The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2026

Volume 39, Pages 40-49

IConTech 2026: International Conference on Technology

Harmonic Injection Scenarios for Enhanced DC-Link Utilization in Seven-Phase VSI-Fed Motor Drives

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Abstract: Multiphase motor drives have enjoyed a lot of attention because they have a higher credibility of reliability, less torque ripple, and flexible fault tolerance as opposed to the conventional three-phase systems. Specifically, the seven-phase voltage source inverter (VSI) fed motor drives give extra modulation design and harmonic control degrees of freedom. But conventional sinusoidal pulse width modulation (SPWM) will restrict the fundamental voltage actually available in the linear modulation area and can result in poor harmonic performance at high modulation. The paper includes a comparative systematic investigation of harmonic injection pulse width modulation strategies of a two-level seven-phase VSI to serve a seven-phase motor drive. A number of injection cases are studied such as single harmonic injection (3^{rd} , 5^{th} and 7^{th}), combined harmonic injections and triple harmonic injected. Effects of each configuration are considered with regard to the maximum possible fundamental modulation index, total harmonic distortion (THD) of the phase voltage, and a voltage based torque ripple index (TRI). Generalized reference waveform formulation that involves the ability to choose harmonic amplitude and phase shifts is created and provided in MATLAB to assess performance comprehensively. The outcomes of the simulation prove that low-order harmonic injection, the third and the fifth harmonics in particular, can effectively enhance the utilization of the DC-link voltages by flatting the peaks of the reference waveform and expanding the linear modulation range. There is however, an increase in harmonic distortion and torque ripple. Conversely, seventh harmonic injection displays insignificant effect on fundamental voltage enhancement and has lowest THD and TRI since it is basically a common-mode phenomenon in seven-phase systems. The results obtained indicate a definite trade-off between DC-link utilization and quality of the waveforms positioned at the significance of choosing a suitable harmonic injection strategy based on the requirement of the application.

Keywords: Seven-phase inverter, Multiphase motor drives, Harmonic injection PWM

Introduction

The use of multiphase VSI-based drives has become a promising alternative to traditional three phase systems in high reliability and high power systems, because it offers the necessary benefits of enhanced fault tolerance, lower torque ripple and decreased DC link capacitor ratings (Ameen et al.,2020; Sultan& Al-Badrani, 2023). Phase VSI fed drives are of specific interest to this class due to the higher degrees of freedom of the space vector representation that allow the independent control of different harmonic subspaces and provide a significantly greater flexibility of modulation (Casadei et al., 2008; Hamedani, 2020). Such capabilities can be used to enhance the use of DC link voltages, enhance the density of the torque, and tailor harmonic spectra to meet application requirements (Yang et al., 2021; Yang et al., 2023). Nevertheless, though it has the advantages of space vector modulation, especially the positive realization of enchaining DC-link utilization, it has the disadvantage of complexity in implementation when compared to the traditional sinusoidal pulse width modulation (SPWM), which is still common because of its simplicity and satisfactory performance in the linear modulation range (Hamedani, 2020; Batkhishig et al., 2025).

As a matter of fact, in multiphase inverters, traditional SPWM approach can result in poorer performance in cases where a larger fundamental voltage is needed, e.g. when running at high speed or in flux weakening areas, hence the question that has been posed here is: Is it possible to combine the good characteristics of Space Vector Modulation with the advantages of SPWM? The short answer to that is yes, but with an appropriate modification to the reference signal or modulation signal by injecting desired harmonic components. Consequently, several more advanced modulation schemes have been suggested, such as general carrier based schemes of seven phase inverters, universal sequential over modulation schemes, optimized harmonic injection PWM schemes of multilevel converters (Yang et al., 2021; Casadei et al., 2008; Yeganeh et al., 2020; Yang et al., 2023). These methods prove that reference waveforms can be flattened by injecting low and high order harmonics appropriately, the linear modulation limit can be extended (Yang et al., 2021; Yeganeh et al., 2020; Yang et al., 2023; Manjesh, & Dabhade, 2019).

Regardless of these developments, systematic comparative studies on particular harmonic injection scenarios in two level seven phase VSIs, particularly, the interaction between DC link utilization, total harmonic distortion (THD), and torque ripple still do not exist. The current seven phase studies are primarily on space vector frames, over modulation area design, or broad principles of generalized modulation, without a specific analysis of the impact of various combinations of injected harmonics on voltage quality and torque related measures (Yang et al., 2021; Casadei et al., 2008; Hamedani, 2020; Yang et al., 2023). Moreover, most harmonic injection studies on multilevel inverters focus on minimization of THD or switching loss optimization instead of the use of DC-link utilization in multiphase motor drives (Yeganeh et al., 2020; Arun et al., 2022).

Driven by these shortcomings, the paper will provide a comparative study of harmonic injection cases of improved DC link exploitation in seven phase VSI fed motor drives. Based on the literature of multiphase and seven phase modulation (Yang et al., 2021; Sultan& Al-Badrani,2024; Hamedani, 2020; Yang et al., 2023; Vujacic et al., 2020; Batkhishig et al., 2025), the paper establishes a generalized reference waveform formulation that accepts selectable amplitudes and phase shifts of low order harmonics, and compares single, dual, and triple harmonic injection schemes by the This offers design oriented information on the compromise between long linear modulation range and the quality of the waveforms and practical information on the selection of harmonic injection strategies based on the requirements of the specific application.

Mathematical Modeling of the Seven-Phase VSI with Harmonic Injection

Seven-Phase Two-Level VSI Model

Each inverter leg in a two-level seven-phase VSI, as shown in (Figure 1), generates a pole voltage with respect to the DC midpoint given by.

$$v_k(t) = (2S_k(t) - 1)\,\frac{V_{dc}}{2}\,, \tag{1}$$

where Sk(t) ∈ {0,1} is the switching function of phase k, for k = 1,2,...,7.

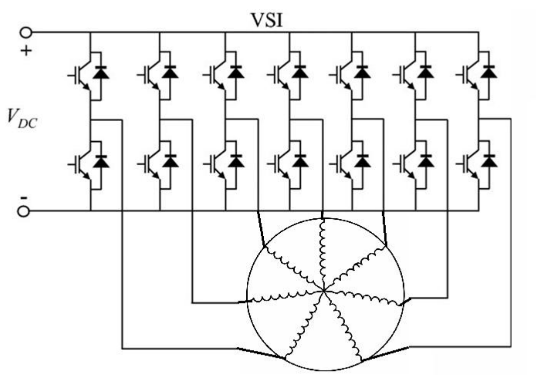


Figure 1. 7-phase VSI drive system

In the case of a balanced seven-phase system with a floating neutral, common-mode voltage may be eliminated to obtain the phase voltage

$$v_{ph,k}(t) = v_k(t) - \frac{1}{7}\sum_{i=1}^{7} v_i(t) \tag{2}$$

The fundamental phase displacement of the neighboring phases is

$$\theta = \frac{2\pi}{7}, \qquad \phi_k = (k-1)\theta. \tag{3}$$

Whereas, the fundamental reference for phase k is

$$v_{1,k(t)} = m_1 \sin(\omega t + \phi_k) \tag{4}$$

where m_1 is the fundamental modulation index and ω is the fundamental angular frequency.

The generalized injected reference waveform is written as:

$$v_{ref,k(t)} = m_1 \sin(\omega t+\phi_k)+a_3 \sin(3\omega t+3\phi_k+\psi_3)+a_5 \sin(5\omega t+5\phi_k+\psi_5)+a_7 \sin(7\omega t) \tag{5}$$

The third and fifth harmonic amplitudes are a3 and a5 with phase shifts ψ3 and ψ5. In seven-phase systems, the seventh harmonic exhibits a common-mode property because

$$7\phi_k = 7(k-1)\frac{2\pi}{7} = 2\pi(k-1) \tag{6}$$

Therefore, it becomes identical across phases and is represented as a common-mode injection term a7 sin(7ωt). On the other hand, a carrier-based PWM is employed using a common triangular carrier vc(t) with crossing with switching frequency fs. The switching function can be expressed as:

$$S_k(t) = \begin{cases} 1, & v_{ref,k}(t) \geq v_c(t) \\ 0, & v_{ref,k}(t) < v_c(t). \end{cases} \tag{7}$$

To keep the modulation in the linear region the following condition should be satisfied:

$$|vref,k(t)| \leq 1 \qquad \forall t, \forall k. \tag{8}$$

Methodology

The current section presents the proposed harmonic injection strategy, the performance indicators adopted for evaluation, and the MATLAB-based simulation framework that is used for validation.

Proposed Harmonic Injection Strategy.

The harmonic injection strategy introduced here in this paper relies on the generalized reference formulation in (5) that allows the systematic investigation of the harmonic injection scenarios in seven-phase systems. The main goal is to increase the use of DC-link voltage utilization and yet achieve reasonable harmonic performance. To achieve the above-mentioned features, the proposed strategy is to minimize the peak value of the modulation reference signal. To demonstrate this strategy let $v_{ref,k}(t)$ denote the unscaled modulation reference of phase k, which includes the fundamental component of amplitude m_1 and the injected harmonic components. The peak magnitude of the reference waveform is determined as:

$$V_{pk} = \max_{\{t,k\}} |\, v_{ref,k}(t)| \tag{9}$$

To guarantee linear carrier-based PWM operation, the reference must satisfy $|v_{ref,k}(t)| \leq 1$. So, the maximum permissible fundamental modulation index before over modulation is obtained as follows:

$$m_{1,max} = \frac{m_1}{V_{pk}} \quad (10)$$

This expression shows that reducing V_{pk} through appropriate harmonic injection directly increases $m_{1,max}$, consequently enhancing DC-link voltage utilization.

Performance Indicators

Three performance indicators are used to determine the effects of harmonic injection on the quality of the waveform and the pulsating torque. The phase voltage THD calculated is as below.

$$\text{THD} = \sqrt{\frac{\sum_{n=2}^{\infty} V_n^2}{V_1^2}} \quad (11)$$

V_1 is the fundamental voltage component and V_n is the amplitude of the n^{th} harmonic component. Further, a torque ripple index (TRI) that is defined in terms of voltages is given as:

$$\text{TRI} = \frac{\sum_{h \in \mathcal{H}_T} V_h^2}{V_1^2} \quad (12)$$

where H_T represents collection of low-order harmonic components which are the main contributors to the torque pulsations in multiphase drives. This index is a normalized level of the harmonic content with respect to the torque ripple. It is worth noting that the last indicator is the DC-link utilization factor. In fact, these indicators enable a comprehensive trade-off analysis between DC utilization, harmonic distortion and torque pulsating characteristics.

Investigated Harmonic Injection scenarios

In order to examine the effect of harmonic injection, the following scenarios are considered: (i) SPWM with no injection, (ii) third-harmonic injection, (iii) fifth-harmonic injection, (iv) seventh-harmonic injection, (v) third- and fifth-harmonic injection, (vi) third- and seventh-harmonic injection, (vii) fifth- and seventh-harmonic injection, and (viii) third-, fifth-, and seventh-harmonic injection. There are positive and negative injection polarities of harmonic injection to be taken into account in each scenario. Moreover, the phase variations of ψ_3 and ψ_5 are adjusted to determine which arrangement produces the minimum reference peak while remaining within the linear modulation boundary.

Simulation Model and Implementation

A MATLAB/Simulink model of a two-level inverter of a seven-leg voltage source that ultimately delivers power to a balanced seven-phase load is constructed, as shown in Figure 2, to verify the proposed methodology. The generalized harmonic injection reference of carrier-based SPWM is used to produce the gating signals. It assumes a floating neutral condition, and the common-mode voltage component has been eliminated by (2) to obtain the applied phase voltages. Harmonic parameters all of the parameters of the simulation are kept constant within all the harmonic injection circumstances of interest to compare fairly and consistently. Table 1 reports the key parameters of the simulation.

Table 1. Simulation parameters

Parameter	Value
DC-link voltage Vdc	600 V
Switching frequency fs	5 kHz
Fundamental frequency f1	50 Hz
Time step Ts	1/(80fs)
Simulation duration	Two fundamental cycles

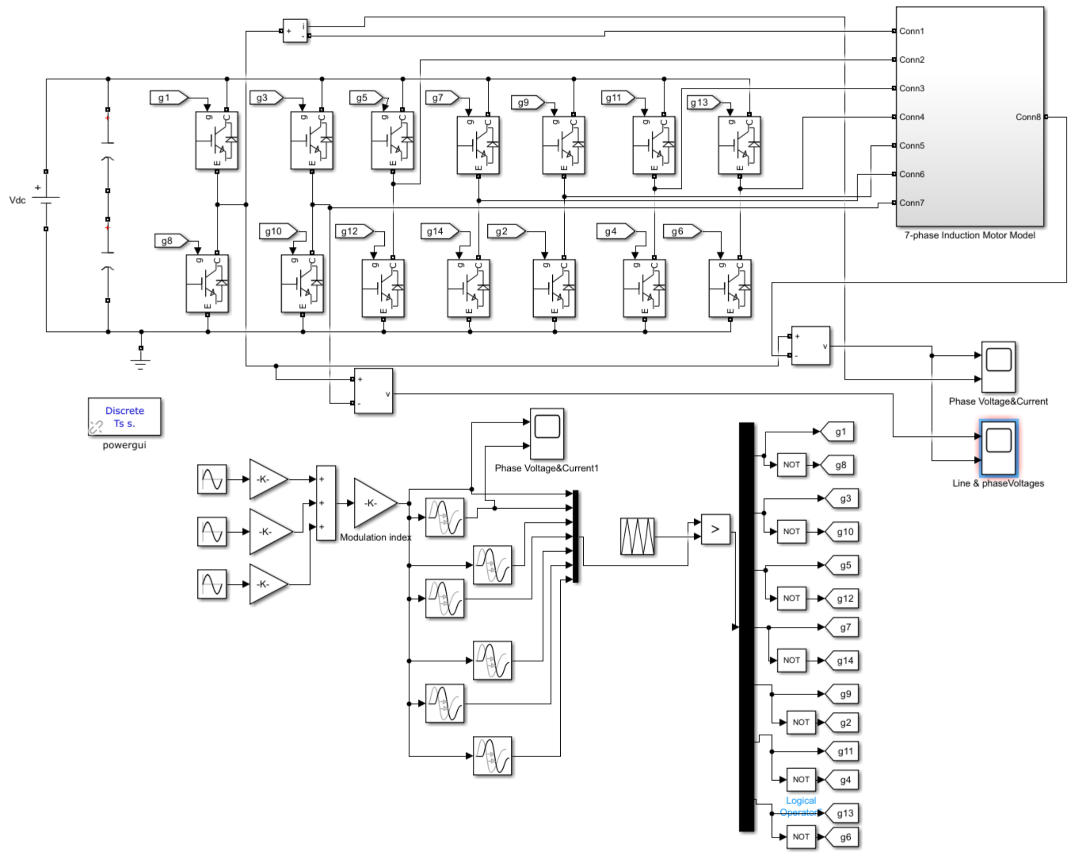


Figure 2. MATLAB simulink model

Results and Discussion

In this section, a detailed analysis of the studied harmonic injection scenarios s in a seven-step carrier based SPWM inverter is provided. The analysis is devoted to the increase in the utilization of DC-link, waveform shaping behavior, harmonic distortion features, and the tendency of the torque ripple. The results obtained are summarized in Table 2 and demonstrated with the help of the time-domain and frequency-domain plots presented in (Figures. 3, 4, and 5). Specifically, (Figure 3) shows reference waveform decomposition for some selected injection scenarios showing the fundamental component, injected harmonics, and the total reference signal within the linear modulation boundary. The harmonic injection distorts the modulation waveform such that it flattens the peak amplitude of the reference signal. The third harmonic has the dominant role in the reduction of the peaks whereas the fifth and seventh harmony will give additional fine tunings to the harmonic based on the phase alignment. The harmonics mutual interaction is easily seen in the joint injection cases where the waveform is more uniformly distributed in the linear modulation boundary.

DC-Link Voltage Utilization Results

The highest permissible fundamental modulation index achieved in each case is given in Table 2. Traditional SPWM that does not inject harmonic gives a baseline value of $m_{1,max}$ = 1.0.When the third harmonic is injected, the modulation limit to $m_{1,max}$ = 1.1547 along with an approximate improvement of 15.5% in the DC-link usage is reached. The fifth-harmonic injection gives an intermediate improvement ($m_{1,max}$ = 1.0515), and the seventh-harmonic injection alone gives a minor improvement ($m_{1,max}$ = 1.0257), as is expected of a common-mode signal in seven-phase systems. Each of the harmonics is maximally enhanced by combining several harmonics. The combination of harmonic frequencies three and five results in the $m_{1,max}$ = 1.2071 and the combination of harmonic frequencies three and seven results in the $m_{1,max}$ = 1.1708. Good DC-Link Voltage utilization is achieved by injecting all three harmonics at the same time so that $m_{1,max}$ = 1.2311 is obtained which is an improvement of utilization of about 23 percent of the conventional SPWM.

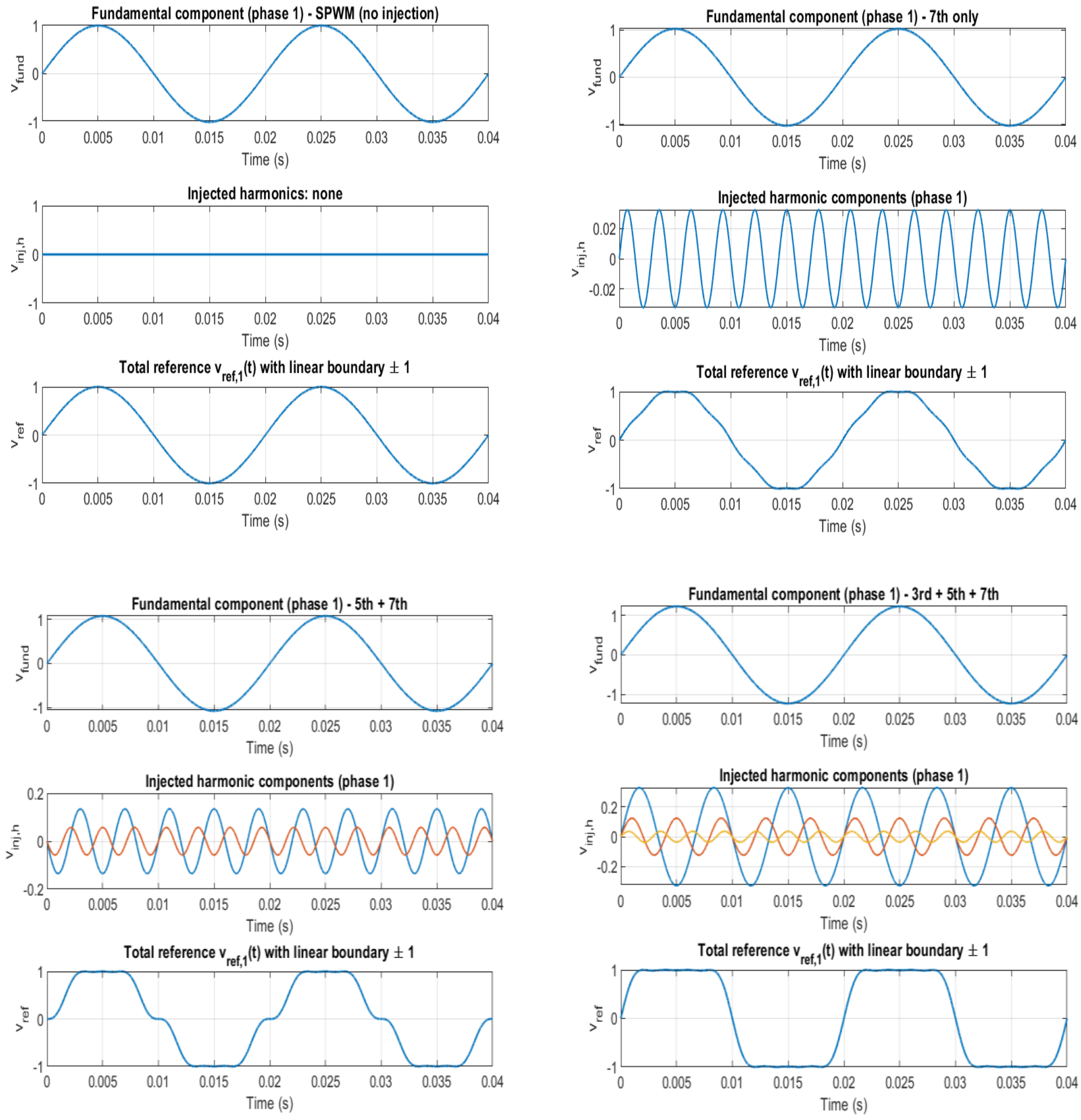


Figure 3. Reference waveform decomposition for selected injection scenarios

Table 2. Summary of optimal harmonic injection results for all investigated scenarios

Scenario	$m1,max$	$vpeak$	THD_{ph} (%)	TRI_{ph}	TRI_{ll}	a_3	a_5	a_7
SPWM (no injection)	1.00	1.00	1.6269	0.00011	0.00034	–	–	–
3_{rd} only	1.1547	1.00	16.748	0.02798	0.14059	0.19243	–	–
5^{th} only	1.0515	1.00	6.4415	0.00404	0.014222	–	-0.06503	–
7^{th} only	1.0257	1.00	1.4946	0.00012	0.00055	–	–	0.032
3^{rd} + 5^{th}	1.2071	1.00	24.532	0.06011	0.29598	-0.28038	-0.07328	–
3^{rd} + 7^{th}	1.1708	1.00	17.320	0.02994	0.14881	0.19196	–	-0.02
5^{th} + 7^{th}	1.0774	1.00	12.570	0.01567	0.05103	–	-0.13488	-0.05
3^{rd} + 5^{th} + 7^{th}	1.2311	1.00	28.988	0.08397	0.40570	0.32658	0.12317	0.035

Phase and Line Voltage Waveforms

The phase and line voltage waveforms of each injection case are depicted in (Figure. 4). As illustrated in this figure, harmonic injection enhances the importance of the modulation depth of the phase voltages whilst sustaining the switching properties of carrier-based SPWM. The waveform envelopes depict better DC-link exploitation, especially in the cases of multi-harmonic injections. Nonetheless, greater oscillatory behavior is recorded in cases of strong harmonic injection implying increased harmonic distortion levels.

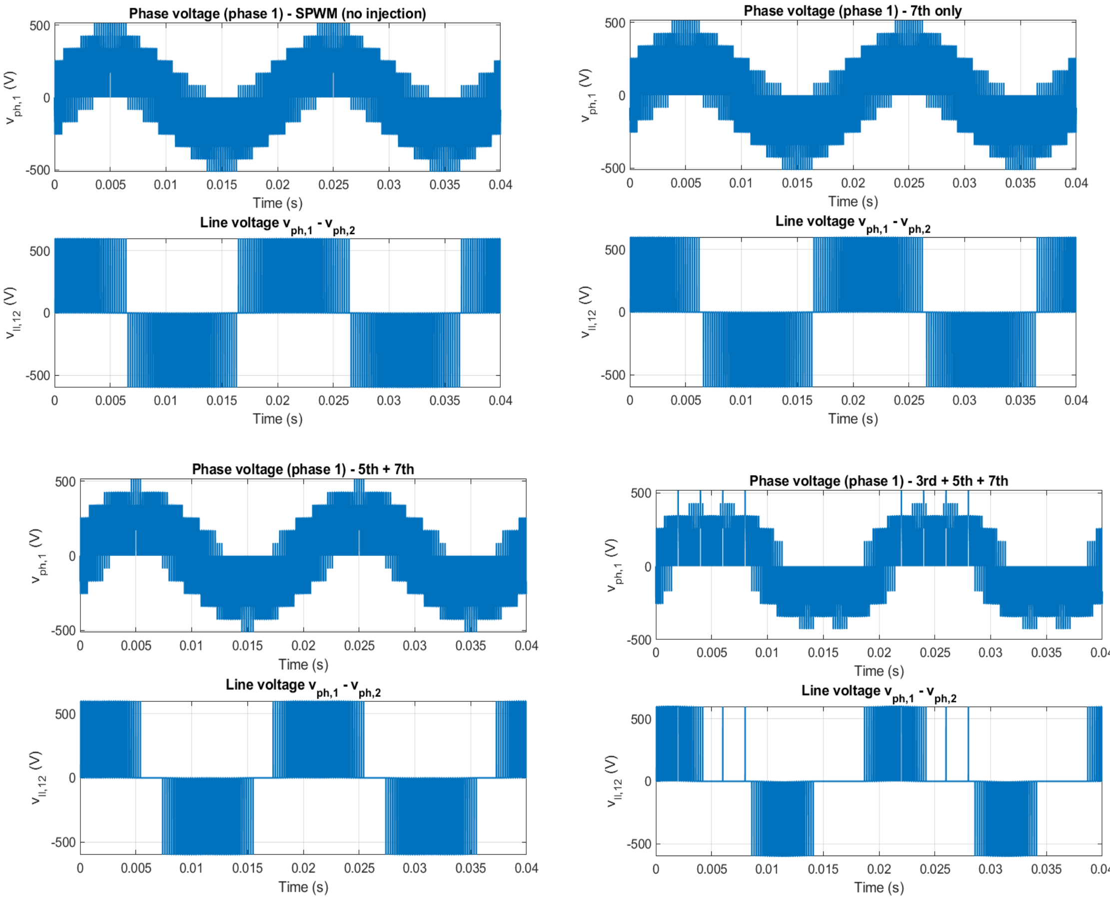
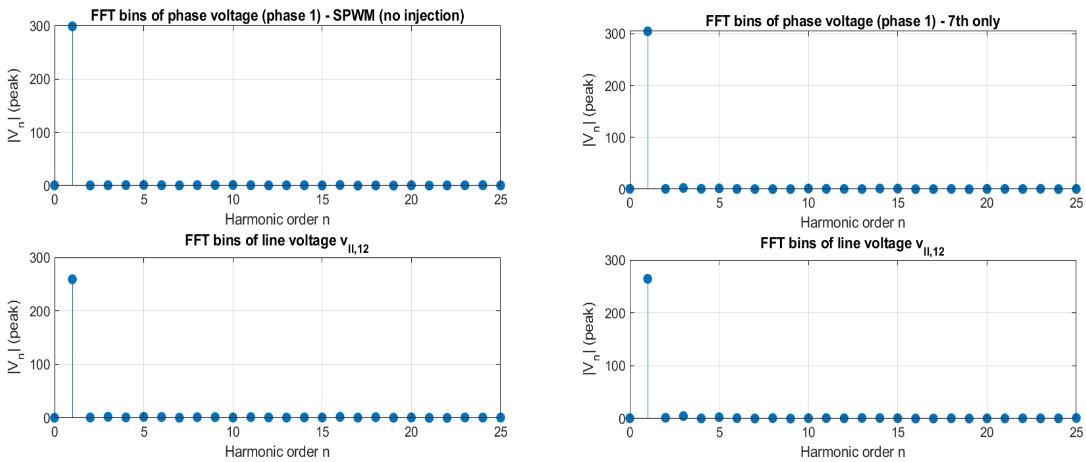


Figure 4. Phase and line voltages using different harmonic injection scenarios

Frequency-Domain Analysis

The FFT spectra of the phase and line voltages are presented in (Figure 5). The content of the harmonic in the baseline SPWM case is very low, which validates the high quality of the waveforms of the traditional sinusoidal modulation. Conversely, in cases of harmonic injection, the harmonic components of lower order are strong with respect to the injected frequencies. As can be clearly seen in the FFT results, the increase in the utilization of DC-link is done at the cost of a greater harmonic distortion. İt is also worth to mention that in seven-phase systems, the peak magnitude of the line voltage is inherently lower than that of the phase voltage, not like conventional three-phase systems, due to the reduced phase displacement between adjacent phases.



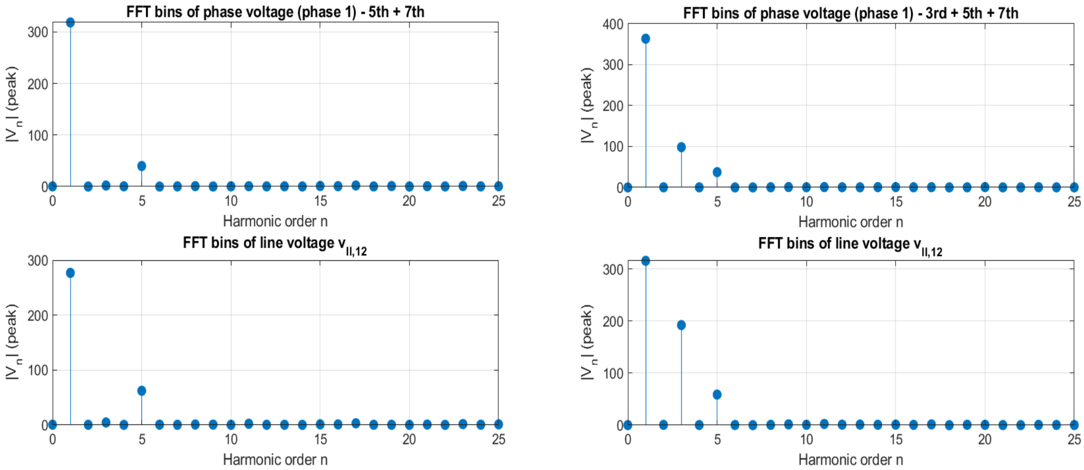


Figure 5. FFT spectra of the phase and line voltages for selective harmonic injection scenarios

Torque Ripple Tendency

The voltage-based torque ripple index (TRI) further contributes to the knowledge of the impact of harmonic injection on drive performance. As can be seen in Table 2, the baseline SPWM condition has extremely low values of TRI, which implies that it only has a low propensity of torque pulsation. The addition of third harmonic injection would add a lot to the TRI due to the existence of harmonic components of low order. Multi-harmonic injection cases produce maximum TRI, particularly of line voltages which are higher orders of oscillatory energy which can be transformed into pulsating torques in a practical multi-phase machine. Conversely, the fifth-harmonic injection produces moderately large TRI values, and the seventh-harmonic injection produces minor alteration in the torque ripple since it is a common-mode interference. but this fact is all the more notable when it comes to specially constructed seven-phase machines whose winding configuration and harmonic subspace can be deliberately optimized to take advantage of harmonic injections of special choice (e.g. 3rd, 5th, or both) to increase torque density, widen voltage range, and to allow fault-tolerant operation without excessive torque pulsations. Harmonic injection is, therefore, not just a modulation enhancement, it is also a co-design parameter between the inverter and a seven-phase machine purpose-designed.

Conclusion

The paper examined the behavior of a seven-phase voltage source inverter under varied modulation conditions, such as traditional SPWM and the harmonic injection methods. It was revealed that harmonic injection affects the voltage exploitation, harmonic spectrum and torque ripple inclination of multiphase drive systems significantly. The reference SPWM was stable and had a low torque ripple tendency, but limited use of DC-link voltage. Voltage capability was improved by introducing low order harmonic components, especially third-harmonic injection, but the tendency to torque ripple was increased by the existence of the main harmonic components interacting with machine electromagnetic fields. Multi-harmonic injection generated the greatest levels of oscillatory energy, which means it can have negative implications on the torque smoothness and the performance of the drives. Fifth-harmonic injection, in contrast, provided a moderate compromise between the use of voltages and torque ripple, and seventh-harmonic injection had little effect on the pulsation of the torque, as it acts predominantly as a common-mode factor in seven-phase machine. This observation is true to the fact that it is possible to make good use of higher-order harmonic injection to improve the performance of modulation without making the quality of torque substantially worse. In general, the paper proves that the harmonic injection is not only a modulation increase method but is a design oriented tool that can be customized to suit a given seven-phase machine design. With suitable winding layouts, and electromagnetic design, the harmonic components chosen can enhance the use of DC-link, greater range of operating speeds, as well as acceptable smoothness of torque. It allows harmonic-assisted modulation to be very applicable to high-end multiphase drive applications e.g. electric vehicles, aerospace actuators, and fault-tolerant industrial systems.

Recommendations

Based on the findings of this study, when better DC-link voltage utilization is needed for seven-phase inverters, harmonic-injected SPWM is advised, but careful component injection selection is crucial. Fifth-harmonic injection provides a workable compromise between voltage enhancement and torque quality. Seventh-harmonic injection is better when modulation improvement is required with little torque pulsation, and third-harmonic injection should be used with caution because of its effect on torque ripple. It is not advised to use excessive multi-harmonic injection, and the modulation strategy chosen should be in line with the drive's operational priority and the electromagnetic properties of the seven-phase machine.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

Funding

* The authors received no financial support for the research of this article.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Technology (www.icontechno.net) held in Budapest/Hungary on February 05-08, 2026.

* The authors would like to express their sincere gratitude to the University of Mosul and the University of Fallujah for their continuous support and for providing the necessary facilities and resources that contributed to the completion of this research.

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To cite this article:

Ameen, Y.M.Y., Mohammed, M. H., & Alwan, M. M. (2026). Harmonic injection scenarios for enhanced DC-link utilization in seven-phase VSI-fed motor drives. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 39,* 40-49.