter is connected to normal R load under unfiltered and filtered condition. A low pass LC filter is used as filter to change the square wave shaped AC into a smooth symmetrical AC output voltage. Usually, the performance of SHEPWM is first tested without LC filter as to see whether the decided harmonic elimination is eliminated. Connecting an inverter to a LC filter is the purpose of to power up the normal AC load application. The modulation index set for this project is 0.8 the performance of inverter working fine under condition of under modulated [8].

4.1.1 Unfiltered inverter

A) Inverter output voltage

The circuit is first tested without LC filter and compared between the conventional and modified SHEPWM as in Figure 6.

![Fig 6. a) The conventional SHEPWM b) The modified SHEPWM](image-url)
As shown above the comparison between two-switching scheme and the modified switching scheme has a lesser switching state even though it has the same switching frequency. A lesser switching state will result a better performance of efficiency as the higher switching state will lead to a huge switching loss.

B) Total harmonic distortion
As presented above on Figure 6 the inverter is tested with a normal resistive load. Usually for harmonic elimination resistive load is used at the beginning before performing for inductive load as resistive load nature behaviour will not have criteria such lagging and leading for rise current of the inverter. The rise and fall will lead the output voltage not align in a right phase in one cycle time of 50 Hz. If with resistive load, the cancelation is perfectly eliminated, an inductive load test is ready to be tested. Figure. 7 shows the fast Fourier transform, FFT of THD output voltage of the developed system.

Figure 7. a) THD result for conventional SHEPWM  b) THD result for modified SHEPWM

| Switching strategy | Overall percentage |
|--------------------|--------------------|
| Conventional       | 37.2 %             |
| Modified SHEPWM    | 38.5 %             |
In Figure 7a above, it can be observed on 3rd and 5th harmonic order is still appeared. On 3rd harmonic appear to be slightly higher than 5th harmonic and the rest of the harmonic is eliminated. While for Figure 7b, 3rd and 5th harmonic has the same magnitude and appearance of harmonic on 15th order. The possible reason of this phenomenon is during the combination of high switching state and 50 Hz ON-state reducing some of the switching state and it may not suitable.

4.1.2 Filtered inverter

A) Inverter output voltage

In this section, inverter will be tested with the low pass active filter with the value of inductor and capacitor mention in Table 3 earlier.

For filtered cases, both inverter with different switching scheme are tested with the same LC filter design as to study the performance of the filter on handling higher switching scheme of the inverter and the other one with lesser switching. It can be observed that on Fig. 8, a), there is some disturbance during the switching is changing from positive side to negative side and the graph is not that smooth. This phenomenon is due to the high switching state undergo the filtering process where the rise and fall current need to be considered as well as sometime it need a longer time for filtering the square wave inverter into a better symmetrical AC voltage. The distortion occurs at 0.01 second and repeat the same problem at the second phase and third phase of the inverter.

B) Total harmonic distortion

Using an active low pass LC filter usually will clear all the small noise occurred in the inverter output simultaneously will result a better performance of THD of the inverter. Using filter also will clear some cases like smoothing the side band harmonic which usually appears at high order harmonic [7].
The amount of harmonic reduction after the filter is around 30% ~ 35% and it reduced to a value lesser than 5% as shown in table 5. It can be observed that the modified switching scheme has a lower THD percentage compared to the conventional one even before filter the result, the conventional THD is slightly lesser than the modified SHEPWM. For inverter efficiency, the modified SHEPWM gives out 87.4% which are higher 6.2% of the conventional SHEPWM inverter.

### 5. Conclusion
This paper presented a modification made to a normal unipolar SHEPWM inverter. The main objective is to study the performance of the modified switching scheme related to THD performance for both unfiltered and filtered cases. It can be concluded that the modified SHEPWM are way better than the conventional SHEPWM as the measurement of THD is slightly lower and the efficiency of the system also improve by 6.2%.
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