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Harmonic Generation and Mitigation Techniques for Variable Frequency Drives (VFDs)

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Abstract*—Power quality is a critical concern for both electric utilities and end-users, with the term "power quality" encompassing various disturbances within power systems. This paper addresses the growing importance of addressing harmonic distortions introduced by Variable Frequency Drives (VFDs) – devices widely employed for their efficiency and control benefits. The aim is to investigate and compare multiple harmonic reduction techniques to mitigate the adverse effects of VFD-generated harmonics. Through simulations using MATLAB/Simulink and ETAP software, the paper evaluates the effectiveness and economic viability of passive filters, reactors, multi-pulse converters, and phase-shifted drives. Results reveal distinct performance characteristics and trade-offs among the techniques, shedding light on their applicability in maintaining power quality and compliance with standards.*

Keywords— Harmonics, Variable Frequency Drives (VFDs), Power Quality, Harmonic Mitigation, Total Harmonic Distortion Index (THDI), and Comparative Analysis.

1. INTRODUCTION

In recent decades, the rapid proliferation of Variable Frequency Drives (VFDs) has led to significant advancements in industrial processes, enabling enhanced control, energy savings, and improved productivity[1]. However, this widespread adoption has brought attention to a critical issue: the generation of harmonics and their deleterious impact on power quality. Power quality, encompassing a range of electrical phenomena affecting voltage, current, and frequency, has emerged as a paramount concern for both electric utilities and end-users of electric power [2]. The term "power quality" has garnered considerable attention within the power industry, encompassing diverse disturbances that affect the reliability and efficiency of electrical systems [3]. A predominant source of these disturbances is the harmonic currents produced by VFDs [4].

As VFDs facilitate motor speed control and energy savings, they simultaneously introduce harmonic currents into the power network[5]. These harmonics, characterized by non-sinusoidal waveforms and frequencies that are integral multiples of the fundamental frequency, give rise to voltage distortion, increased losses, overheating, and electromagnetic interference[6]. Consequently, there is a compelling need to understand the mechanisms of harmonic generation by VFDs and to devise effective mitigation techniques to counter their adverse effects on power quality[7].

This paper delves into the intricate relationship between VFDs, harmonic generation, and power quality. It aims to shed light on the underlying mechanisms responsible for harmonic production within VFDs, emphasizing the role of rectifier and inverter components in shaping harmonic currents. Subsequently, a comprehensive exploration of various harmonic mitigation techniques is undertaken. Passive filters, active filters, isolation transformers, and reactor-based solutions are scrutinized for their efficacy in alleviating harmonic distortion. The investigation further extends to the utilization of simulation tools and experimental validation to assess the real-world impact of these mitigation strategies.

In essence, this paper seeks to address the pressing issue of harmonic generation by VFDs and its implications for power quality. By unraveling the complex interplay between VFD operation and harmonics, and by evaluating the effectiveness of diverse mitigation techniques, this study aims to provide engineers and practitioners with insights that can inform sound decision-making in industrial settings. Through a comprehensive understanding of harmonic generation and mitigation, the industrial community can adopt strategies to safeguard power quality, enhance system reliability, and optimize the performance of VFD-driven systems.

2. PROBLEM STATEMENT

The widespread integration of Variable Frequency Drives (VFDs) in industrial processes has ushered in remarkable advancements in energy efficiency, control, and productivity[8]. However, this proliferation has introduced a significant challenge in the form of harmonic generation[9]. Harmonics, characterized by non-sinusoidal waveforms and frequencies that are integer multiples of the fundamental frequency, are generated by the operation of VFDs[10]. These harmonic currents give rise to power quality issues, including voltage distortion, increased losses, and interference with sensitive equipment[11]. The increasing emphasis on power quality and the need for reliable and efficient electrical systems necessitate a thorough investigation into the mechanisms of harmonic generation by VFDs and the development of effective mitigation strategies[12]. Addressing this problem is vital to ensure the seamless integration of VFDs without compromising the integrity of power distribution networks and industrial processes.

3. THE MAIN OBJECTIVES

The primary objective of this research is to comprehensively analyze the harmonic generation phenomenon caused by Variable Frequency Drives (VFDs) and to propose effective mitigation techniques to alleviate the associated power quality issues. Specifically, the research aims to:

- Investigate the fundamental mechanisms of harmonic generation by VFDs, elucidating the role of switching devices and modulation techniques in shaping harmonic spectra.
- Evaluate the impact of harmonic currents on power distribution networks and connected equipment, quantifying voltage distortion, increased losses, and potential resonances.
- Develop and assess various harmonic reduction techniques, to mitigate the adverse effects of VFD-generated harmonics.
- Perform extensive simulations using advanced software tools, such as MATLAB/Simulink and ETAP, to validate the effectiveness of proposed harmonic mitigation strategies.
- Compare the technical and economic feasibility of different mitigation techniques, considering factors such as cost, implementation complexity, and compatibility with existing systems.
- To provide recommendations and guidelines for selecting appropriate harmonic mitigation strategies for VFD systems in different industrial applications, considering both technical effectiveness and economic considerations.

4. HARMONIC GENERATION BY VARIABLE FREQUENCY DRIVES (VFDS)

The proliferation of Variable Frequency Drives (VFDs) in industrial applications has ushered in a new era of energy-efficient motor control and process optimization[13]. These sophisticated electronic devices offer precise speed control and enhanced energy savings, making them indispensable components in modern manufacturing and automation systems[14]. However, their widespread adoption has also introduced a formidable challenge in the form of harmonic generation, significantly impacting the power quality of electrical distribution networks[15]. Harmonics, which are integer multiples of the fundamental frequency, can lead to detrimental effects on power systems, causing voltage distortion, overheating of transformers and cables, resonance conditions, and interference with sensitive equipment. The non-linear switching behavior of VFDs produces these harmonics, propagating them into the power grid and affecting nearby loads. As a result, a comprehensive understanding of the harmonic generation phenomenon by VFDs is imperative to ensure the reliable and efficient operation of industrial systems.

This paper delves into an in-depth exploration of the harmonic generation mechanisms induced by VFDs. It investigates the intricate interplay between VFD control strategies, switching devices, and modulation techniques that contribute to the emission of harmonics. By scrutinizing these factors, the paper aims to shed light on the underlying causes of harmonic distortion, facilitating the development of effective mitigation strategies. Through simulation studies and analytical investigations, the paper will quantify the extent of harmonic generation by VFDs and its impact on power quality. Moreover, it will propose and assess a spectrum of mitigation techniques to curb the adverse effects of harmonics. These techniques encompass both passive and active approaches, such as filters, phase-shifting transformers, and impedance-based solutions, providing a comprehensive toolkit for mitigating harmonic distortion.

The findings and insights presented in this paper will contribute to a deeper understanding of the harmonic generation phenomenon associated with VFDs and offer valuable guidance to engineers, researchers, and practitioners seeking to ensure the optimal operation of power systems while preserving power quality. By unraveling the intricacies of harmonic generation and its mitigation, this research endeavors to foster sustainable and reliable industrial practices in the presence of VFD-driven systems.

5. HARMONIC REDUCTION TECHNIQUES

In the pursuit of harmonics mitigation, various techniques have emerged as effective means to suppress harmonic distortions and improve power quality[16]. This section delves into a comprehensive examination of three prominent techniques: passive filters, active filters, and isolation transformers. These methods, which are extensively used to counteract the adverse impact of harmonics, offer distinct advantages and trade-offs based on their operational principles and applications.

- **Passive Filters:** Passive filters are a common approach to mitigating harmonics generated by VFDs[17]. These filters consist of passive components, such as inductors, capacitors, and resistors, that are carefully tuned to absorb specific harmonic frequencies[18]. Various configurations exist, including single-tuned and multi-tuned filters, which target specific harmonic orders. Passive filters offer simplicity and reliability but may require careful design and tuning to ensure optimal performance. They effectively attenuate targeted harmonics by introducing impedance that absorbs harmonic currents, preventing their propagation into the distribution system.
- **Active Filters:** Active harmonic filters employ advanced electronic circuitry to detect and generate anti-phase harmonic currents that neutralize the effects of harmonics. These filters are capable of real-time monitoring and adjustment, ensuring accurate harmonic compensation over a wide range of load conditions[19]. Active filters offer the advantage of adaptability, making them suitable for applications with varying loads and harmonics profiles. However, their higher complexity and cost compared to passive filters should be considered during selection[20].
- **Isolation Transformers:** Isolation transformers provide another avenue for harmonics mitigation. By introducing a phase shift between the primary and secondary windings, isolation transformers can attenuate certain harmonics in the output waveform[21]. This technique is particularly effective for mitigating specific harmonic orders that are known to cause resonance and instability in the system. Isolation transformers also offer the benefit of providing galvanic isolation between the load and the source, enhancing safety and reliability. However, their application may be limited by size, cost, and complexity[22].

In the upcoming sections, this paper will delve into a detailed analysis of the performance, advantages, and limitations of these techniques. Through simulation studies and empirical investigations, their effectiveness in reducing harmonic distortions will be rigorously evaluated. The obtained insights will equip practitioners and engineers with valuable information for selecting the most appropriate technique based on their specific operational requirements and harmonic profiles.

6. SIMULATION TOOLS AND METHODOLOGY

The accurate assessment of harmonic reduction techniques necessitates a robust and reliable simulation framework. In this section, the simulation tools and methodology employed for the comprehensive analysis of the selected techniques are discussed. The methodology provides insights into how the simulations were set up, the parameters considered, and the expected outcomes.

6.1 Simulation Tools: MATLAB/Simulink and ETAP (Electrical Transient Analyzer Program) software platforms were used in this study to simulate and analyze the impact of harmonic reduction techniques. MATLAB/Simulink facilitated the creation of detailed system models, enabling precise representation of power electronic devices, motor drives, and associated control strategies. This allowed for investigating the complex interactions between different components within the system. Additionally, ETAP was employed for results validation and verification[23]. ETAP's comprehensive library of power system components, harmonics analysis capabilities, and support for industry standards such as IEEE 519 made it an invaluable tool for assessing the effectiveness of harmonic mitigation techniques in practical power systems[24].

6.2 Methodology:

- **System Modeling:** The power distribution system, including VFDs, motors, transformers, and other components, was accurately modeled using MATLAB/Simulink. The simulation model captured the transient and steady-state behaviors of the system, considering parameters such as impedance, load profiles, and control strategies.
- **Harmonic Analysis:** Harmonic analysis was conducted to quantify the harmonic distortion present in the system under different operating conditions. The harmonic orders, total harmonic distortion (THD), and individual harmonic magnitudes were calculated to assess the extent of harmonic pollution.
- **Technique Implementation:** Various harmonic reduction techniques, such as passive filters, active filters, and isolation transformers, were incorporated into the simulation model. The behavior of these techniques was evaluated by observing their impact on the harmonic content of the system.
- **Results Validation:** The simulation results were validated using ETAP software. The same system configuration and parameters were replicated in ETAP to ensure consistency between the simulation tools. Any discrepancies or deviations between the two platforms were carefully analyzed to ensure accurate results.
- **Performance Assessment:** The effectiveness of each harmonic reduction technique was assessed based on its ability to mitigate harmonic distortions. Parameters such as THD reduction, voltage and current waveforms, and compliance with relevant standards (e.g., IEEE 519) were used to quantify the performance of the techniques.

- **Parametric Analysis:** Sensitivity analyses were performed to evaluate the influence of varying parameters, such as load levels, system impedance, and control settings, on the performance of the harmonic reduction techniques.

By following this methodology, the study aims to provide a comprehensive understanding of the behavior of different harmonic reduction techniques and their impact on power quality. The combination of MATLAB/Simulink and ETAP software ensures robustness, accuracy, and practical applicability of the results obtained.

7. RESULTS AND ANALYSIS

This section presents the findings of extensive simulation studies, assessing various harmonic reduction techniques' efficacy in mitigating the adverse impacts of Variable Frequency Drives (VFDs) on power quality.

The system model used in the MATLAB/Simulink program is depicted in Fig(1), outlining the subject under examination. The voltage and current waveforms of a 6-Pulse drive without mitigation are shown in Fig(2-a). Observing Fig(3-b), a substantial Total Harmonic Distortion Index (THDI) value (95.53%) highlights AC drives as potent harmonic sources within the electrical network, with the 5th, 7th, 11th, and 13th harmonics being dominant. This elevated THDI arises from the rectifier and inverter, which draw non-linear currents, distorting the source current waveform.

Conversely, Fig(3-a) reveals a lower Total Harmonic Voltage Distortion (THDV) due to source impedance effects. While the small THDV adheres to IEEE 519 (2014), addressing the exceeded standard for current distortion necessitates harmonic mitigation techniques. Fig(2-b) depicts the pulse-based voltage waveform resulting from high-frequency switching, while Fig(4-b) underscores a concerning voltage distortion (68.19%) at the motor side. This distortion risks insulation breakdown and motor failure due to increased dv/dt ratios. Fig(4-a) displays comparatively lower current distortion on the motor side, attributed to the high-frequency switching inverter technology's application.

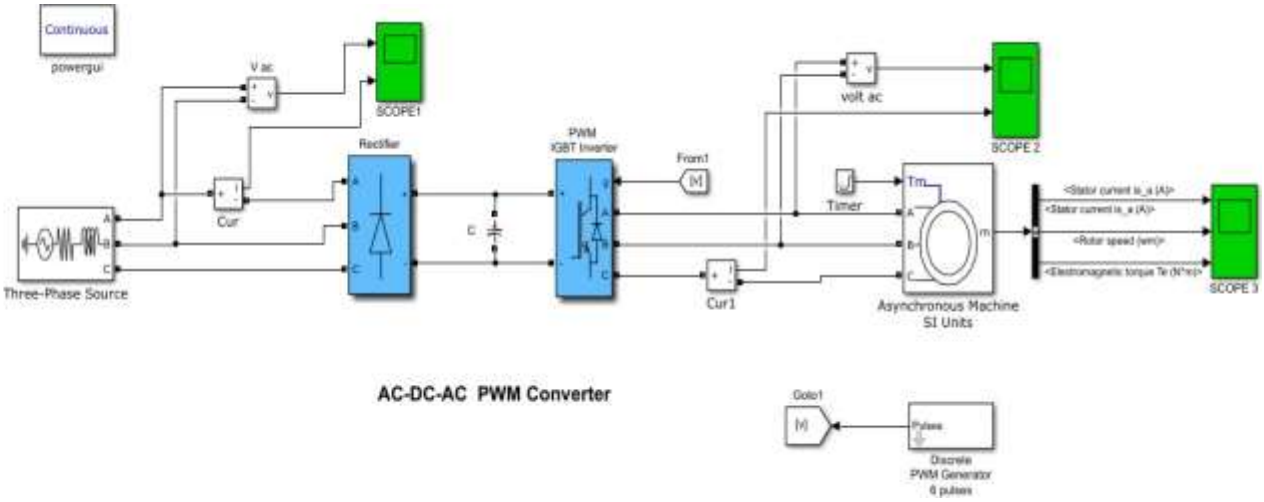
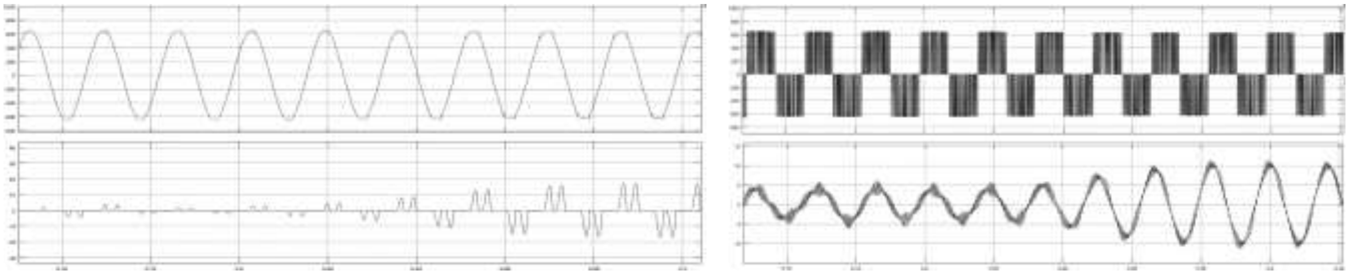


Fig. 1. *Model of VFD using MATLAB/Simulink program*

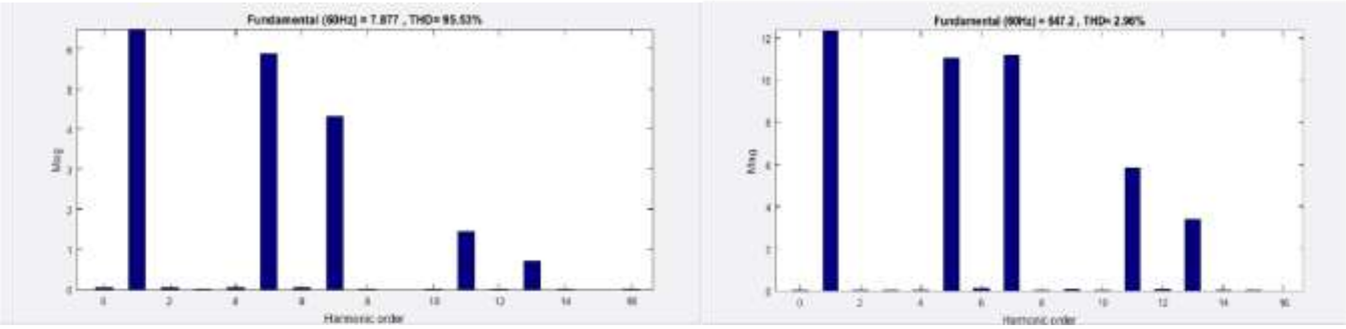


a.

a. voltage and current waveforms of supply side for 6-pulse VFD

b. voltage and current waveforms of the motor side for 6-pulse VFD

Fig. 2. *Voltage and current waveforms of supply and motor sides for 6 Pulse VFD*

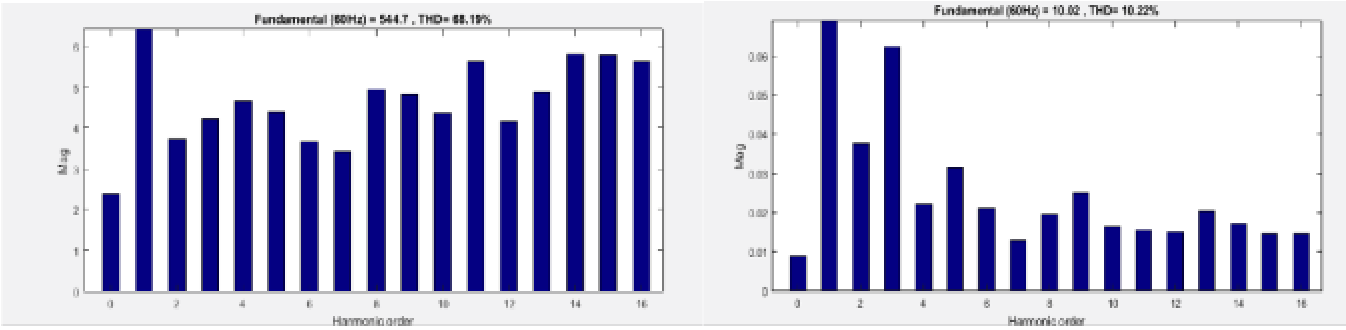


b.

a. Harmonic spectrum for current of supply side of VFD

b. Harmonic spectrum for voltage of supply side of VFD

Fig. 3. *Harmonic spectrums for voltage and current of the supply side of VFD*



c.

a. Harmonic spectrum for current of motor side of VFD

b. Harmonic spectrum for voltage of motor side of VFD

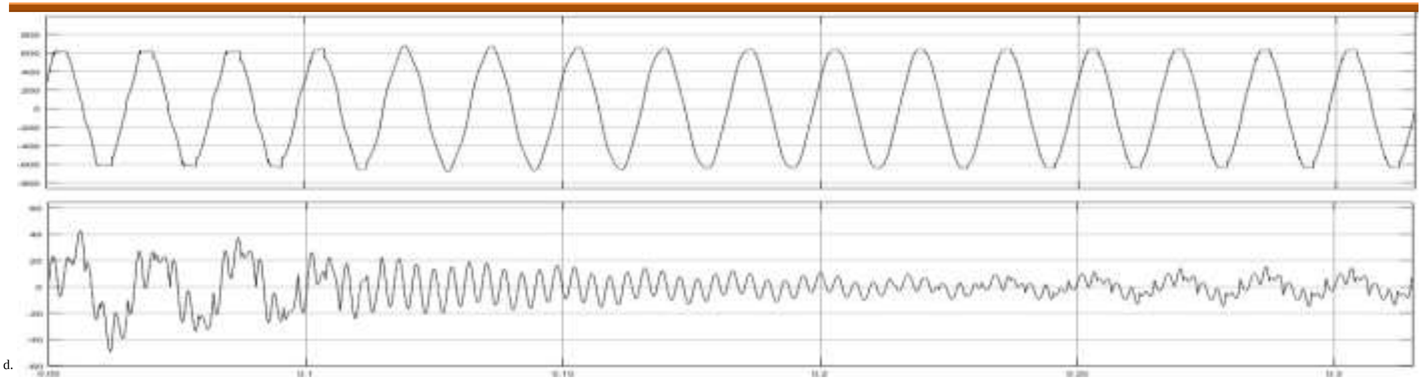
Fig. 4. *Harmonic spectrums for voltage and current of the motor side of VFD*

7.1 Harmonic Mitigation Strategies on the Supply Side

In our pursuit of mitigating harmonics, we have explored a range of methodologies that demonstrate their efficacy in addressing this issue.

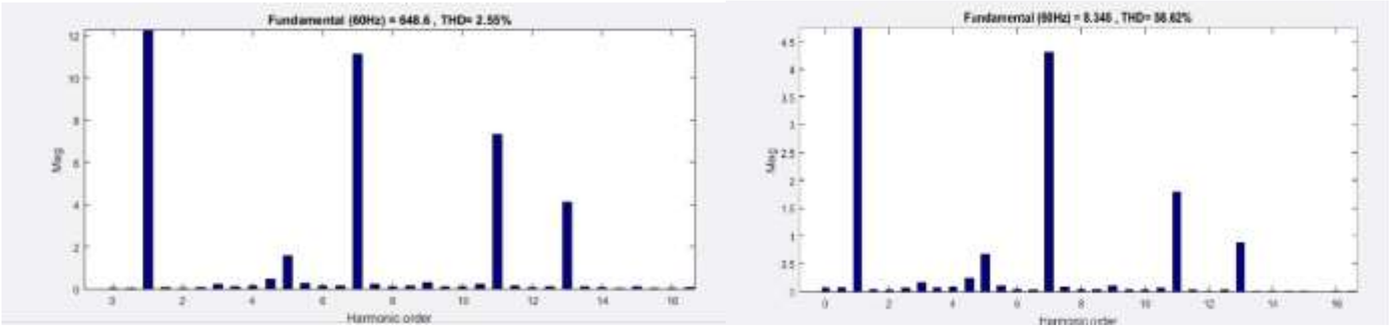
- **Passive Filters:** A cornerstone of our investigation lies in the deployment of passive filters, a time-honored technique for attenuating harmonics. Specifically, we focus on two distinct passive filtering methodologies:
    A. **Single-Tuned 5th Harmonic Filter:** Within this framework, a meticulous analysis of the current waveform yields illuminating insights. Fig(5) and Fig(6-b) underscored the transformation of the current waveform, manifesting marked enhancements in its shape. Notably, the Total Harmonic Distortion (THD) value, a critical metric in quantifying harmonics, witness a reduction from a formidable 95.48% to a more acceptable 58.62% upon integrating the 5th harmonic filter. Equally noteworthy is the manifestation of this improvement in voltage distortion (THDV), as evidenced by the decrease from 2.96% to 2.55%—a direct response to the decrease in harmonic current. A consequential decrease in the voltage distortion at the 5th harmonic resonates as well, diminishing from 10.71% to a mere 1.58%. To illuminate the efficacy of our filter, we present a comparative analysis in Fig(7), underlining its performance against an AC drive without any mitigation strategy. Notably, this analysis considers dominant harmonic orders—fundamental, 5th, 7th, 11th, and 13th—where the filter's pronounced impact on the 5th harmonic order is apparent, witnessed in the drop from 5.9 A to 0.67 A. It is prudent to note that marginal increases appear in the 11th and 13th harmonic orders.

    B. **Double-Tuned Filter:** Further enriching our repertoire, we delve into the deployment of the double-tuned filter, a construct constituted by two single-tuned filters tailored to specific harmonic orders. Delving into the current waveform, Fig(9) reveals an enhancement when juxtaposed with the unfiltered VFD waveform (Fig(2-a)). Upon analysis, Fig(10) endorses the double-tuned filter's efficacy in filtering both the 5th and 7th harmonics. The harmonic currents witness substantial reductions—from 5.9 A to 0.59 A for the 5th harmonic and from 4.33 A to 0.23 A for the 7th harmonic—underscoring the filter's adeptness. This influence also resonates modestly with other harmonic orders, evidenced by slight increments in the 11th and 13th harmonics. A distinct advantage emerges with the double-tuned filter: a parsimonious use of inductors, translating to cost efficiency. This attribute positions the double-tuned filter as a pragmatic preference, outshining the multi-arm single-tuned filter.



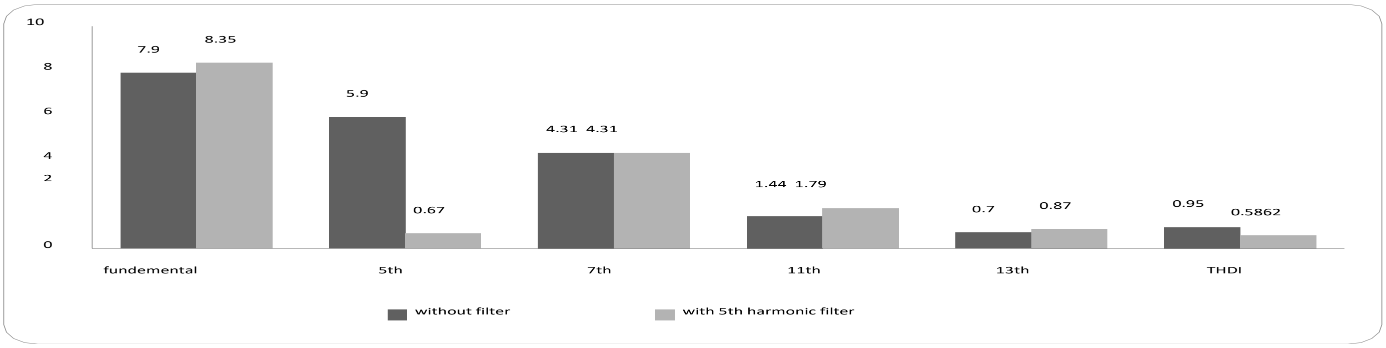
d.

Fig. 5. *Voltage and current waveforms for supply side with 5th harmonic filter installed*



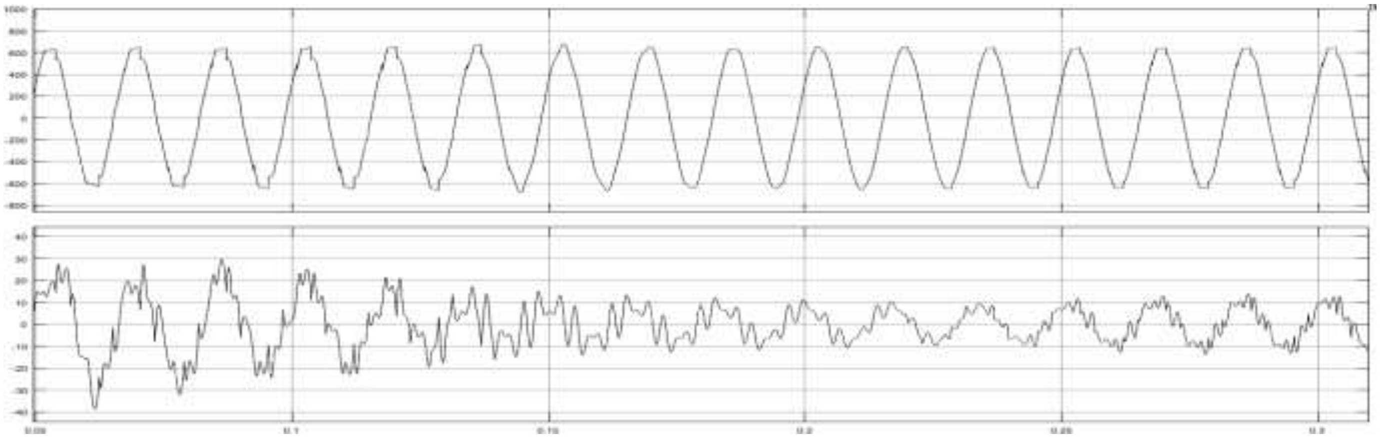
e. a. Harmonic spectrum for voltage b. Harmonic spectrum for current

Fig. 6. *Harmonic spectrum for voltage and current of supply side when a 5th harmonic filter is installed*



f.

Fig. 7. *Comparison of current harmonic orders with and without the 5th harmonic filter*



g.

Fig. 8. *Voltage and Current Waveforms for Supply Side with Double-Tuned Harmonic Filter*

h.

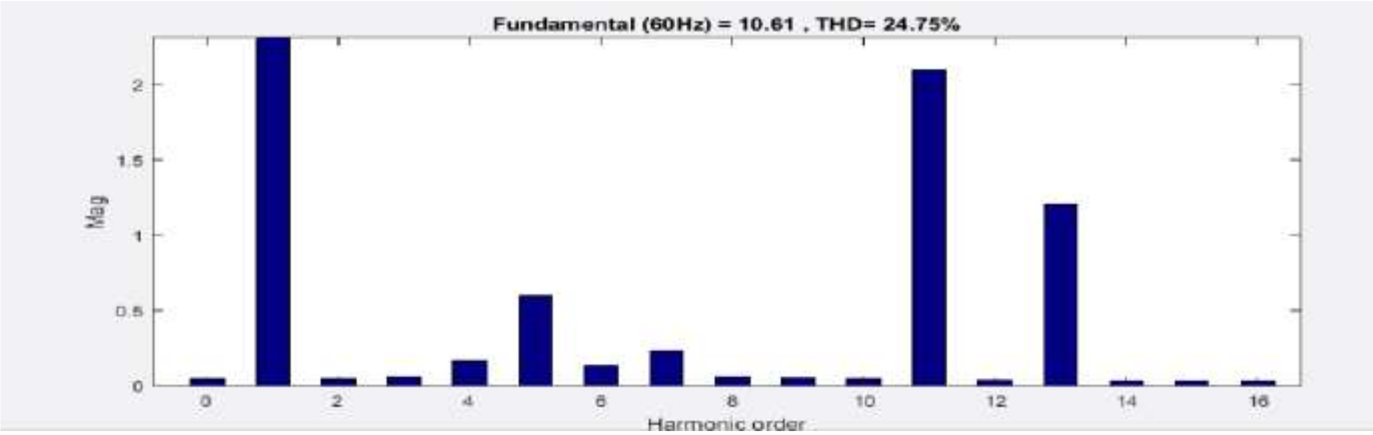


Fig. 9. *Harmonic spectrum of current for supply side with Double-Tuned harmonic Filter*

i.

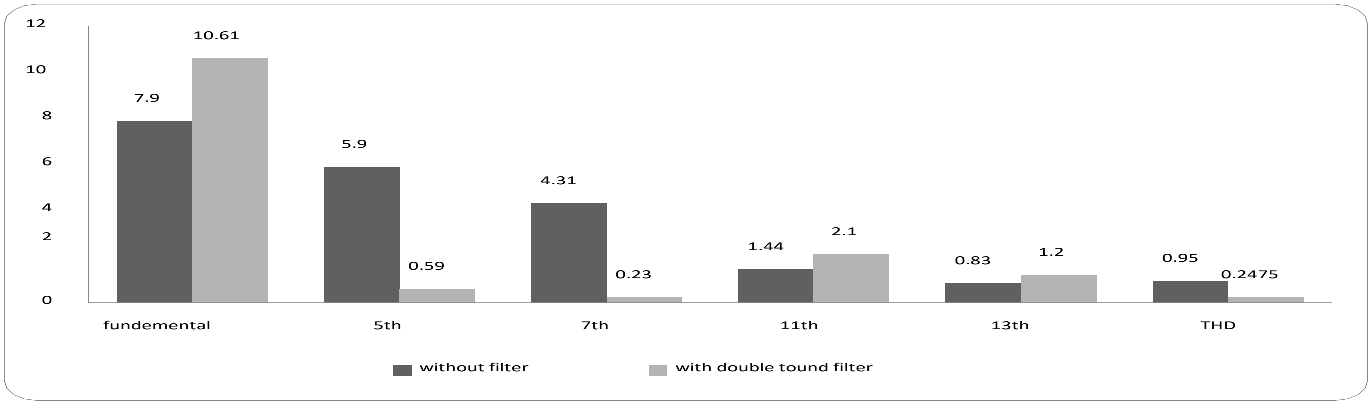


Fig. 10. *Comparison of current harmonic orders with and without Double-Tuned Harmonic Filter*

- **12-Pulse Drive:** An alternative avenue for the mitigation of harmonics resides within the realm of 12-pulse drives—a methodology that capitalizes on multi-rectifier configurations coupled with specialized transformers to orchestrate harmonics reduction. These intricate configurations facilitate the cancellation of lower-order harmonic amplitudes and emerge as a potent approach to harmonics management1. The realization of a 30° phase shift, imperative for the operation of the 12-pulse configuration, mandates the employment of DELTA-DELTA or DELTA-WYE transformers, a "ZigZag" transformer, or an auto-transformer2.

a) **Three-Phase Isolation Transformer:** Through meticulous design considerations, a three-phase three-winding transformer is harnessed from the MATLAB/Simulink sim power system library to forge the 12-pulse drive. Essential modifications are undertaken—aligning with a vector group of (D11) on the secondary—to elicit the requisite 30° phase shift. The primary and secondary voltages are calibrated to 460 V, imbuing the transformer with isolation transformer functionality. Fig(11) and Fig(12) chronicle the transformation, where the discernible enhancements in the current waveform underscore the substantial reduction of the prevailing 5th and 7th harmonic orders. Notably, the influence extends to the 11th and 13th harmonics, inducing a commensurate decrease in their magnitudes. Fig(13) magnifies this effect, revealing the augmentation of the fundamental current component alongside the dramatic reduction of the 5th and 7th harmonics. While total harmonic distortion (THD) manifests a significant decrease, it still falls short of the IEEE STD 519 threshold of 20%.

j.

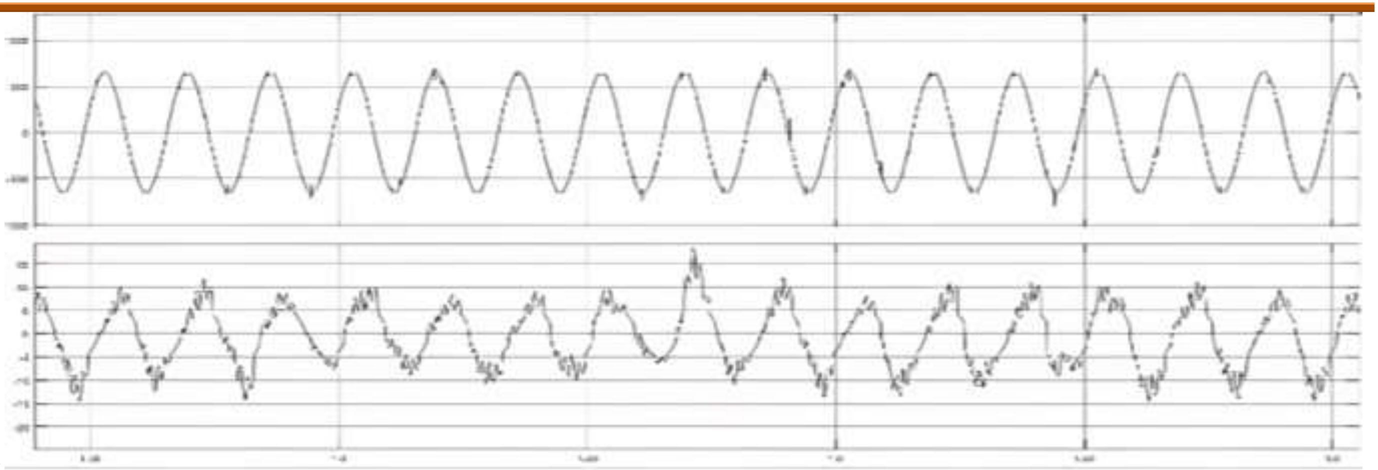


Fig. 11. *Voltage and current waveforms for the supply side with IsolationTransformer*

k.

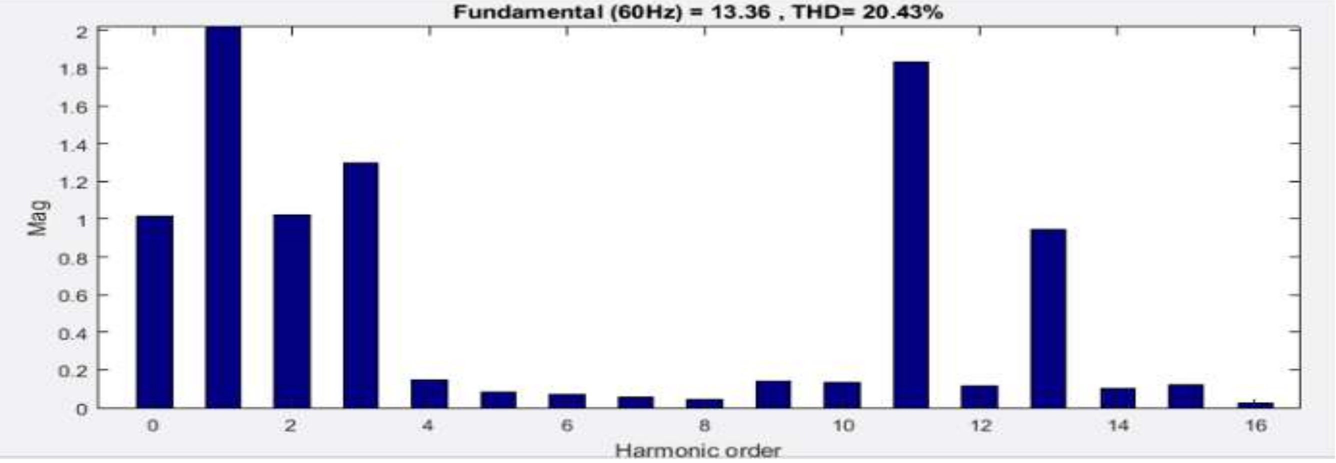


Fig. 12. *Harmonic spectrum of current on the supply side with Isolation Transformer*

b) **Three-Phase ZigZag Shifting Transformer:** The efficacy of phase shifting in the ZigZag transformer configuration is palpably evident in Fig(14), wherein the waveform's improved contour substantiates the cancellation of lower-order harmonics. Our analysis intensifies as we probe the outcomes of these methods through Fig(15) and Fig(16). The transformative influence of phase shifting using the ZigZag transformer springs to life, delivering a precipitous reduction of the THDI from 95% to 9.75%. The elimination of the 5th and 7th harmonics leaves the spotlight on the 11th and 13th harmonics. This technique capitalizes on the antagonistic phase relationship of positive and negative harmonics, along with the nullification of zero sequence harmonics, resulting in a substantial cancellation of harmonic orders.

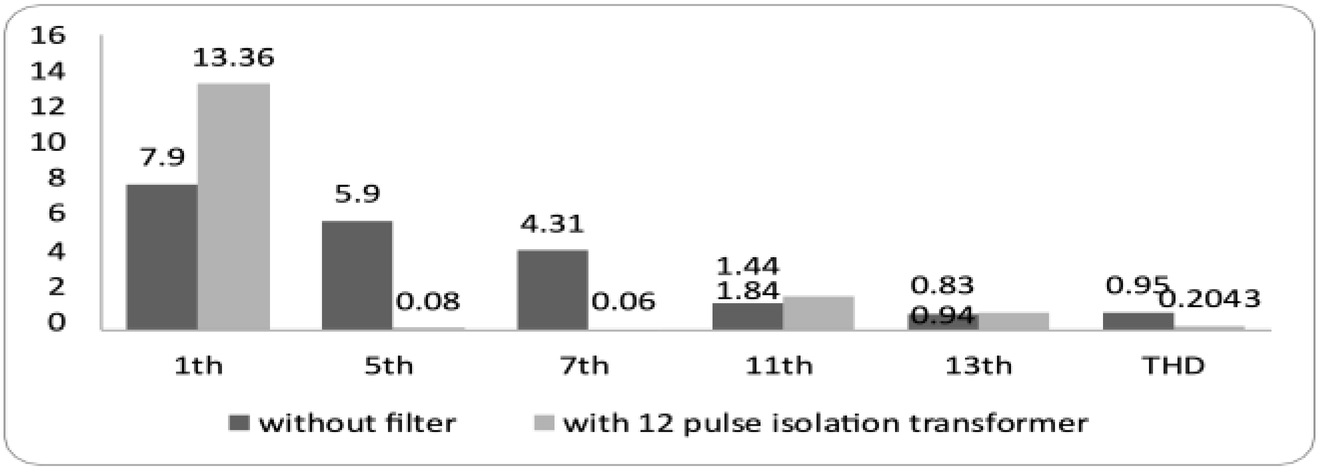
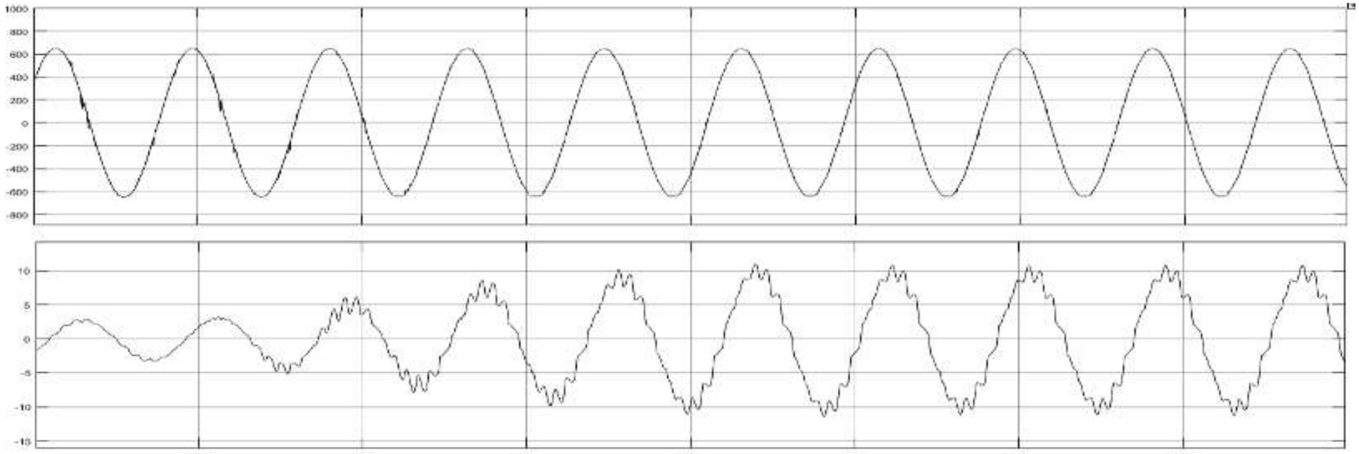
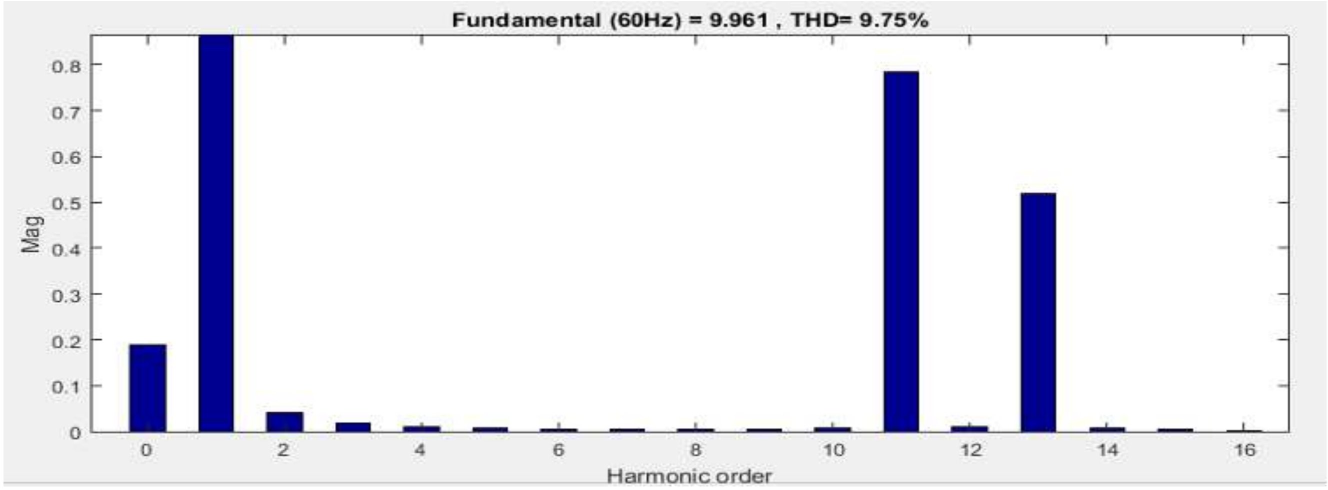


Fig. 13. *Comparison of current harmonic orders with and without an Isolation Transformer*



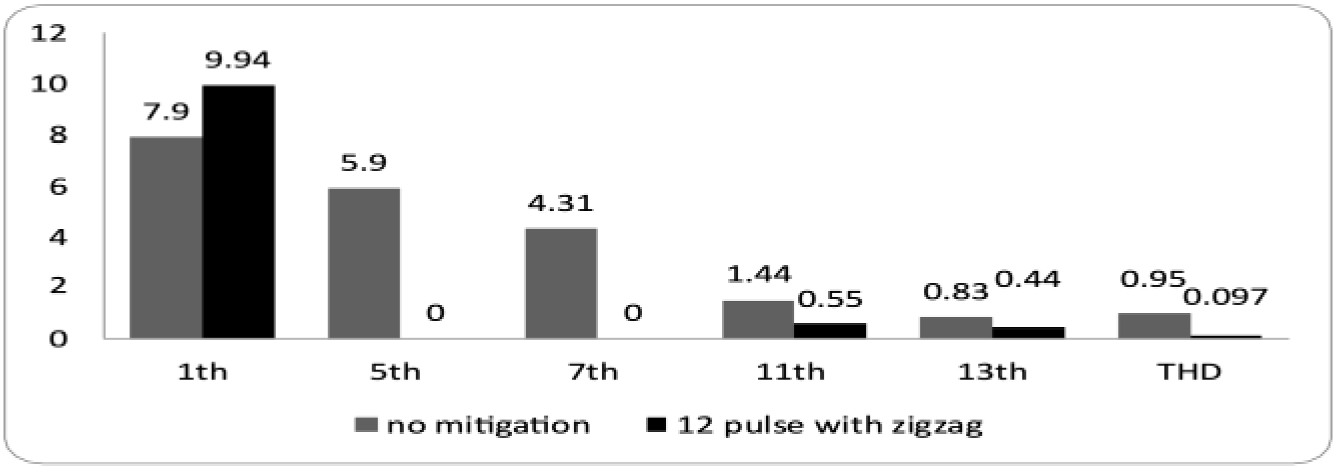
l.

Fig. 14. *Voltage and current waveforms for the supply side with ZigZag Shifting Transformer*



m.

Fig 15. *Harmonic spectrum of current on the supply side with ZigZag Shifting Transformer*



n.

Fig. 16. *Comparison of current harmonic orders with and without a ZigZag Shifting Transformer*

7.2 The implication of Switching Frequency:

Pulse Width Modulated (PWM) inverters, intrinsic to Variable Speed Drives (VSDs), command high-frequency switching to effectuate a refined output current waveform. This is particularly realized through the deployment of power MOSFETs in VSD applications spanning the 300–600volt spectrum. Renowned for their swift switching capabilities (ranging from 10 nsec to 100 nsec), power MOSFETs render themselves indispensable for switching frequencies within the gamut of 30kHz to 1GHz. In a parallel vein, Insulated Gate Bipolar Transistors (IGBTs) emerge as a robust contender, adroitly servicing 3-phase AC VSDs rated up to 500 kW at 380 V/415 V/480 V. These versatile devices accommodate switching frequencies extending up to 100kHz1. Ultimately, the discerning choice between power MOSFETs and IGBTs warrants considerations of power handling capacities and switching swiftness. Noteworthy is the discernible impact of escalating switching frequency, effectuating a conspicuous reduction in the Motor Total Harmonic Distortion Index (THDI).

7.3 Comprehensive Comparative Analysis

The culmination of this extensive investigation resides within a comprehensive comparative analysis that focuses on four specific harmonic reduction techniques: Single-Tuned 5th Harmonic Filter, Double-Tuned Filter, Three-Phase Isolation Transformer, and Three-Phase ZigZag Shifting Transformer. The culmination of these efforts is distilled into Table 1, meticulously assembling the exhaustive assessment of the various mitigation strategies undertaken in this research.

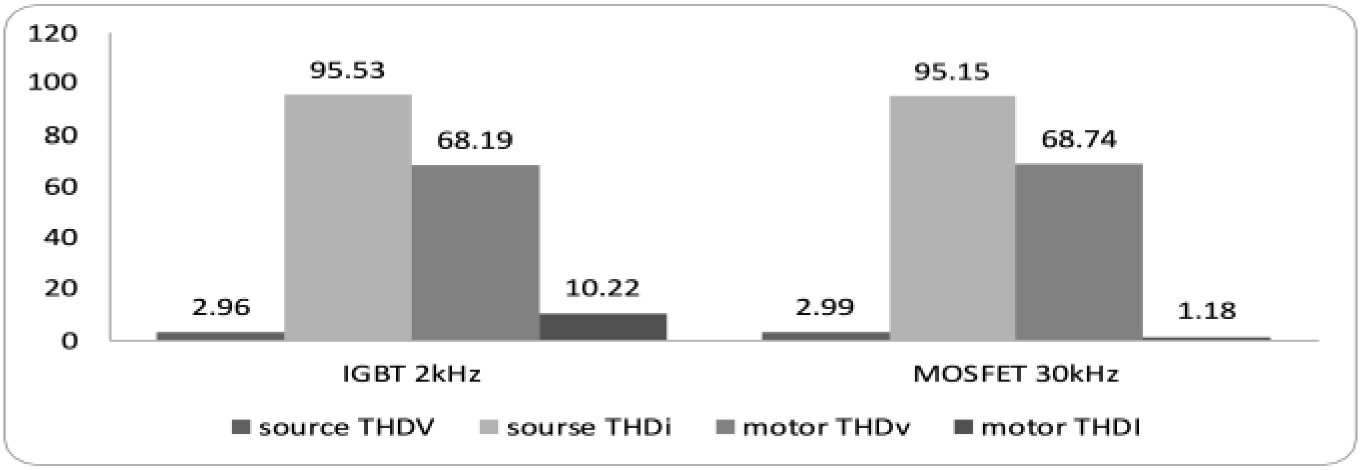
Table 1 encapsulates the essence of the comprehensive chart that was meticulously curated, providing a visual representation of the outcomes and intricacies of the diverse methodologies explored. Fig (18-a) illustrates the outcomes, revealing nuanced insights into the performance of these techniques.

The study underscores that single-tuned passive filters targeting specific harmonic orders (such as 5th or 7th) not only fall short of meeting IEEE STD 519 standards but also exhibit suboptimal performance, possibly leading to system resonance. However, their efficacy improves when extended to address multiple harmonic orders—particularly the 5th, 7th, 11th, and 13th. This extended configuration not only absorbs tuning harmonics effectively but also offers the advantage of mitigating harmonics across multiple interconnected drives sharing a common bus bar. This observation is further corroborated through verification using ETAP software.

Fig (18-a) highlights the remarkable efficiency of the 12-pulse drive coupled with an isolation transformer in substantially reducing harmonic current distortion. However, this configuration necessitates the inclusion of a DC link reactor to optimize performance, which introduces additional costs.

The study reveals that the most significant harmonic reduction is achieved through strategic integration of a 12-pulse drive phase-shifted with a zigzag transformer. This collaboration results in a remarkable reduction of THDI from an initial 95% to an impressive 9.7%. Nonetheless, economic considerations warrant attention. While 12-pulse drives demonstrate outstanding technical efficacy, their adoption is tempered by substantial expenses.

Highlighting economies of scale, double-tuned filters offer a more cost-effective option compared to single-tuned filters. A critical advantage lies in the immunity of reactors L1 and L2 to supply-line factors, as previously discussed in the methodology section.



o.

Fig. 17. Comparison between MOSFET and IGBT and the effect of their switching frequency range on THD of voltage and current

Table 1: Dominant current harmonic orders and their corresponding THD values for All mitigation techniques

Mitigation Technique	**Current Harmonic Orders and Their Corresponding THD Values**					
	Fundamental	***5th***	***7th***	***11th***	***13th***	***THD***
Without mitigation	7.9	5.9	4.31	1.44	0.7	95%

Mitigation Technique	**Current Harmonic Orders and Their Corresponding THD Values**					
	Fundamental	***5th***	***7th***	***11th***	***13th***	***THD***
5th Filter	8.35	0.67	4.31	1.79	0.87	58.62%
Double Tunedfilter	10.61	0.59	0.23	2.1	1.2	24.75%
12 pulse	13.36	0..08	0.06	1.84	0.94	20.43%
12 pulse Zigzag	9.94	0	0	0.55	0.44	9.7%

7.4 Results Verification through ETAP Software

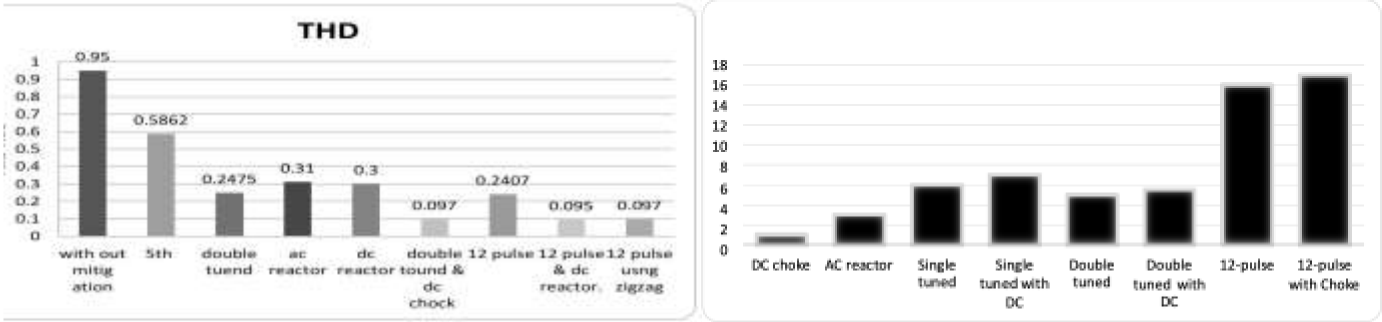
In this segment, the validation of outcomes derived from the MATLAB/Simulink model will be conducted via the utilization of the ETAP software. The chosen system parameters are consistent with the model, encompassing a 5 HP motor rated at 0.46 KV grid voltage, accompanied by a short-circuit capacity of 1 MVA—a congruence mirroring that of the MATLAB/Simulink framework. Within the harmonic domain of the VFD, the THOSHIBA harmonic library stands as the designated reference.

Fig (19-a) below presents a visual juxtaposition of voltage and current harmonic distortions. Evidently, the THDI value obtained through this drive surpasses the corresponding value derived from the MATLAB/Simulink model. This discrepancy arises from ETAP's utilization of distinct manufacturer-provided libraries tailored to specific drive harmonics—thus engendering variances in harmonic distortion.

Fig (20-a) offers a compelling visual alignment, portraying a current waveform akin to that ascertained via MATLAB/Simulink modeling.

Foraying into the harmonic spectrum, Fig (20-b) unfurls, elucidating the prevalence of the 5th and 7th harmonics as the preeminent contenders, echoing the observations discerned within the 6-pulse VFD scenario.

A telling revelation emerges from Fig (19-a), vividly illustrating the pronounced ramifications induced by the introduction of a VFD into the system. The harmonics cascade through the system, engendering voltage distortion across various bus bars. Notably, the magnitude of this voltage distortion transgresses the stipulated threshold articulated by the (IEEE STD 519).



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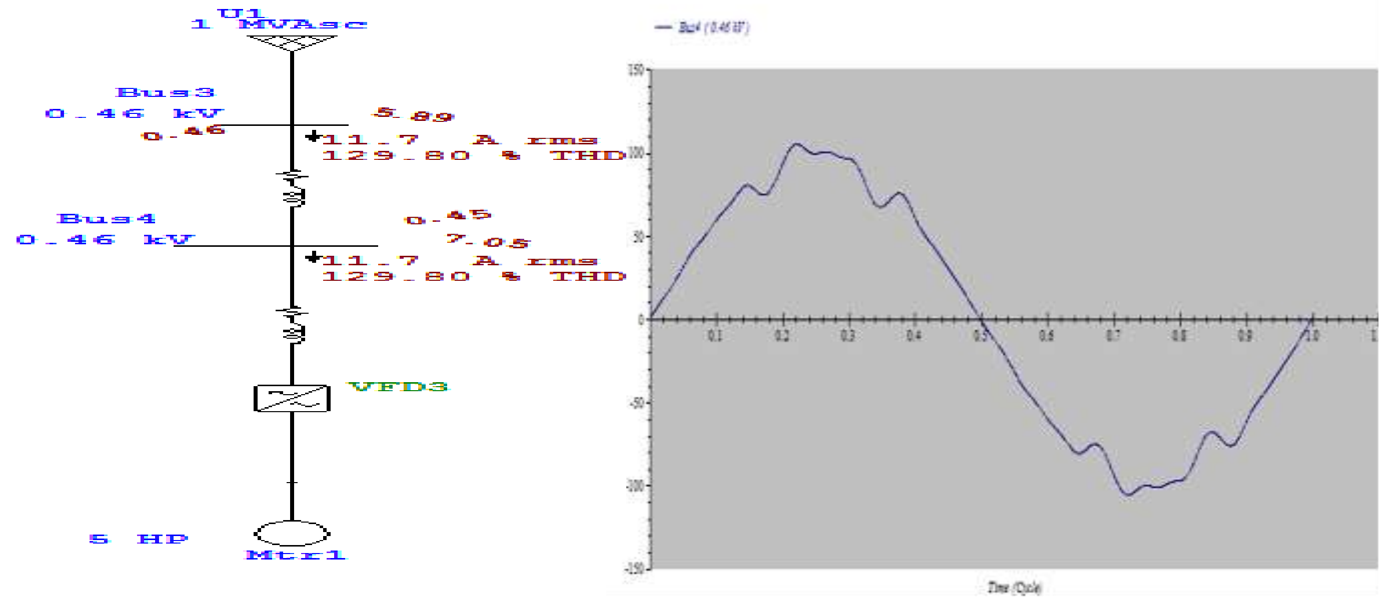
a. Comparison of THDI values

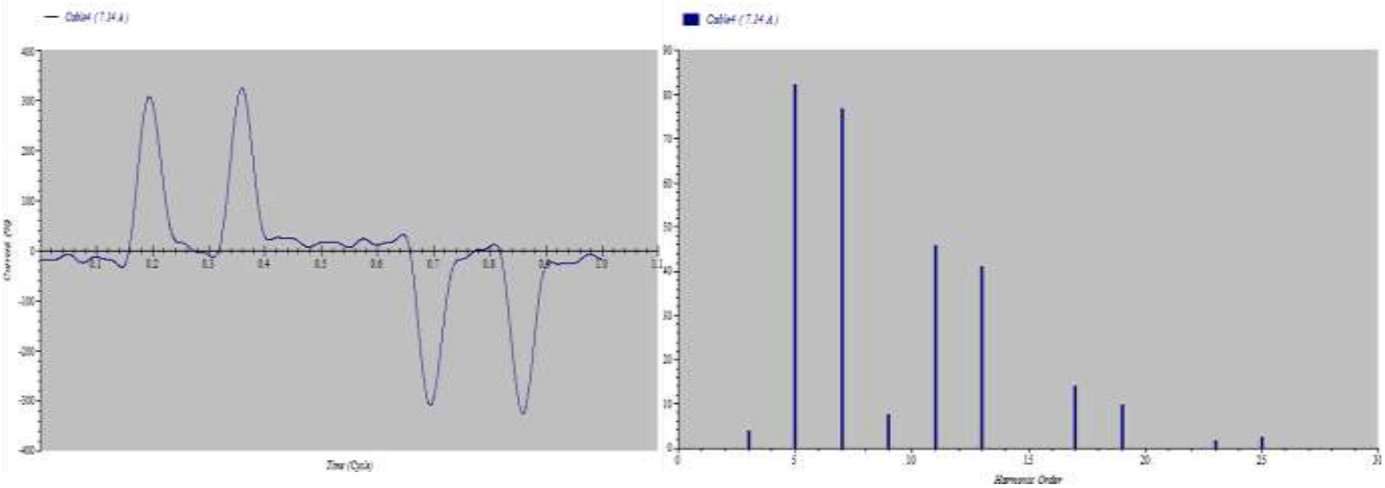
b. Comparison of typical costs

Fig. 18. *Comparison of THDI values & typical costs for all mitigation techniques*



q. a. VFD Connected to a 5 HP Motor with Load Flow of the System b. Voltage waveform at bus bar 4

Fig. 19. *VFD connected to a 5 HP Motor with load flow of the system & voltage waveform at Bus Bar 4*



r. a. Current waveform on cable 4 b. Harmonic spectrum for current on cable 4

Fig. 20. *Waveform & Harmonic spectrum of current on cable 4*

7.5 Harmonic Attenuation Utilizing ETAP Software:

A comprehensive analysis of harmonic distortion within a multi-VFD system has been conducted. The model encompasses a configuration comprising 10 motors under the governance of 10 VFDs. This intricate framework features two transformers: a utility transformer performing a downstep from 33KV to 11KV, and a user transformer further reducing the voltage to 0.46KV. The intersection point, denoted as T1, is situated at the utility transformer, imposing a stringent mandate that the harmonic distortion at this juncture remains within the confines stipulated by the (IEEE STD 519) standard. Construction of the proposed model was realized via the ETAP software, engendering a platform for in-depth harmonic analysis. The outcomes of this endeavor are depicted in Fig (21). Subsequent scrutiny of Fig (24-b) and Fig (25) underscores the dominance of select harmonics within the system, notably the 5th, 7th, 11th, 13th, 17th, and 19th harmonics. The current demand of 77.2 A and a power factor of 85.2% are manifested at bus 3, coupled with a system reactive power requisition of 61 KVAR. Evidently, applying a 12-pulse system proves cost-prohibitive given the context, rendering it an impractical recourse. Moreover, the system's augmented reactive demand necessitates a more judicious approach. Herein, the multi-arm passive filter emerges as the preferred countermeasure, effectuating reactive power compensation and power factor enhancement. Application of the multi-arm passive filter is meticulously executed through ETAP's filter design tool.

Upon installation of the multi-arm filter, discernible improvements materialize, as delineated in Fig (22-b) and Fig (23-b). Fig (24-b) encapsulates the remarkable diminution in harmonic current across the system, as the THDI plunges from 120% to a mere 3.78%—a conformity that demonstrably adheres to the stipulations mandated by (IEEE STD 519).

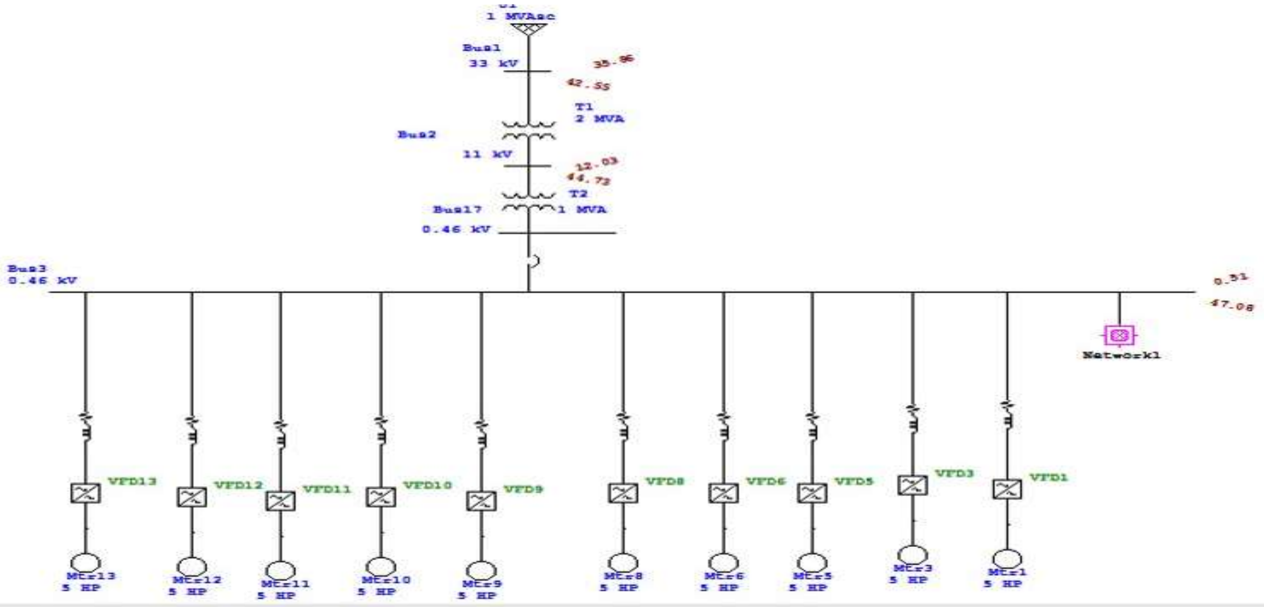
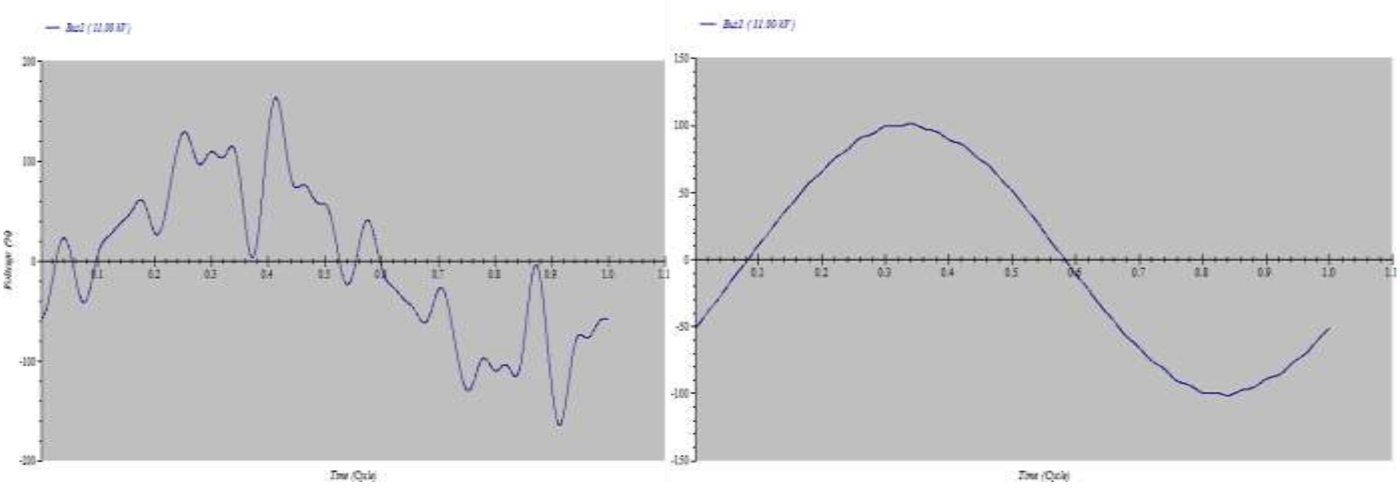


Fig. 21. *ETAP model of the proposed 10 motors system*

Table 2: Voltage distortion of different Bus Bars in the system

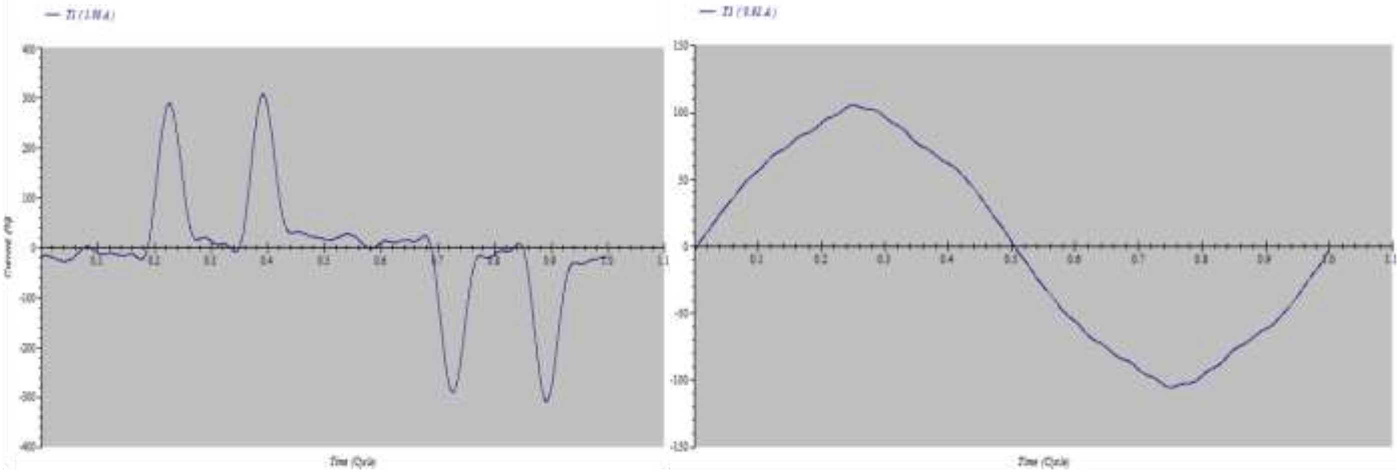
Bus Bar	**Voltage distortion**
Bus 3	47.08%
Bus 7	47.08%
Bus 2	44.73%
Bus 1	42.55%



a. Voltage Waveform at Bus 2 Before Filters Implementation

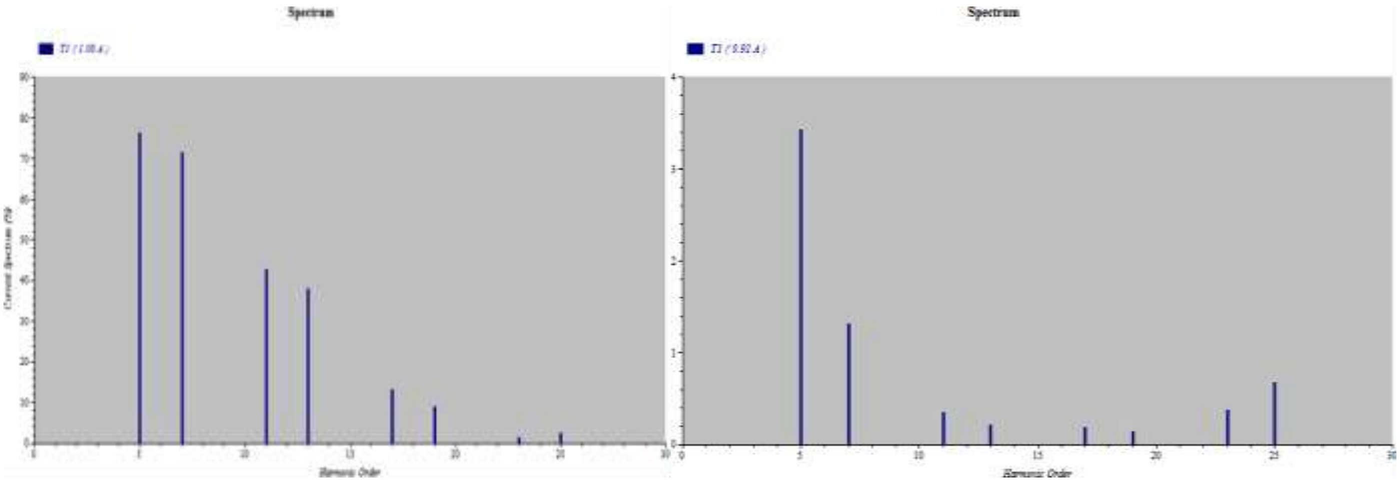
b. Voltage Waveform at Bus 2 After Filters Implementation

Fig. 22. *Voltage waveform at Bus 2 before and after Filters implementation*



u. a. Current waveform at (T1) before Filters implementation b. Current waveform at (T1) after Filters implementation

Fig. 23. *Current waveform at Utility transformer (T1) before & after Filters implementation*

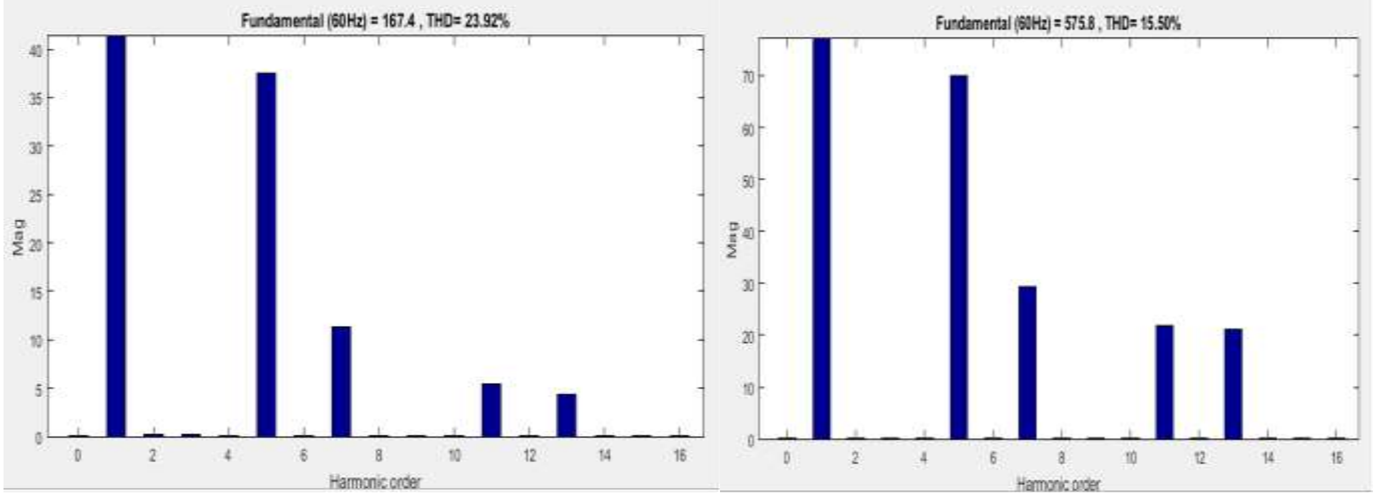


v. a. Harmonic spectrum of current at (T1) before Filters implementation b. Harmonic spectrum of current at (T1) after Filters implementation

Fig. 24. *Harmonic spectrum of current at Utility transformer (T1) before & after Filters implementation*

7.6 Impact of Motor Rating on Harmonic Characteristics

An exploration into the influence of motor size on harmonic behavior necessitates the scrutiny of a distinct motor configuration, simulated through MATLAB/Simulink. In this context, a 100 HP motor was chosen as the subject of examination. Employing FFT analysis, the aggregate harmonic distortion of both voltage and current was meticulously unveiled. Fig (25-a) lucidly illustrates the harmonic spectrum of the current pertaining to the 100 HP motor. Within Fig (25-a), a discernible escalation in harmonic current values relative to the 5 HP motor scenario is evident, stemming from the 100 HP motor's heightened demand for nonlinear current from the supply. Intriguingly, the overall harmonic distortion exhibited by this motor manifests as lower in comparison to its 5 HP counterpart. Conversely, as depicted in Fig (25-b), the Total Harmonic Distortion Voltage (THDV) attains a value of 15.5%, which supersedes the THDV associated with the 5 HP motor. Furthermore, Fig (26) elucidates the evolving waveform characteristics. While the voltage waveform assumes a less sinusoidal contour—attributed to the increased THDV compared to the 5 HP motor—the current waveform displays noticeable enhancement. This amelioration is attributed to the reduction in Total Harmonic Distortion Current (THDI), which descends from 95.53% to a commendable 23.93%.

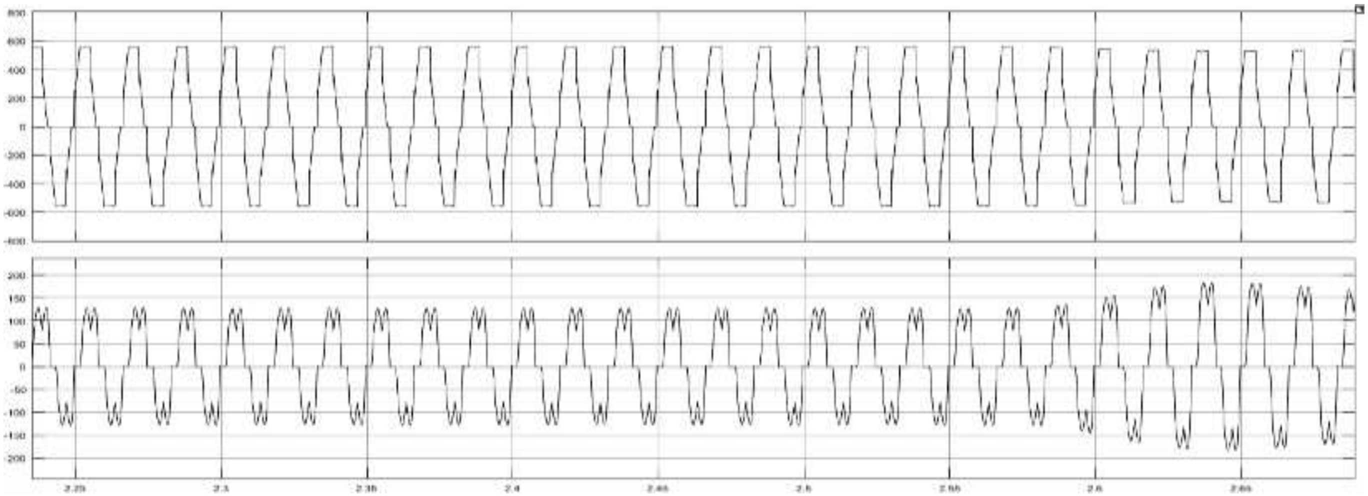


w.

a. Harmonic spectrum of current to 100 HP motor.

b. Harmonic spectrum of voltage to 100 HP motor.

Fig. 25. *Harmonic spectrum of current & voltage to 100 HP motor*



x.

Fig. 26. *Voltage and current waveforms of 100 HP motor*

7 CONCLUSION

In this comprehensive investigation, we embarked on a meticulous exploration of various techniques to mitigate the adverse impact of harmonics generated by Variable Frequency Drives (VFDs) on power quality. Our examination focused on Single-Tuned 5th Harmonic Filters, Double-Tuned Filters, Three-Phase Isolation Transformers, and Three-Phase ZigZag Shifting Transformers, elucidating their efficacy through a rigorous analysis. The findings illuminated a nuanced landscape of harmonic reduction strategies, each possessing unique advantages and limitations.

The investigation unveiled that while Single-Tuned 5th Harmonic Filters exhibited limited success in harmonics mitigation, extending their scope to address multiple harmonic orders yielded improved performance. Nevertheless, these filters encountered challenges in meeting the rigorous IEEE STD 519 standards, necessitating further enhancements. Conversely, the integration of Double-Tuned Filters showcased an inherent cost-effectiveness and resistance to supply-line factors, making them a viable alternative for comprehensive harmonic reduction.

Remarkably, the amalgamation of a 12-pulse drive phase-shifted with a Three-Phase ZigZag Shifting Transformer emerged as the pinnacle of harmonic reduction. This synergistic pairing achieved an unprecedented reduction in Total Harmonic Distortion Index (THDI), redefining the standards of harmonic mitigation. However, it's crucial to consider the economic implications of these high-power solutions, as their implementation is associated with substantial costs. The impact of motor size on harmonic characteristics was examined, with a 100 HP motor displaying unique harmonic behavior compared to a 5 HP motor. Validation of results through ETAP software corroborated the findings, affirming the accuracy and applicability of the simulated models.

This study provides a holistic view of the multifaceted landscape of harmonic reduction techniques, shedding light on their performances, feasibility, and limitations. The insights garnered from this investigation are poised to inform decisions in the design and implementation of harmonic mitigation strategies, paving the way for enhanced power quality and reliable system performance in modern industrial contexts.

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