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Third Harmonic Injection for Two-Level Five-Phase Inverters for Electric Vehicle Using Time-Division Sampling (TDS)

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Abstract

Five-phase inverters (FPIs) have gained increasing attention in electric vehicle (EV) applications due to their inherent advantages such as improved fault tolerance, reduced torque ripple, and higher power density compared to conventional three-phase systems. Despite these benefits, the control and modulation of FPIs remain challenging, particularly when advanced harmonic injection techniques are required to enhance voltage utilization and output waveform quality. To address these challenges, this study proposes a new space-vector modulation method for five-phase inverters with four degrees of freedom (FDOF), specifically aimed at EV drive systems. The proposed approach introduces the simultaneous injection of the third harmonic component along with the fundamental component as an optimization objective, while maintaining the required voltage utilization constraints. Unlike conventional methods that handle fundamental modulation and harmonic injection separately, the proposed strategy integrates both within a unified framework. The excitation times of the four fundamental voltage vectors are calculated such that their total duration does not exceed the switching period, and the voltage vectors in both the fundamental and third harmonic subspaces satisfy the corresponding vector balance equations. This ensures accurate voltage synthesis and stable inverter operation. A notable feature of the proposed method is that voltage vector selection and duty-cycle optimization are performed simultaneously. This coordinated optimization enables the determination of an optimal switching sequence within each sampling interval, effectively minimizing current tracking errors. As a result, the inverter achieves improved current waveform quality and enhanced dynamic performance, which are essential for high-performance EV traction applications. To further enhance third harmonic injection, a time-division sampling (TDS) method is introduced. In this technique, the total sampling period is divided between the fundamental and third harmonic components based on the required level of third harmonic injection. This flexible allocation allows precise harmonic control without increasing switching complexity or adversely affecting fundamental voltage performance. The proposed modulation strategy is validated through detailed simulations conducted in MATLAB™/Simulink®. Simulation results confirm that the method significantly improves third harmonic injection capability while keeping total harmonic distortion (THD) at a low level. In addition, higher-order harmonics (HOHs) are effectively suppressed. Overall, the results demonstrate that the proposed FDOF-based method provides an efficient and robust solution for harmonic control in five-phase inverter-fed electric vehicle drives.

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1. Introduction

Multiphase inverters (MPI) are superior to conventional three-phase inverters due to their high efficiency, reduced torque ripple, reduced DC link current distortion, and reliability under fault conditions specially in electric vehicle drives (EVs). While three-phase inverters, despite their widespread use in industry, suffer from harmonic distortion and reduce system efficiency and lifespan [1]-[2].

In three-phase inverters, sinusoidal pulse width modulation (SPWM) and selective harmonics elimination pulse width modulation (SHEPWM) methods are used to generate the main voltage and eliminate harmonics, but in multiphase inverters they are not able to control high-order harmonics. For this reason, methods such as carrier-based SPWM and SVPWM are used to control harmonics in MPIs. [3]-[7]. Five-phase inverters (FPIs) are widely used in power conversion and drive of various motors in EV drives such as induction motors [8]-[12], brush-less DC [13], and permanent magnet synchronous motors (PMSMs) [14]. Research has shown that their performance and stability can be improved by using control techniques such as SVPWM and FOC. However, FPIs always produce additional harmonics, which cause temperature increase and energy waste.

Research on FPIs has mainly focused on voltage source inverters (VSIs) [15]-[16], and current source inverters (CSI) [17]. However, new approaches in [18] have also been proposed, such as the use of quasi-impedance inverters, which lead to reduced harmonic distortion. In addition to the conventional two-level inverters, three- and five-level inverters have also been investigated for improved performance. Advanced techniques such as SVPWM and new algorithms have been used to reduce common-mode voltage (CMV) and unwanted harmonics. In some cases, harmonics are used to increase the torque and efficiency of the system, rather than eliminating them. Finally, choosing the right switching strategies to control these harmonics is of great importance [19]-[21].

There is a lot of research on SVPWM techniques. However, complete elimination of higher order harmonics (HOHs) is not always the best solution, as these harmonics can also have benefits. For example, injecting the third harmonic into the system can significantly increase efficiency and improve motor torque in highly sensitive applications such as EVs and aerospace. To do this, various methods have been developed based on PWM and SVPWM techniques [22]-[24].

To generate the required voltage and inject the third harmonic (THI), it is very important to choose the right voltage vectors in the inverters [25]-[26]. For this purpose, various techniques such as model predictive control (MPC) and scalar PWM are used to reduce voltage problems such as common mode voltage (CMV). More advanced techniques such as four -degree of freedom Overmodulation FDOF are also used to reduce undesirable harmonics in systems with SVPWM technique [27].

Recent researches for THI in FPIs use PWM and SVPWM techniques. However, these methods require heavy and time-consuming computations, especially due to the complexity of voltage vector selection. This paper introduces a new method based on the FDOF strategy for SVPWM. This method uses a technique called time-division sampling (TDS) to control the fundamental and third harmonics simultaneously and separately. The main advantage of this method is that it can inject the third harmonic into the system while greatly reducing the THD.

The organization of paper is given as follows: Section II presents constructure of two-level FPVSI and Section III illustrates SVPWM technique for FPVSIs. In Section IV, THI using proposed TDS is explained. Simulation results, analysis and discussion are given in Sections V and VI, respectively. Finally, conclusion is expressed in Section VII.

2. Constructure of two-level FPVSI

The two-level FPVSI inverter consists of 10 switches (two switches in each of the five arms). Fig.1 shows the constructure of two-level FPVSI. The inverter is capable of producing 32 different switching states, determined by the state of the upper switches in each arm. Of these 32 states, two special states (when all switches are on or off) are called zero vectors. In this system, the switches in each arm are never turned on simultaneously [28].

To study of FPVSI, phase to neutral voltages V_{an}, V_{bn}, V_{cn}, V_{dn}, and V_{en} should be defined. For example, V_{an} can be described as follow:

$$V_{an} = V_{aN} + V_{Nn} \tag{1}$$

And

$$V_{Nn} = -\frac{V_{aN} + V_{bN} + V_{cN} + V_{dN} + V_{eN}}{5} \tag{2}$$

For example, V_{an} can be described based on switch state as follows:

$$V_{aN} = S_a V_{dc} \tag{3}$$

The voltage vectors in fundamental subspace (dq_1) and third harmonic subspace (dq_3) can be realized based on neutral voltages as follows:

$$\begin{aligned} V_{dq1} &= V_{d1} + jV_{q1} \\ V_{dq1} &= \frac{2}{5}\left(V_{an} + aV_{bn} + a^2V_{cn} + a^3V_{dn} + a^4V_{en}\right) \\ V_{dq3} &= V_{d3} + jV_{q3} \\ V_{dq3} &= \frac{2}{5}\left(V_{an} + bV_{bn} + b^2V_{cn} + b^3V_{dn} + b^4V_{en}\right) \end{aligned} \tag{4}$$

Where, $a = \exp\frac{j2\pi}{5}$ and $b = \exp\frac{j6\pi}{5}$

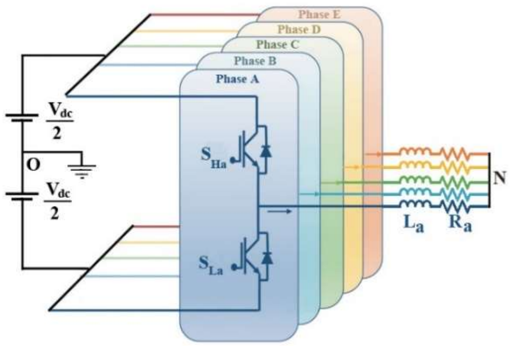


Fig. 1: Constructure of two-level FPVSI

3. SVPWM technique for FPVSIs

The possible voltage vectors for a FPVSI in the dq1 and dq3 spaces are depicted in Fig 2. As can be seen in the Figure, the dq1 space consists of ten sectors and three types of vectors: small (red), medium (green), large (blue) which large vectors in the dq1 space are converted to small vectors in the dq3 space. Also, small vectors in the dq1 space are converted to large vectors in the dq3 space. However, the medium vectors in both spaces remain constant. Using (3), 32 voltage vectors from V0 to V31 can be generated in ten different sectors. Table 1 shows the switching table of two-level FPVSI.

Using FDOF, $\overrightarrow{V_s}$ can be obtained based on sampling time T_s as follows:

$$\overrightarrow{V_s} = \overrightarrow{V_{i1}}\frac{T_1}{T_s} + \overrightarrow{V_{i2}}\frac{T_2}{T_s} + \overrightarrow{V_{i3}}\frac{T_3}{T_s} + \overrightarrow{V_{i4}}\frac{T_4}{T_s} + \overrightarrow{V_{i0}}\frac{T_0}{T_s} \tag{5}$$

$$m_1 + m_2 + m_3 + m_4 + m_0 = 1 \tag{6}$$

Where, $m_i = T_i/T_s (i = 1,2,3,4)$ are active duration of $V_{i1}, V_{i2}, V_{i3}, V_{i4}$, and V_0 none-zero vectors. Also, m_0 is active duration of zero vector. Principally, these vectors are chosen based on one, two, or three sectors. For example, in sector 1 and dq_1 subspace (Fig.2(a)),V_1, V_2, V_{11}, V_{12}, and V_0 can be selected which lead to generate third harmonic in dq_3 subspace (Fig.2(b)).

Table 1: Switching table of two-level FPVSI

States	S_a	S_b	S_c	S_d	S_e	Space vectors
0	0	0	0	0	0	V_{00}
1	0	0	0	0	1	V_{19}
2	0	0	0	1	0	V_{17}
3	0	0	0	1	1	V_{08}
4	0	0	1	0	0	V_{15}
5	0	0	1	0	1	V_{27}
6	0	0	1	1	0	V_{06}
7	0	0	1	1	1	V_{07}
8	0	1	0	0	0	V_{13}
9	0	1	0	0	1	V_{21}
10	0	1	0	1	0	V_{25}
11	0	1	0	1	1	V_{28}
12	0	1	1	0	0	V_{04}
13	0	1	1	0	1	V_{24}
14	0	1	1	1	0	V_{05}
15	0	1	1	1	1	V_{16}
16	1	0	0	0	0	V_{11}
17	1	0	0	0	1	V_{10}
18	1	0	0	1	0	V_{29}
19	1	0	0	1	1	V_{09}
20	1	0	1	0	0	V_{23}
21	1	0	1	0	1	V_{30}
22	1	0	1	1	0	V_{26}
23	1	0	1	1	1	V_{18}
24	1	1	0	0	0	V_{02}
25	1	1	0	0	1	V_{01}
26	1	1	0	1	0	V_{22}
27	1	1	0	1	1	V_{20}
28	1	1	1	0	0	V_{03}
29	1	1	1	0	1	V_{12}
30	1	1	1	1	0	V_{14}
31	1	1	1	1	1	V_{31}

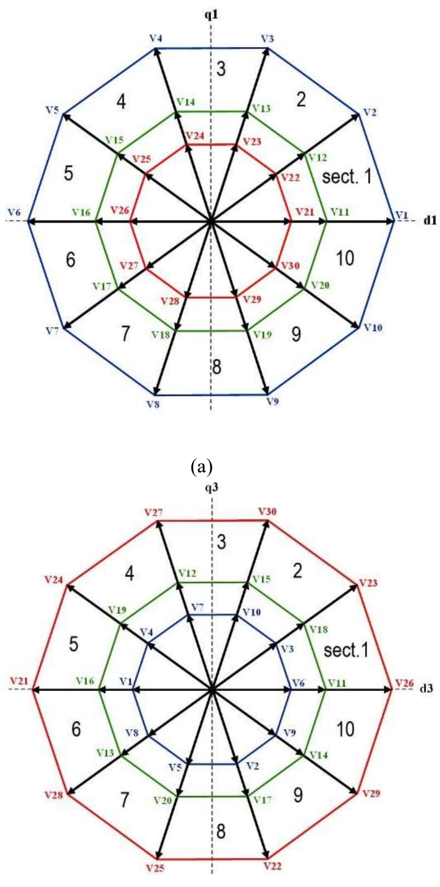
Projection of five vectors in dq_1 and dq_3 subspaces can be obtained based on m_1, m_2, m_3, m_4, and m_0 as follows:

$$\begin{bmatrix} V_{d1s} \\ V_{q1s} \\ V_{d3s} \\ V_{q3s} \end{bmatrix} = \begin{bmatrix} V_{d1,i1} V_{d1,i2} V_{d1,i3} V_{d1,i4} V_{d1,i0} \\ V_{q1,i1} V_{q1,i2} V_{q1,i3} V_{q1,i4} V_{q1,i0} \\ V_{d3,i1} V_{d3,i2} V_{d3,i3} V_{d3,i4} V_{d3,i0} \\ V_{q3,i1} V_{q3,i2} V_{q3,i3} V_{q3,i4} V_{q3,i0} \end{bmatrix} \begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_0 \end{bmatrix} \tag{7}$$

Where, V_{d1s} , V_{q1s} , V_{d3s} , and V_{q3s} are total projected five vectors. Using (7), $\overrightarrow{V_s}$ obtains as [29]:

$$|V_s| = \sqrt{V_{d1s}{}^2 + V_{q1s}{}^2}.\cos(\omega t) + \sqrt{V_{d3s}{}^2 + V_{q3s}{}^2}.\cos(3\omega t + \varphi) \tag{8}$$

$$\varphi = \tan^{-1}\frac{V_{d1s}}{V_{q1s}} - \tan^{-1}\frac{V_{d3s}}{V_{q3s}} \tag{9}$$



(a)

(b)

Fig. 2: Space vectors in two-level FPVSI (a) fundamental subspace dq1 (b) 3rd harmonic subspace dq3

4. THI using proposed TDS

Vector selection strategies in FPVSI are studied for two main purposes: harmonic rejection and THI. For harmonic rejection, three main methods are used: non-adjacent vector selection [10], multi-vector approach [6], and selective harmonic rejection (SHE) [3]. For THI, the third harmonic component is injected into the reference signal, which can be done using SVPWM [22]-[25] or combining THI with optimal vector selection [20]. Zero vectors do not play a role in power delivery but are important for delay time calculations.

This study describes a proposed method called TDS for vector selection in two-level FPIs, which is designed to simplify and speed up practical implementation. To reduce complexity, four vectors from the dq1 subspace and four vectors from the dq3 subspace (each containing two large vectors and two medium vectors) are selected. Fig. 3 and Table 2 show these selections for each sector. A zero vector is also used for both subspaces. Time Allocation In this method, the total sampling time (Ts) is divided between five dq1 vectors and five dq3 vectors based on the ITHP of the reference voltage. For example, in sector one, the dq1 vectors are activated for time (1-ITHP)×Ts and the dq3 vectors for time ITHP×Ts. This method uses the reference and transformation matrices to calculate the excitation time of each vector.

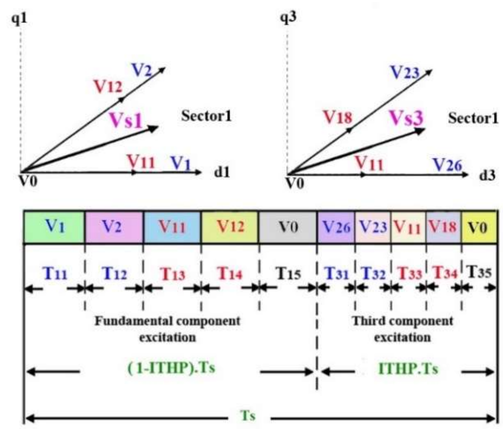


Fig. 3: Proposed TDS

To implement TDS approach, reference and transformation matrixes are described as:

$$V_{ref} = [V_{d1}\ V_{q1}\ V_{d3}\ V_{q3}\ \ 1]^T \quad (10)$$

$$V_{u1} = [U_{11}\ U_{21}\ U_{31}\ U_{41}\ U_{51}],\quad V_{u3} = [U_{13}\ U_{23}\ U_{33}\ U_{43}\ U_{53}] \quad (11)$$

$$U_{x1} = [u_{11}\ u_{12}\ u_{13}\ u_{14}\ 0],\quad U_{x3} = [u_{31}\ u_{32}\ u_{33}\ u_{34}\ 0] \quad (12)$$

Where, V_{ref}, V_{u1}, V_{u3} U_{x1}, and U_{x3} are 5×1, 5×5, 5×5, 5×1, and 5×1 matrixes, respectively. In sector one, excitation time of five vectors in dq_1 subspaces and five vectors in dq_3 subspaces can be calculated based on $M_1=[m_{11}, m_{12}, m_{13}, m_{14}, m_{15}]$ and $M_3=[m_{31}, m_{32}, m_{33}, m_{34}, m_{35}]$ respectively as follows:

$$M_1 = V_{u1}{}^{-1}.V_{ref} \quad (13)$$

$$M_3 = V_{u3}{}^{-1}.V_{ref} \quad (14)$$

Table 2: Vectors selection in dq1 subspace and dq3 subspace

Sector number	dq1 subspace vectors	dq3 subspace vectors
1	V_1–V_2–V_{11}–V_{12}–V_0	V_{26}–V_{23}–V_{11}–V_{18}–V_0
2	V_2–V_3–V_{12}–V_{13}–V_0	V_{23}–V_{30}–V_{18}–V_{15}–V_0
3	V_3–V_4–V_{13}–V_{14}–V_0	V_{30}–V_{27}–V_{15}–V_{12}–V_0
4	V_4–V_5–V_{14}–V_{15}–V_0	V_{27}–V_{24}–V_{12}–V_{19}–V_0
5	V_5–V_6–V_{15}–V_{16}–V_0	V_{24}–V_{21}–V_{19}–V_{16}–V_0
6	V_6–V_7–V_{16}–V_{17}–V_0	V_{21}–V_{28}–V_{16}–V_{13}–V_0
7	V_7–V_8– V_{17}–V_{18}–V_0	V_{28}–V_{25}–V_{13}–V_{20}–V_0
8	V_8–V_9–V_{18}–V_{19}–V_0	V_{25}–V_{22}–V_{20}–V_{17}–V_0
9	V_9–V_{10}–V_{19}–V_{20}–V_0	V_{22}–V_{29}–V_{17}–V_{14}–V_0
10	V_{10}–V_1–V_{20}–V_{11}–V_0	V_{29}–V_{26}–V_{14}–V_{11}–V_0

Time of each vector in dq1 subspace and dq3 subspace obtains as follow:

$$T_1 = (1 - \text{ITHP}).M_1.T_s \quad (15)$$
$$T_3 = \text{ITHP}.M_3.T_s \quad (16)$$

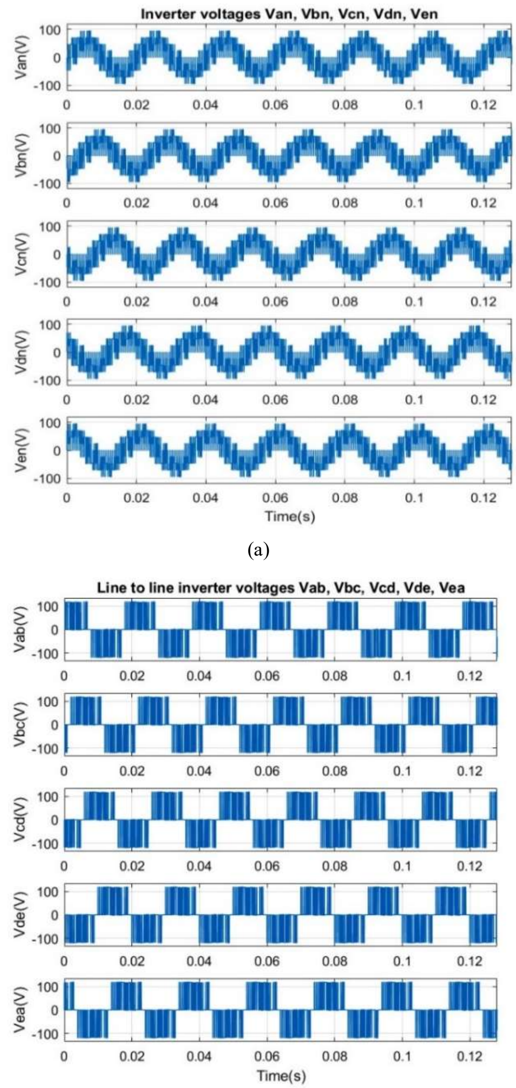
Where, T1=[T11, T12, T13, T14, T15] and T3=[T31, T32, T33, T34, T35].

5. Simulation results

To investigate the proposed FDOF method for two-level FPVSI, simulations were performed with a DC bus voltage of 120 V. The results were obtained using MATLAB™/SIMULINK® under a load of ZL=32Ω+30mH, a fundamental frequency of 50 Hz, and a sampling time of 2 kHz. The phase-to-neutral voltages, line-to-line voltages, reference voltage, dq_3 subspace voltage, phase currents, and current harmonic analysis were investigated for 0%, 5%, 10%, and 15% THI. Fig. 4 shows the phase-to-neutral and line-to-line voltages of the five-phase inverter. The phase-to-neutral voltage of the inverter is 95 V and the line-to-line voltage is 120 V. The maximum main amplitude of the reference voltage is set to 60 V. In Fig. 5, the dq_3 subspace voltages with increasing THI are 0 V (0% THI), 3 V (5% THI), 6 V (10% THI), and 9 V (15% THI), respectively. Fig. 6 shows the phase current results with different THIs; increasing THI from 0% to 15% reduces the peak phase current from 2 A to 1.8 A.
Finally, Fig. 7 shows the harmonic composition of the phase current, which with increasing THI, the amplitude of the fundamental component of the current decreases from 1.90 A to 1.66 A, while the amplitude of the third harmonic increases from 10% to 16%. The THD of the current is also 14.07%, 15.94%, 17.51%, and 19.46%, respectively.

6. Analysis and Discussion

The simulation results clearly show the performance impacts of the proposed TDS method under different THIs. The inverter phase-to-neutral and line-to-line voltages were analyzed under different THI conditions. As seen in Fig. 4, voltages of 95 V and 120 V were obtained and the maximum output voltage was limited due to the inherent limitations of the FPVSI with a maximum fundamental amplitude of 60 V. The dq_3 subspace voltages depicted in Fig. 5 show the incremental effect of THI on the inverter. Fig. 6 confirms the reduction of peak current with increasing THI percentage, demonstrating the effectiveness of this technique in minimizing current distortion. The harmonic analysis of the phase current in Fig. 7 shows that the fundamental component decreases slightly with increasing THI, while the third harmonic component increases. Finally, the THD values, which vary from 14.07% to 19.46%, indicate the balance that must be struck between the increase in fundamental voltage and the increase in harmonic distortion. Fig. 8 and Table 3 show simulation results of harmonic of harmonic synthesis of current.



(a)

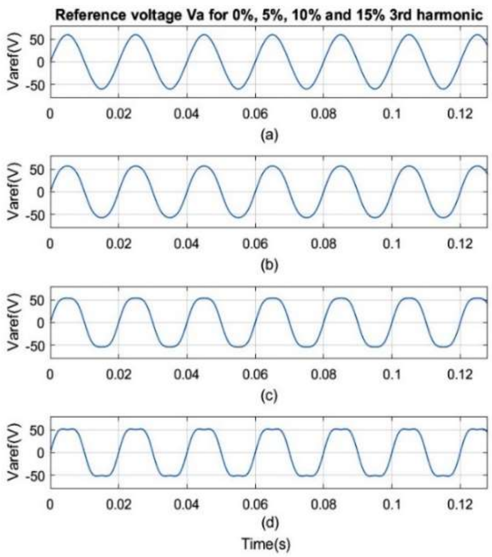
(b)

Fig. 4: Simulation results (a) voltages to neutral, (b) line to line inverter voltages

Table 3: Simulation data of current, ZL=32Ω+30mH, Vdc=120V

THI (%)	I (A)	I_{H1} (A)	I_{H3} (A)	I_{H3}/I_{H1} (%)
0	2.02	1.90	0.19	10
5	1.95	1.83	0.24	13

10	1.90	1.75	0.26	15
15	1.80	1.66	0.26	16



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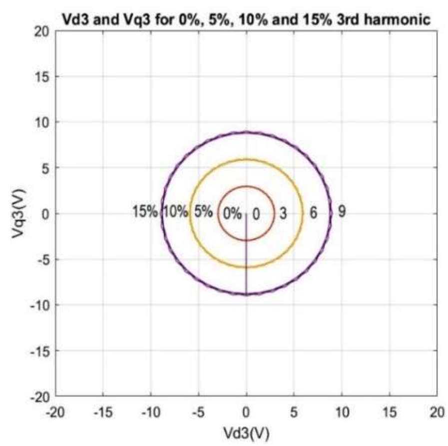


(b)

Fig. 5: Simulation results with THI 0%, 5%, 10%, and 15% (a) reference voltage, (b) dq_3 subspace voltages

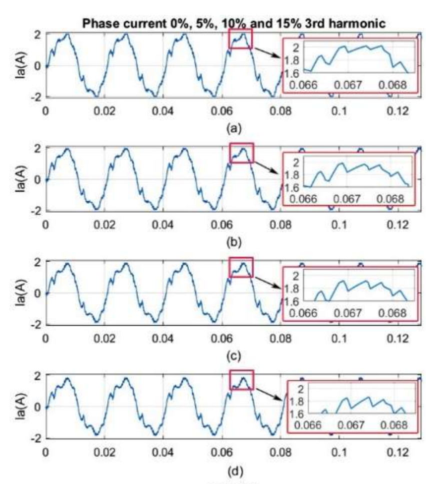
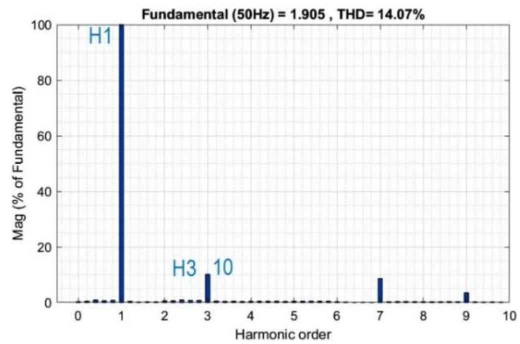
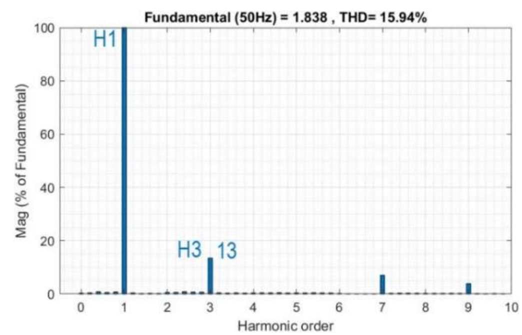


Fig. 6: Simulation results of phase current with ZL=32Ω+30mH and THI (a) 0%, (b) 5%, (c) 10%, (d) 15%



(a)



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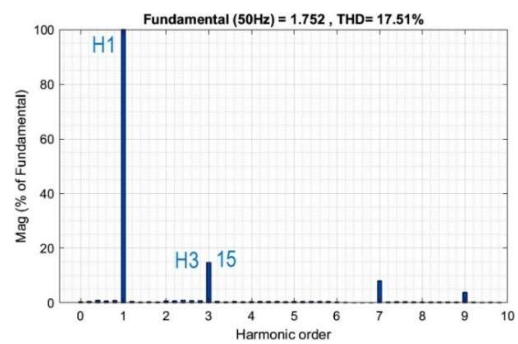

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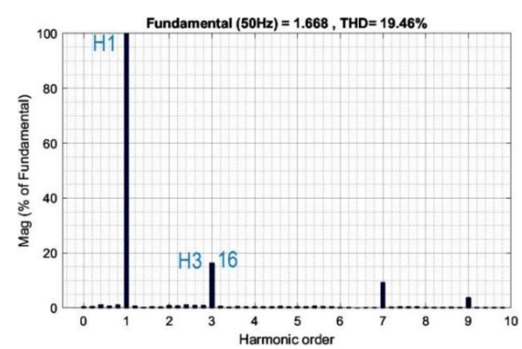

(d)

Fig. 7: Simulation results of harmonic spectrum of phase current with THI (a) 0%, (b) 5%, (c) 10%, (d) 15%

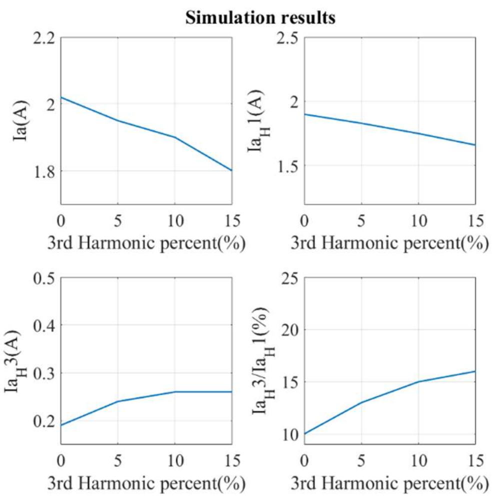

Fig. 8: Simulation results of harmonic of harmonic synthesis of current

6. Conclusions

In this study, THI method is introduced using the proposed TDS technique for two-level FPIs. Simulation results confirm that the proposed method effectively increases the THI efficiency while maintaining a good balance between the mains voltage amplitude and harmonic distortion. This technique successfully reduces the peak phase current and increases the third harmonic component proportionally. This balance helps to suppress HOHs and keeps the THD at a desirable level. A detailed analysis of Table 3 and Fig. 8 proves the stability and efficiency of the TDS algorithm. The proposed TDS method is a significant advancement in harmonic control of FPIs and provides a reliable solution to improve performance while controlling harmonic distortion. This method can be implemented in the future for special motor drive applications such as EVs with higher efficiency and effectiveness.

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