Third harmonic injection PWM technique for maximizing DC-BUS utilization of Five-Phase VSIs

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ABSTRACT

Nowadays, applications of advanced power electronic technology enable producing an AC supply with a phase number higher than three-phase. Five-phase voltage source inverters (5Ph-VSI) have been used in advanced power electronic drives to improve the reliability of the drive system and to boost the power capability of the converter as well as to their other inherent merits. This paper shows the mathematical analysis and simulation of the third harmonic injection-pulse width modulation (THI-PWM) 5Ph-VSI connected with inductive load in three scenarios i.e. star, pentagon and pentacle. The presented THI-PWM technique for a 5Ph-VSI aims to increase the inverter fundamental voltage and hence to maximize the utilization of DC bus without causing over-modulation. The simulation results are compared with typical sinusoidal pulse width modulation (SPWM) and the 10-step mode operation. The proposed scheme may be considered as a compromise case between the two references cases; as low harmonic components compared with 10-step mode operation and a high utilization factor compared with SPWM.

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1. INTRODUCTION

The DC/AC converters are widely used in electric drives. In general, these converters are used to obtain a single-phase or three-phase voltage source (3Ph-VSI) at the required voltage and frequency. Due to improvements in power electronic tecnologies, it becomes possible to design a voltage source inverter, VSI that supplies a load greater than three-phase. This direction of research will increase the rating of the power converters. Previously, the maximum rating of the power converter was restricted at a certain level due to the power limits of the semiconductor switches. In order to overwhelm the dilemma two approaches are stated in the last three decades that are, either by increasing the number of phases or by increasing the number of voltage levels [1-3]. In fact, multi-phase systems such as a 5Ph-VSI have additional merits, particularly when used as a driver for multi-phase electric machines, such as: the ripple of DC-bus voltage is lower, a high tolerance under a wide range of faults, increasing in reliability and decreasing line-current for the same power capacity [4-7].

Numerous works have been developed on 5Ph-VSI in literature. One of the main concerns of these works is to increase the utilization factor of the input DC-bus voltage. Two methods have been presented to achieve this issue, either using (i) carrier-based PWM with a zero-sequence harmonic injection or (ii) space-vector PWM. The carrier-based PWM with a zero-sequence harmonic injection for 5Ph-VSIs is discussed in [8-10]. They showed that the injection of the fifth harmonic in the fundamental reference signals increases the fundamental output voltage and hence increases the DC-bus utilization by 5.15%, compared to the sinusoidal PWM without injection techniques. In the case of space-vector PWM, an increase in DC-bus utilization with the same percentage is also obtained and it is well established in [9, 11]. It is noteworthy to mention that, for a 3Ph-VSI, both methods allow an increase up to 15.47% rather than 5.15% [12-13]. The third and fifth harmonics with their odd multiples, triple and quintuple harmonics, are the zero sequence components for the three and five phase systems, respectively. Therefore, the injection of such components does not cause the emergence of the injected harmonic-order in their related system. However, unlike three-phase systems, the presence of the third-harmonic component in the 5Ph system may be useful for some applications. In general, some literatures [14-18] have been mentioned that injection of odd harmonic order less than number of phases (i.e. less than 5-order for the 5Ph system), with the fundamental component, can improve the developed electromagnetic torque capabilities for the multiphase motor of concentrated windings. According to previous research findings, this paper proposes to use THI-PWM with the 5Ph-VSIs, instead of fifth harmonic injection PWM scheme, in order to maximize the dc-bus utilization compared to conventional SPWM. Besides, it shows an improvement in THD using this scheme compared to the 10-step operation mode. The study investigates the above aspects at the possible connections of a 5Ph load, pentagon, star, and pentacle connections.

2. 5Ph-VSI OPERATION METHODOLOGY.

Figure 1 shows the power circuit topology of the 5Ph-VSI. It consists of five inverter legs. It used to supply a 5Ph load from a constant DC source. The gating signal of 5Ph-VSIs should be delayed or advanced by (2π/5) concerning each other to obtain balanced voltages. The following sections show the possibilities of its load connections and some of the useful formulae to understand and analyze its operation concepts.

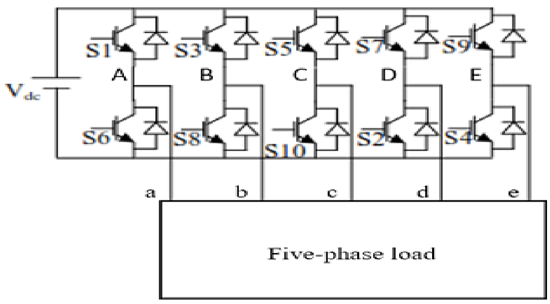


Figure 1. 5ph-VSI topology

2.1. Load Connections For A 5Ph-VSI.

Delta and star connections are the famous arrangements for the 3-phase system. In fact, other connections are available in multiphase systems. In general, for any odd number of phases (u), there are $\left(\frac{u+1}{2}\right)$ different connections allowed [19]. For a 5Ph load, there are three possibilities of the connections: a star, pentagon, and pentacle [20] as illustrated in Figure 2. Figure 3 shows the vector diagram of phase and line voltages for 5-ph load connections. Based on this diagram the following formulae can be deuced:

Assuming V_a , V_b , V_c , V_d , and V_e are the phase voltages with unity magnitudes, i.e V_a= 1∠0º, then V_{ab} , V_{bc} , V_{cd} , V_{de} , and V_{ea} are the voltage between two adjacent lines, where $V_{ab}=\sqrt{\left(\left(5-\sqrt{5}\right)/2\right)}\angle 54^{o}$, i.e. its magnitude is about 1.175 times the magnitude of the phase voltage and leading the phase voltage by (3π/10).

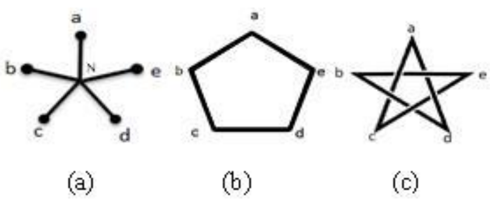


Figure 2. Possibilities of load connections of 5-ph; (a) star, (b) pentagon and (c) pentacle

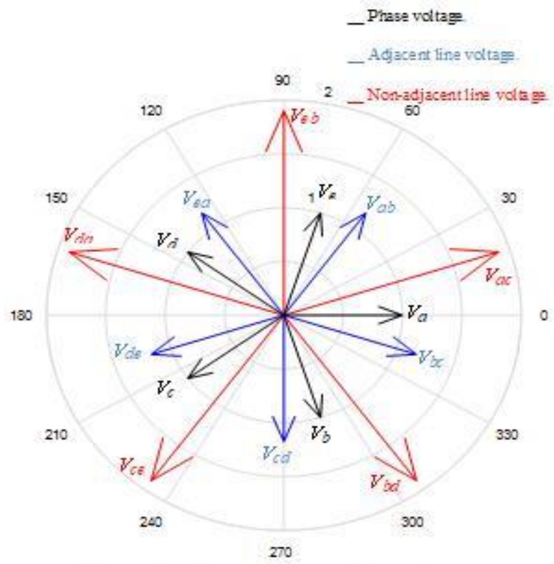


Figure 3. Vector plots of five phase voltages

Whereas, the voltage between two non-adjacent lines are V_{ac}, V_{bd}, V_{ce}, V_{da}, and V_{eb}, where $V_{ac}=\sqrt{((5+\sqrt{5})/2)}\angle 18^{o}$ that equal about 1.902 times the magnitude of the phase voltage with ($\pi/10$) phase angle shift. These simple relations can be used later to verify the simulation results.

2.2. 10-Step Operation Mode of 5Ph-VSI

For a 3Ph-VSI, when each IGBT is conducting for 180°, the phase voltage across the Y-connected load consists of 6-steps for each cycle. The line and phase voltages are expressed using Fourier series in (1) and (2), respectively [21]:

$$v_{ab} = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_{dc}}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\pi}{3} \sin\left[n\left(\omega t + \frac{\pi}{6}\right)\right] \tag{1}$$

$$v_{aN} = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_{dc}}{n\pi\sqrt{3}} \sin\frac{n\pi}{2} \sin\frac{n\pi}{3} \sin\left[n\left(\omega t + \frac{\pi}{6}\right) \mp \frac{\pi}{6}\right] \tag{2}$$

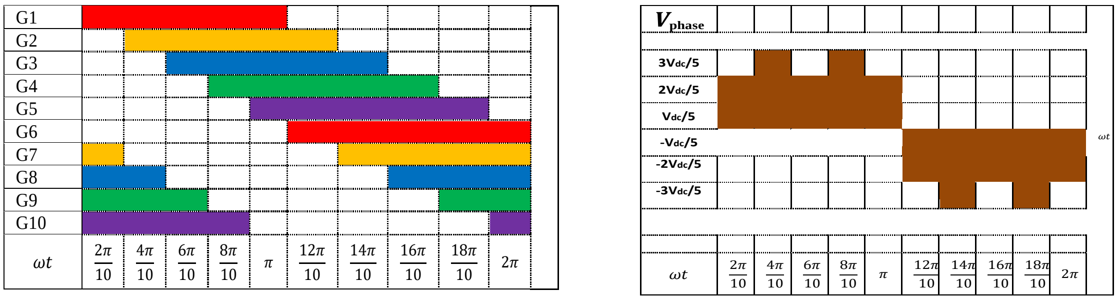
The disappearance of the third harmonic and its multipliers in both output phase and line voltages can be observed from these equations. Whereas in 5Ph-VSI, when each IGBT is conducting for 180°, the phase voltage across the 5Ph connections load is formed of 10-steps as shown in Figure 4 [22]. The load phase voltage and the voltages between two adjacent and nonadjacent lines can be expressed in Fourier series as follows:

$$v_{aN} = \sum_{\substack{n=1,3,7,\ldots,\\ n\neq 5,15,25\ldots}}^{\infty} \frac{2V_{dc}}{n\pi} \sin(n\omega t) \tag{3}$$

$$v_{ab} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{dc}}{n\pi} \sin\frac{n\pi}{5} \sin\left[n\left(\omega t + \frac{3\pi}{10}\right)\right] \tag{4}$$

$$v_{ac} = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_{dc}}{n\pi} \cos\frac{n\pi}{10} \sin\left[n\left(\omega t + \frac{\pi}{10}\right)\right] \tag{5}$$

As shown in (3) and (4) show the existence of the third harmonics component and its multiples. The relations between the magnitudes in (3-5) for the fundamental, n=1, or even for any harmonic if its sequence is taken to account, realize the previous relations deduced from the phasor diagram of Figure 3.



(a) (b)

Figure 4. (a) 180° conduction sequences, (b) Phase to neutral voltage for star connection load

3. THI-PWM SCHEME

To increase the DC-bus utilization for the 3Ph-VSIs, the third harmonic with, or without its odd multipliers can be injected into the reference signal of the PWM generator. As mentioned previously, these harmonics have a zero-sequence that do not appear in the line voltage of 3Ph-VSI output. In the case of the 5Ph-VSIs, the third harmonic is considered a non-zero-sequence harmonic. If this harmonic is injected with the reference signal of the 5Ph PWM generator, then it is expected to see this harmonic component in the inverter output voltages. However, the third-order harmonic already exists in output voltages for the 10-step operation mode. Besides, the third harmonic may be seen in the output voltage of 5Ph-VSI even with large or medium space-vector PWM [9]. At any rate, the steps for determination of the maximum amplitude value of the injected signal, M_3, that ensure the linear modulation of the THI-PWM and the maximum utilization of DC-bus are demonstrated below and Figure 5 represents the implementation steps. As shown in (6) describes the newly constructed reference signals after third harmonic component injection.

$$\begin{aligned}
v_{a_ref} &= \sin\theta + M_3 sin3\theta \\
v_{b_ref} &= \sin(\theta - 2\pi/5) + M_3 sin3(\theta - 2\pi/5) \\
v_{c_ref} &= \sin(\theta - 4\pi/5) + M_3 sin3(\theta - 4\pi/5) \\
v_{d_ref} &= \sin(\theta - 6\pi/5) + M_3 sin3(\theta - 6\pi/5) \\
v_{e_ref} &= \sin(\theta - 8\pi/5) + M_3 sin3(\theta - 8\pi/5)
\end{aligned} \tag{6}$$

The value of M_3 that gives the maximum utilization of input DC source can be determined as illustrated in the following steps,

Step 1: form the new formula of the fundamental component due to third-harmonic injection for the first phase:

$$f(\theta, M_3) = v_{a\_ref} = \sin\theta + M_3 sin3\theta \tag{7}$$

Step 2: by equaling $df(\theta, M_3)\ /d\theta$ to zero, the values of θ that give the extreme points can be obtained:

$$\theta_3 = cos^{-1}\left(\frac{\sqrt{3}*\sqrt{M_3(9M_3-1)}}{6M_3}\right) \tag{8}$$

Step 3: find $f(\theta, M_3)$ at $\theta = \theta_3$

$$\begin{aligned}
f(\theta_3, M_3) = M_3 * \sin\left(3\cos^{-1}\left(\frac{\sqrt{3}*\sqrt{M_3(9M_3-1)}}{6M_3}\right)\right) \\
+\sqrt{1-\frac{9M_3-1}{12M_3}}
\end{aligned} \tag{9}$$

Step 4: when $\frac{df(\theta_3,M_3)}{dM_3} = 0$, gives $M_3 = {}^1/_6$ at this value

As shown in (8) gives $\theta_3 = {}^{\pi}/_3$

Step 5: determine $f(\theta, M_3)\ at\ \theta = \theta_3 = {}^{\pi}/_3\ and\ m_3 = {}^1/_6$ yields: $f({}^{\pi}/_3\, ,{}^1/_6) = \frac{\sqrt{3}}{2} = 0.866$

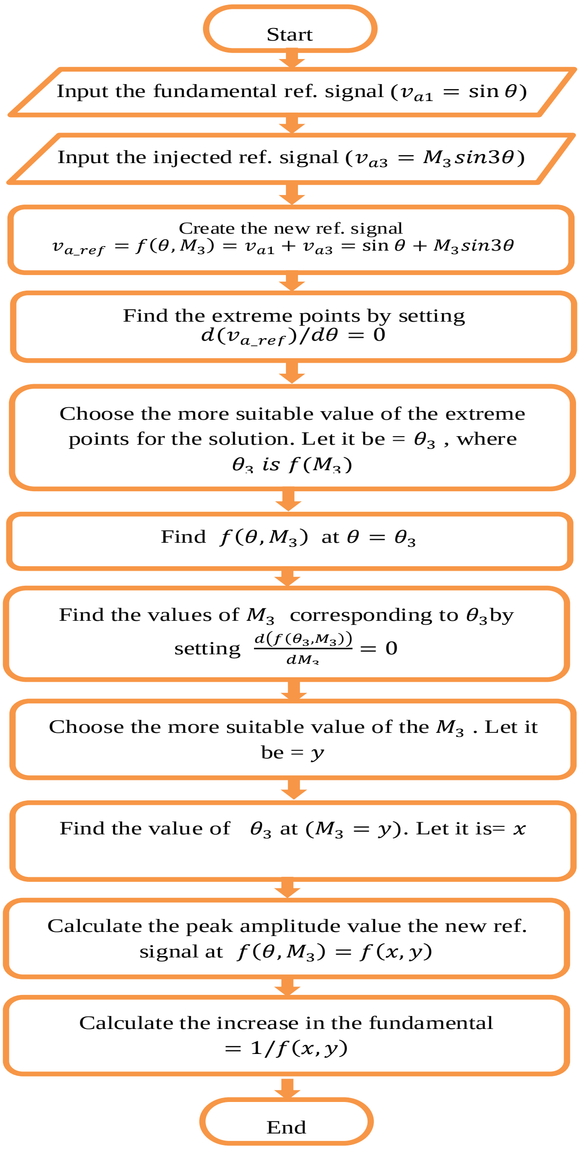


Figure 5. Determination steps of the injected harmonic amplitude and finding the increase in the output fundamental signal

Which means that the peak amplitude value of the newly formed reference signal is equal to 0.866, the peak amplitude value of its fundamental is a unity and the peak amplitude value of the injected third harmonic component is equal to $^1/_6$. In the other words, the amplitude of the newly formed reference signal and consequently the fundamental value can be increased up to($^2/_{\sqrt{3}} = 1.1547$) without causing an overmodulation; it means an increase in the utilization percent from dc source about approximately 15.47%.

Here, it is appropriate to specify the followings:

The ratio of the output fundamental RMS component, $V_{1(rms)}$, to the main DC bus voltage, V_{dc}, is defined as the DC utilization factor and can be calculated from the following equation:

$$\text{DC utilization factor} = \frac{V_{1(rms)}}{V_{dc}}. \tag{10}$$

Third harmoniccontent factor is defined as the ratio of is the third harmonic component, $V_{3(rms)}$, to $V_{1(rms)}$ and can be determined as follows:

$$\text{Third harmonic content factor} = \frac{V_{3(rms)}}{V_{1(rms)}} \tag{11}$$

The modulation index (M_i) is defined as [11]:

$$M_i = \frac{\sqrt{2}V_{1(rms)}}{0.5\,V_{dc}} \tag{12}$$

The maximum modulation index (M_{max}) in the case of using harmmnic injection technique is equal to [8]:

$$M_{max} = \frac{1}{cos\left(\frac{\pi}{2n}\right)} \tag{13}$$

Where n is the order of the injected harmonic. Thus, for the third harmonic injection scheme (M_{max}) =1.1547. In the case of SPWM, it should be noted that (M_{max}) for the maximum linear mode modulation rang is equal to unity.

4. RESULTS AND DISCUSSION

Modeling and analyzing the proposed 5Ph-VSI are undertaken in Matlab/Simulink. Simulation parameters are as follows: The 5Ph-VSI is used to supply an inductive load of (9+j3.63)Ω from a constant DC source of V_{dc} =400 V. The power factor of the load at the fundamental frequency PF=0.92 lagging. The inverter output frequency is set to 50 Hz, while the switching frequency is chosen integer multiple of five and set to 3.75 kHz, therefore the frequency modulation index (M_f) equal to 75. In this case, the dominant lowest order harmonic of the output voltage will be (M_f -2) [23]. In other words, all the harmonics up to the order (M_f-2), except the third injected harmonic, will be canceled. However, an increase in switching frequency increases switching losses. On the other hand, the fast Fourier transformer (FFT) analysis tool in Simulink is used to analyze phase and line voltage waveforms and it is used to calculate their THD contents. According to IEEE-std 512 [24] the harmonic orders up to 50 are investigated. The simulation study is demonstrated as following:

4.1. Star Connection

Initially, the 5Ph-VSI is simulated with a star-connected load and analyzed under the 10-step operating mode. Figure 6 shows the load phase voltage and its frequency spectrum, whereas Figure 7 shows line voltage and its frequency spectrum. It is clear that a third harmonic component with (33.3%) and (53.9%) of the fundamental component in phase and line voltages respectively and they are compatible with the expression given in (3) and (4). Next step is using THI- PWM technique for 5Ph-VSI to supply the same load at amplitude modulation index M_i=M_{max}.The phase voltage, its frequency spectrum, line voltage, and its frequency spectrum are reported and shown in Figure 8 and Figure 9 respectively.

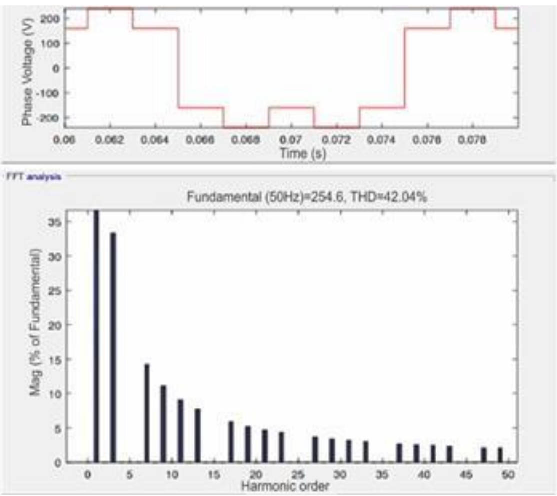


Figure 6. Load Phase voltage and its frequency spectrum for a star- connected load with a 10-step operation mode

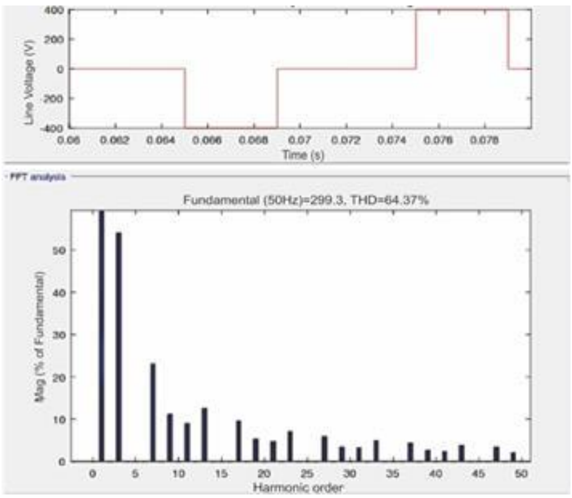


Figure 7. Line voltage and its frequency spectrum for a star-connected load with a 10-step operation mode

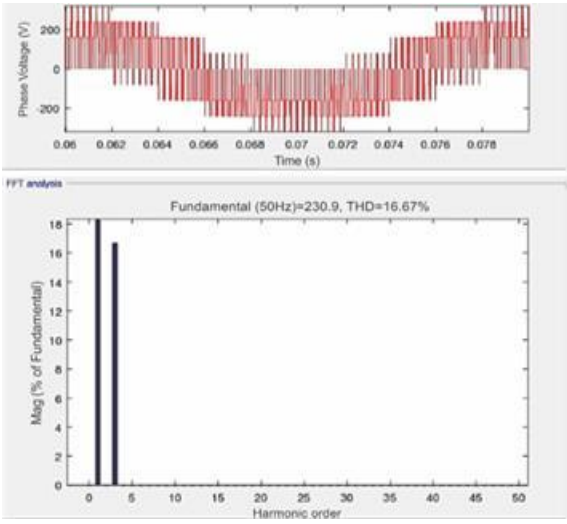


Figure 8. Load Phase voltage and its frequency spectrum for a star-connected load with a THI- PWM

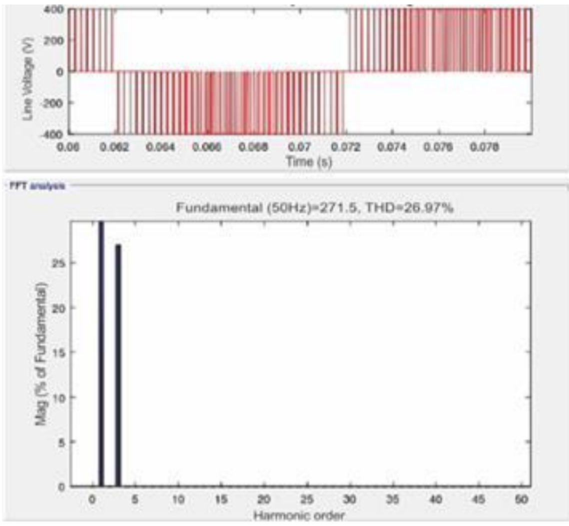


Figure 9. Line voltage and its frequency spectrum for a star-connected load with a THI- PWM

Table 1 summarizes the values of DC utilization Factor, Third harmonic content factor, and THD, for 10-step operation mode, and PWM with and without third harmonic injection. Where natural PWM technique based on sinusoidal reference signal SPWM is considered. The load current and its frequency spectrum relative to fundamental component of both of 10-step and THI-PWM are shown in Figure 10 and Figure 11, respectively with THD of 23.88% and 11.45%.

Table 1. Comparison of Some Harmonic Components of 10-Step, THI-PWM, and SPWM Techniques

Operation Mode	Phase Voltage			Adjacent Line Voltage		
	DC utilization factor (%)	Third harmonic content factor (%)	THD (%)	DC utilization factor (%)	Third harmonic content factor (%)	THD (%)
10-Step	45	33.3	42.04	52.9	53.9	64.37
THI-PWM	40.8	16.67	16.67	47.99	26.97	26.97
SPWM	35.35	0	0.02	41.56	0	0.03

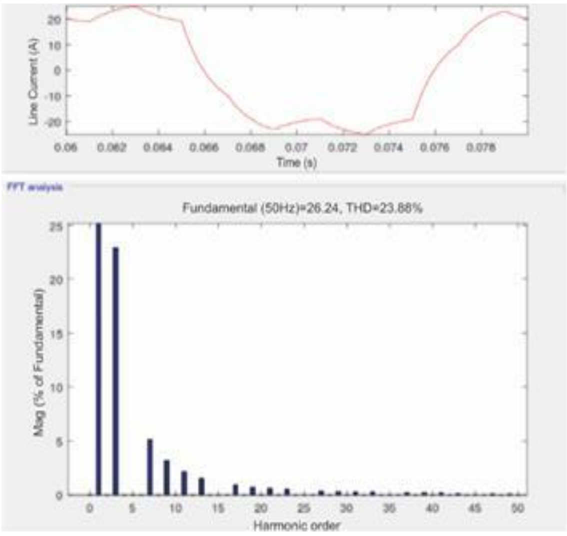


Figure 10. Line current and its frequency spectrum for a star- connected load with a 10-step operation mode

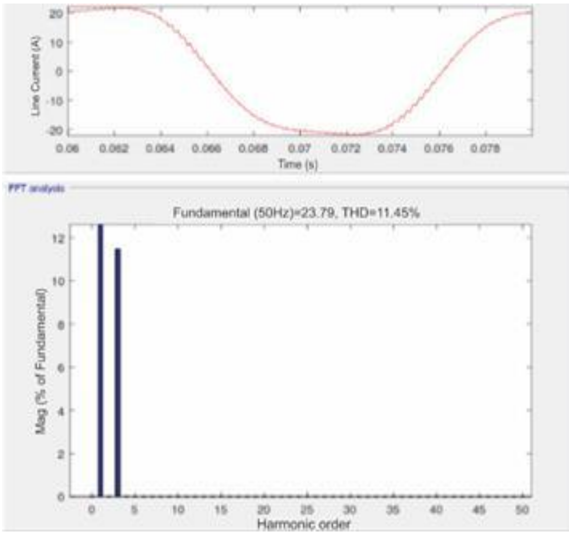


Figure 11. Line current its frequency spectrum for a star-connected load with a THI-PWM

4.2. Pentagon Connection

This connection is similar to a delta connection in a 3-ph system so that the end of the phase is connected to the beginning of the next phase. As in the previous connection, the 5Ph-VSI has been switched on at 180° conduction mode. The line voltage, which is also equal to phase voltage, is shown in Figure 12 with its frequency spectrum, whereas Figure 13 shows the same voltage and its spectrum when the 5Ph-VSI is driven by THI-PWM technique. In addition, the values of DC utilization factor, Third harmonic content factor and THD, for 10-step operation mode, THI-PWM, and operated with SPWM strategy are collected in Table 2. The line currents with their spectrum are shown in Figure 14 and Figure 15.

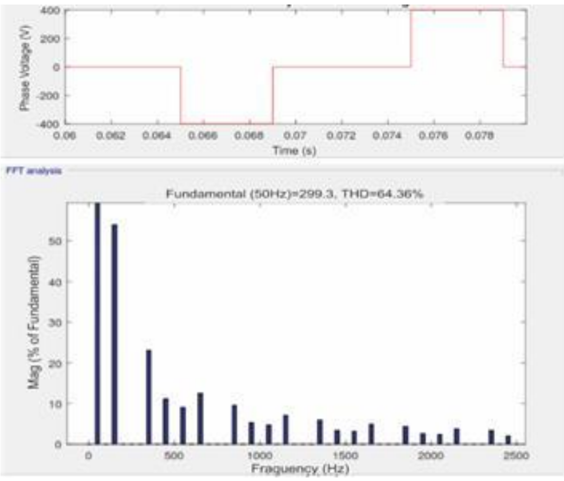


Figure 12. Phase (or line) voltage and its frequency spectrum for a pentagon-connected load with a 10-step mode

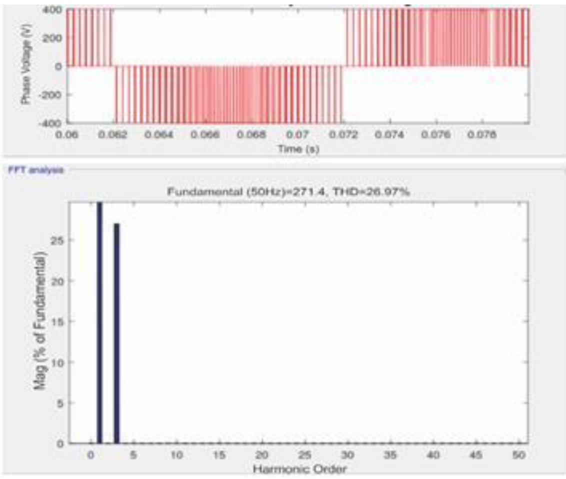


Figure 13. Phase (or line) voltage and its frequency spectrum for a pentagon-connected load with a THI-PWM

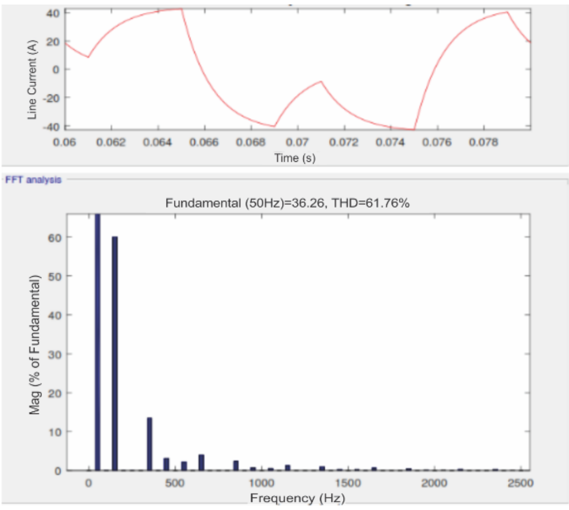


Figure 14. Line current and its frequency spectrum for a pentagon-connected load with a 10-step mode

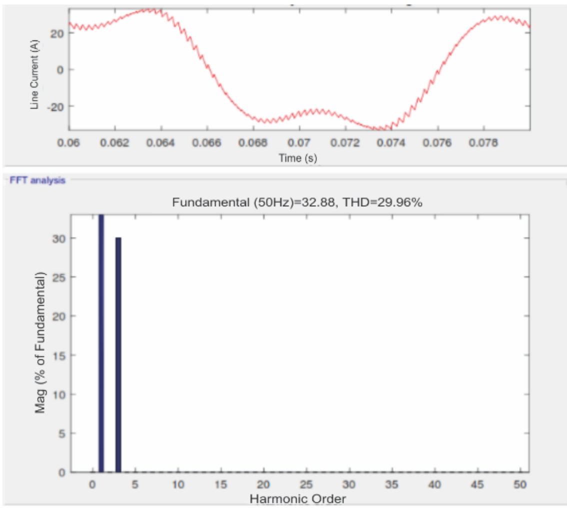


Figure 15. Line current and its frequency spectrum for a pentagon-connected load with a THI-PWM

Table 2. Comparison of Some Harmonic Components of 10-Step, THI-PWM and SPWM Techniques (Pentagon Connected Load)

Operation Mode	Phase Voltage (Adjacent Line Voltage)		
	DC utilization factor (%)	Third harmonic content factor (%)	THD (%)
10-Step	52.9	53.93	64.36
THI-PWM	47.97	26.97	26.97
SPWM	41.55	0	0.03

4.3. Pentacle Connection

Unlike three-phase systems, load can be connected to a 5-ph system in a third way, by connecting each load phase between two non-contiguous lines, so the load connection appears to be a Pentacle shape. When the 5Ph-VSI is run in 10-step operation mode, the load phase voltage or non-contiguous two lines voltage is scoped as shown in Figure 16, and its frequency spectrum can be analyzed as shown in the bottom of the same figure. After that, the 5Ph-VSI is driven with THI-PWM technique; the phase voltage and its spectrum are again scoped and analyzed as shown in Figure 17.

Table 3 summarize DC utilization factor. Third harmoniccontent factor and THD of 10-step, THI-PWM, and SPWM techniques for pentacle connected load. The inverter line current under 10-step operation mode and under operation with THI-PWM strategy are shown in Figure 18 and Figure 19 respectively.

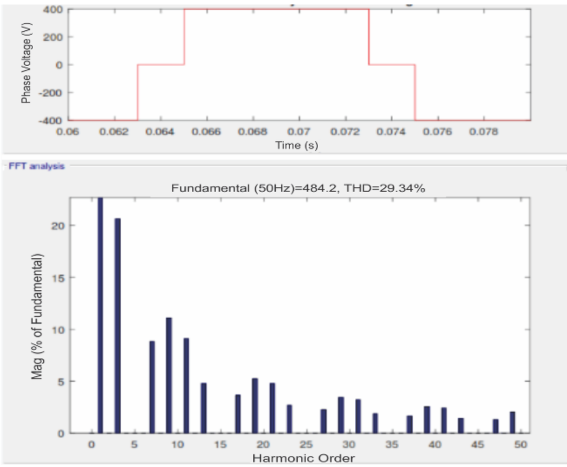


Figure 16. Phase (nonadjacent line) voltage and its frequency a spectrum for a pentacle-connected load with a 10-step mode

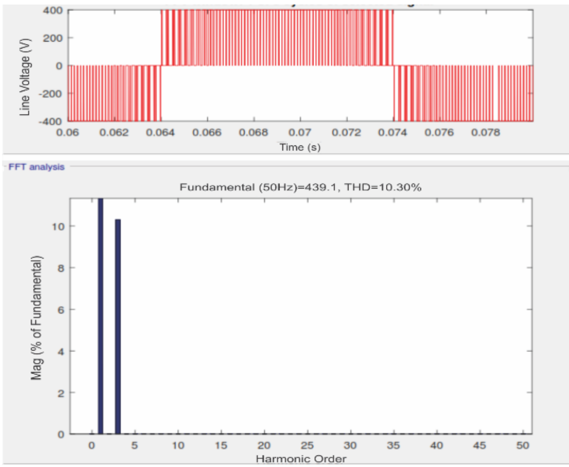


Figure 17. Line (two adjacent lines) voltage and its frequency spectrum for a pentacle-connected load with a THI-PWM

Table 3. Comparison Of Some Harmonic Components Of 10-Step, THI-PWM, And SPWM Techniques (Pentacle Connected Load)

Operation Mode	Phase Voltage			Adjacent Line Voltage		
	DC utilization factor (%)	Third harmonic content factor (%)	THD (%)	DC utilization factor (%)	Third harmonic content factor (%)	THD (%)
10-Step	85.59	20.61	29.34	52.9	53.9	64.37
THI-PWM	77.7	10.31	10.32	47.99	26.97	26.97
SPWM	67.175	0.03	0.78	41.56	0	0.03

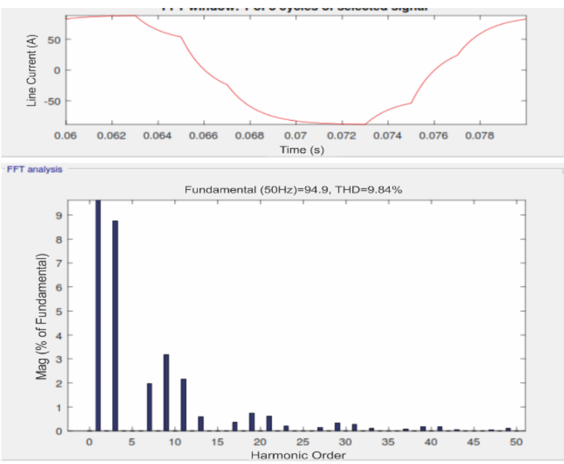


Figure 18. Line current and its frequency spectrum for a pentacle-connected load with a 10-step mode

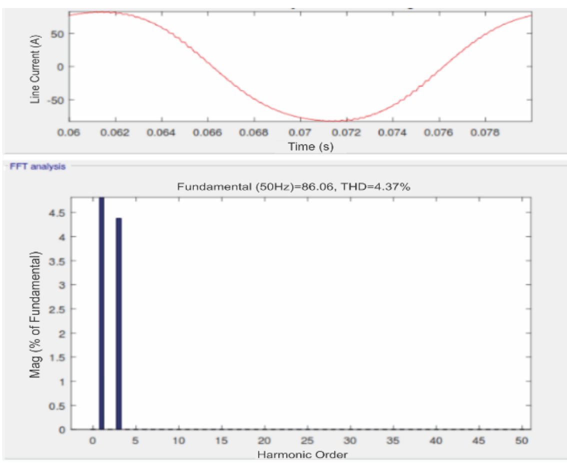


Figure 19. Line current and its frequency spectrum for a pentacle-connected load with a THI-PWM

4.4. Validation of the Results

The mathematical analyses presented in the previous sections are used to validate the obtained simulation results for the DC utilization factor. In the case of star-connected load, the fundamental phase voltage V1rms is calculated using (3) for the 10-step operation mode at (n=1). For THI-PWM and SPWM, as shown in (12) is used to calculate $V_{1(rms)}$ at the maximum modulation indices for both cases. That means (M_i) is equal to 1.1547 and 1 respectively. For the pentagon and pentacle load connections, the formulae that deduced between phase, adjacent line, and non-adjacent line are used to calculate $V_{1(rms)}$ and hence calculating the DC-utilization factor. Table 4 summarizes the results of DC- utilization factor for both of the simulation and mathematical analysis results. It can be seen that the simulation results close to the analytical results.

Table 4. Validation of the DC Utilization Factor (%)

DC utilization factor (%)	Star-connected phase voltage			Pentagon –connected phase voltage			Pentacle -connected phase voltage		
	10-step	THI-PWM	SPWM	10-step	THI-PWM	SPWM	10-step	THI-PWM	SPWM
(Simulation)	45.0	40.8	35.35	52.9	47.97	41.55	85.59	77.7	67.175
(Analytical)	45.02	40.82	35.36	52.92	47.99	41.56	85.63	77.65	67.25

5. CONCLUSION.

In this paper, a new THI-PWM scheme for a 5Ph-VSI has been demonstrated. The proposed scheme is applied for three various connections, i.e. star, pentagon and pentacle. It has been shown that the third harmonic injection can be considered as a compromise between 10-step-mode operation and SPWM. The performance of the proposed scheme is better than the conventional 10-step operation mode regarding THD. Additionally, the proposed scheme has maximum utilization compared with the SPWM scheme. Regarding load connections, it is found that the pentacle connection produces a high utilization factor of 77.7% compared with 47.97% for pentagon connection and 40.8% for the star connection. Finally, a low level of THD in voltage waveform is 10.32% was for pentacle-connection, is 26.97% and 16.67% for pentagon and star connection respectively.

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