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Original Article

Performance Analysis and Harmonic Optimization of a 21-Level Cascaded H-Bridge Multilevel Inverter Using Low-Frequency Modulation Techniques

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Abstract - *The increased application of renewable energy sources requires advanced power electronics for efficient energy conversion and grid integration. Multilevel inverters, particularly the Cascaded H-Bridge Multilevel Inverter (CHMLI), are leading contenders supplying high-quality power for medium- and high-voltage applications. The 21-level CHMLI offers scalability and high harmonic suppression, which makes it particularly suitable for renewable energy systems, industrial drives, and smart grids. The paper studies its performance using low-frequency modulation techniques to minimize THD. The simulation results show a significant reduction of harmonics with THD, which is as low as 0.35% current and 0.73% in voltage. Using unequal DC sources and LC filtering also improves efficiency, confirming the inverter's ability to handle complex loads. These results highlight significant optimizations for renewable energy applications at high power.*

Keywords - *Cascaded H-Bridge Multilevel Inverter (CHMLI), Total Harmonic Distortion (THD) Minimization, Low-Frequency Modulation Techniques, Harmonic Suppression and Power Quality Enhancement*.

1. Introduction

The universal application of renewable energy systems has introduced a paradigm shift in power generation in modern times with the imposition of advanced power electronics for efficient energy conversion and integration into the grid. Of various power electronics technologies, Multilevel Inverters (MLIs) has emerged as a cornerstone for delivering high-quality power in medium- and high-voltage applications. Through the synthesis of multiple voltage levels, MLIs deliver minimized Total Harmonic Distortion (THD), enhanced power quality, and overall system efficiency improvement [1], [2].

Though there are advantages of MLIs, the challenge is to structure their modulation techniques in an optimal way to provide low harmonic distortion and switching loss with high reliability. Cascaded H-Bridge Multilevel Inverters (CHMLIs) are especially remarkable because they are constructed in a modular configuration to be extremely scalable to higher voltage levels without compromising operating simplicity and reliability [3]. Among CHMLIs, 21-level topology achieves superior harmonic suppression and excellent power quality. Therefore, it is a good contender for high-power applications such as renewable energy systems, industrial drives, and smart grids [4]. Optimal performance, however, requires efficient modulation techniques to minimize the switching losses and maximize efficiency.

Low-frequency modulation techniques have shown great promise to overcome these drawbacks by reducing the switching frequency of power electronic converters. The decreased switching frequency results in reduced thermal stress reduced Electromagnetic Interference (EMI), and increased reliability with better high-output waveform quality [5].

However, comprehensive performance analysis of CHMLIs using low-frequency modulation techniques, particularly for high-level configurations such as the 21-level inverter, is limited in the literature.

To bridge this, this paper presents a complete performance analysis of a 21-level CHMLI with low-frequency modulation techniques. From the comprehensive simulation studies carried out in MATLAB/SIMULINK, the study explores the output performance of the inverter, harmonic performance, and THD mitigation. It is revealed that the 21-level CHMLI possesses the potential to significantly enhance harmonic suppression and power quality, further solidifying its position as a key technology for future-generation high-power renewable energy systems.

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2. Literature Review

Multilevel inverters have drawn considerable research attention due to their benefits of THD reduction, power quality enhancement, and efficiency improvement in high-power drives [6]. Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB) are some of the most popular topologies of MLIs that have been addressed in the literature. CHMLIs are scalable and modulated and, therefore, a preferred option for renewable energy systems.

A few of these modulation strategies have been designed to maximize the performance of the MLI. SPWM and SVPWM are two of the high-frequency PWM methods widely used to improve the waveform quality of the output [7]. The techniques generate high switching losses, thermal stress, and electromagnetic interference, thus decreasing the reliability of power electronic devices [8].

In order to solve such issues, low-frequency modulation techniques have been used in research. FFM and SHE have been postulated as candidate solutions, and they provide decreased switching frequency along with good harmonic behavior [9]. Such schemes have been commonly applied to lower-level MLIs, but to higher-level complexes, such as 21-level CHMLIs, it still remains to be explored thoroughly [10].

Low-frequency modulation has been shown in recent research to increase the efficiency and lifespan of power converters dramatically. For example, in [10], comparative studies of various modulation methods for a 15-level CHMLI demonstrated the effectiveness of low-frequency methods in loss reduction and improvement of power quality.

The authors in [10] also explored a 17-level CHMLI and demonstrated that low-frequency modulation reduced switching transitions to achieve lower THD. However, limited work has been presented to measure the performance of 21-level CHMLIs with such modulation techniques.

This paper contributes to the literature by analysing the performance of a 21-level CHMLI with low-frequency modulation techniques. Based on MATLAB/SIMULINK simulations, the paper provides information on THD minimization, waveform quality, and inverter efficiency. The results indicate the potential of this technique in increasing the feasibility of CHMLIs for high-power renewable energy systems.

3. Working Principle of CHML

The Cascaded H-bridge multilevel Inverter (CHMLI) consists of several single-phase H-bridge inverter modules connected in series. Every H-bridge is fed by its own DC source (battery, solar panel, fuel cell, etc.). By modulating the switching states of the semiconductor devices (IGBTs/MOSFETs) of each H-bridge, the CHMLI generates several voltage levels, developing a stepped output waveform very close to a sinusoidal waveform.

$$n = 2m + 1 \qquad (1)$$

The number of levels (n) developed by the CHMLI is calculated using the following formula. m is the number of H-bridge units. Increasing the number of H-bridges reduces Total Harmonic Distortion (THD) and improves power quality, minimizing the need for bulky output filters. [11].

Each H-bridge unit consists of four semiconductor switches arranged in a full-bridge configuration, such as IGBTs or power MOSFETs, as shown in (Figure 1). The toggling states of these switches will enable the H-bridge unit to generate three different levels of output voltage at its terminals: +Vdc: When the upper-left and lower-right switches are turned ON. 0: When either both the upper and the lower switches are simultaneously turned ON. −Vdc: When the lower-left and upper-right switches are ON [12, 13].

The output voltage of each H-bridge unit is connected in series to synthesize a stepped waveform that approximates the sinusoidal waveform. The total number of output voltage levels (n) in a CHMLI is given as n = 2m + 1, where m is the number of H-bridge units. For instance, using three H-bridge units, the CHMLI can generate a 7-level output voltage waveform [14].

The stepped waveform is obtained by summing the output voltages of each H-bridge unit. Smoother waveforms are achieved for an increased number of levels, which reduces the THD. The voltage waveform generated by CHMLI is more like a sinusoidal waveform that results in the minimum requirement for bulky output filters, as shown in Figure 1 [15].

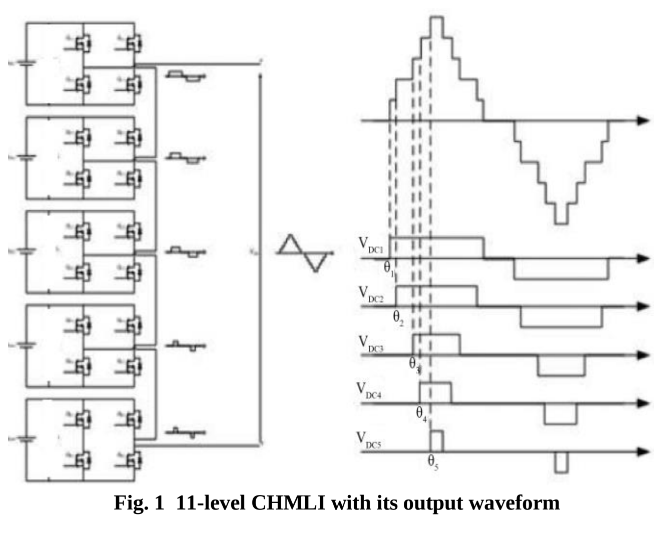

Fig. 1 11-level CHMLI with its output waveform

4. Low Frequency (Fundamental Frequency) Modulation Technique

This modulation technique operates at the fundamental frequency (e.g., 50 Hz), ensuring that each switch turns on and off only once per cycle. The key advantages include:
Lower switching losses: Reduces power dissipation in semiconductor switches.

Minimal thermal stress: Extends the lifespan of power electronics. Simplified control design: The gating signals are straightforward, reducing implementation complexity.

Lower EMI (Electromagnetic Interference): Due to fewer switching transitions.[16]. Every switch turns on and off once in a cycle, which greatly simplifies the design of the gating signal and minimizes the EMI. Under the MATLAB/Simulink environment, two pulse generators with a phase shift of 180° (10 ms for a 50 Hz cycle) are set to drive the four switches in every H-bridge unit. The phase-shifted triggering ensures that pairs of transistors switch on and off in an alternate manner for the right operation of the H-bridge [17-19]. This simplicity of the method is especially suited to applications requiring low harmonic content without resorting to high-frequency switching- a fact illustrated in Figure 2.

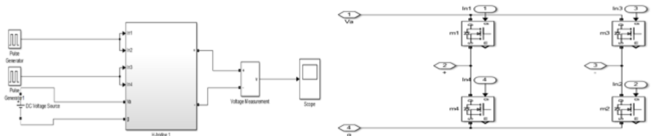

Fig. 2 Single H-bridge (cell) multilevel inverter with its control circuit-MATLAB/Simulink

5. Control Strategy

The CHMLI control strategy emphasizes: Phase-shifted switching: Maintaining alternating switching of transistor pairs. Voltage balancing: Equalizing the voltage at each H-bridge. Minimization of THD: Optimized switching patterns and filtering methods.

6. Parameter Design

Primary design parameters are the number of H-bridges (m), which determines the voltage levels and THD. DC source voltage Should be appropriately selected to ensure balanced operation. Switching devices: Choosing appropriate IGBTs/MOSFETs based on the power levels. Filter design: LC filters may be used to smooth the output waveform further. This approach ensures efficient power conversion, and consequently, CHMLI is utilized in high-power renewable energy systems, industrial drives, and smart grids.

7. Circuit Configuration

The three-phase 21-level Cascaded H-Bridge Multilevel Inverter circuit (Figure 3) includes a series L-C filter and an R-L load of 50 kVA at a power factor of 0.9. This is also a very efficient and flexible configuration, intended for medium to high-power applications, with ten H-bridge units connected in series per phase (Figure 4). This filter is used to dampen the high-frequency switching harmonics, improve the output voltage waveform quality, and reduce EMI. The R-L load of 50 kVA with a power factor of 0.9 ensures the system operates under realistic, inductive load conditions common in industrial applications. With the series connection of the H-bridge units, a 21-level inverter will give a voltage waveform that is nearly sinusoidal and will reduce THD compared with the conventional two-level inverter. The multi-level structure offers the possibility to improve the voltage regulation, increase the system's efficiency, and reduce the switching losses using the proper filtering and control techniques. This makes it scalable regarding the number of H-bridge units per phase, enabling a wider range of power demands and affording more flexibility in handling loads with optimal performance under varying operational conditions.

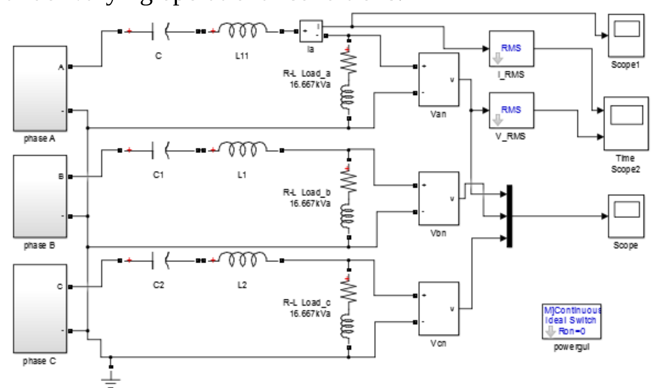

Fig. 3 Three-phase 21-level CHMLI circuit-MATLAB/Simulink

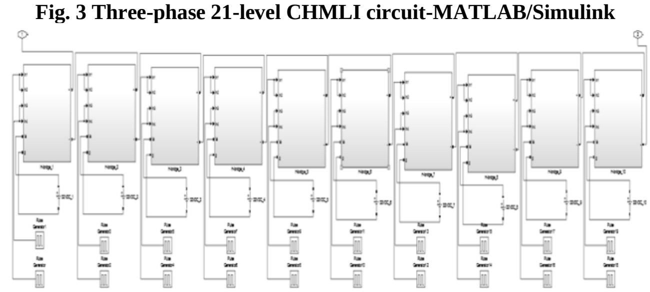

Fig. 4 single-phase 21-level CHMLI circuit controlled using low-frequency modulation technique-MATLAB/Simulink

8. Simulation Results

A 21-level Cascaded H-Bridge Multilevel Inverter will be used for validation, developed by implementing low-frequency modulation techniques. The system has been subjected to a pure resistive load, an R-L load, and a three-phase controlled rectifier under various load conditions. The simulation results for the same have been presented for comparison. As seen in (Figure 5), the output current of the 21-level inverter powered by the same DC sources (32V for each H-bridge) is observed without any filter and with the control of the low-frequency modulation technique. In this case, the THD of the resulting current is 61.94%, representing the expected harmonic content in the inverter output due to the previous conditions. (Figure 6) depicts the phase voltage, whose THD is 61.94%, proving the relation of current and voltage waveform quality within the system.

Under a load of 15 kW per phase, the RMS values of the phase voltage and line current measured are 150.09 V and 46.51 A, which proves that the system can deliver substantial power with relatively low switching frequency. These results prove theoretical predictions to be correct and thus validate the performance of the 21-level CHMLI for voltage, current, and harmonic content.

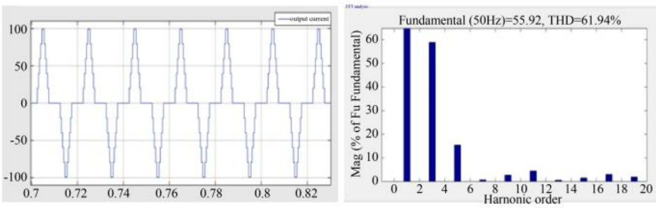

Fig. 5 The output current of a 21-level inverter with equal DC sources without filter (R-load)

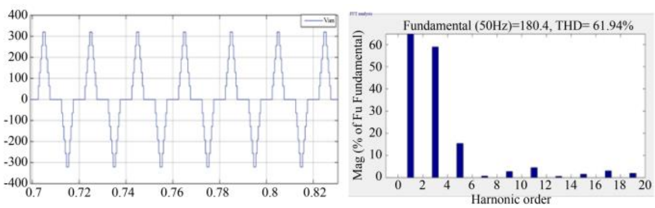

Fig. 6 The phase voltage of a 21-level inverter with equal DC sources without filter (R-load)

The 21-level Cascaded H-Bridge Multilevel Inverter (CHMLI) configuration can achieve a much-improved result using unequal DC sources. (Figure 7) shows the output current of the 21-level inverter with unequal DC sources, which are 192V for the first H-bridge and 12V for the rest of the H-bridges, without a filter. The THD of the current has been drastically improved to 12.75%, as depicted in Figure 7, which signifies a great improvement in the output current quality from the case where equal DC sources were used.

Further, the three-phase voltages also present a THD of 12.75%, as seen in (Figure 8), showing how effective the use of unequal DC sources could be for a smooth and sinusoidal voltage waveform. Under the resistive load of 15 kW per phase, the RMS value of the phase voltage and line current was recorded as 223.4V and 69.23A, respectively.

The performance depicted the enhanced capability of the inverter to deliver higher voltage and current with improved efficiency at reduced harmonic distortion using unequal DC sources. These results underpin the merits of non-uniform DC sourcing as applied to optimizing performance in multilevel inverters, mainly on applications with a critical low harmonic content and efficient active power delivery.

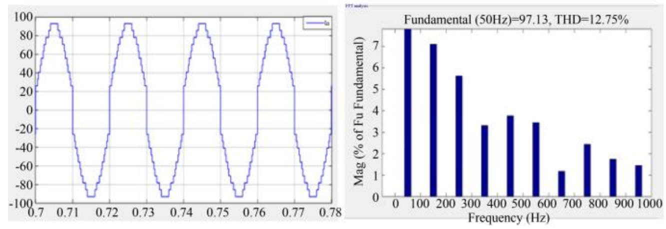

Fig. 7 The output current of a 21-level inverter with unequal DC sources without filter (R-load)

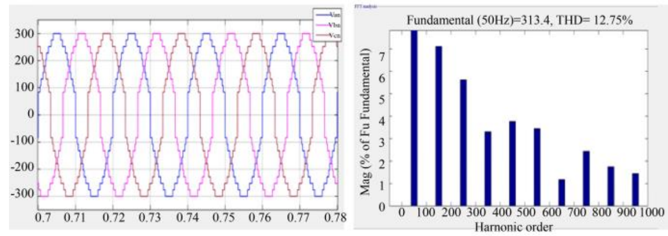

Fig. 8 Three-phase voltages of 21-level inverter with unequal DC sources without filter (R-load)

Furthermore, an L-C series filter is used to mitigate harmonic distortion in the output of the 21-level cascaded H-bridge multilevel inverter system. This series LC filter smooths out high-frequency harmonics generated by the inverter and thus improves the quality of output voltage and current waveforms.

In (Figure 9), the output current of the filtered 21-level inverter supplied from unequal DC sources has been demonstrated for a pure resistive 15 kW load per phase. Accordingly, as will be understood, it is markedly obtained that filtered current THD reaches an ignorable ratio of 0.35%, revealing an excellent harmonic mitigation impact realized by an LC filter in action.

(Figure 10) presents the corresponding three-phase voltages, whose THD is 0.35%, confirming that the waveform at the output of the filter is much more sinusoidal than that at the input.

The RMS values of the phase voltage and line current were equal to 221.62V and 68.68A, respectively, for a resistive load of 15 kW per phase. These results show far less harmonic content and much better system performance with a series LC filter, offering an efficient and cleaner power delivery at maintained power factor and voltage quality.

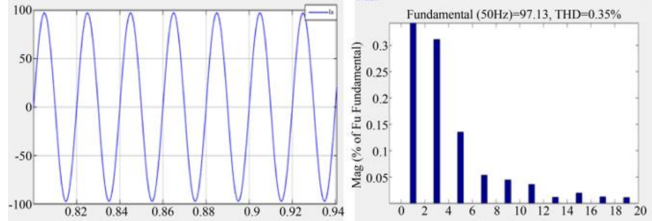

Fig. 9 The output current of a 21-level inverter with unequal DC sources with filter(R-load)

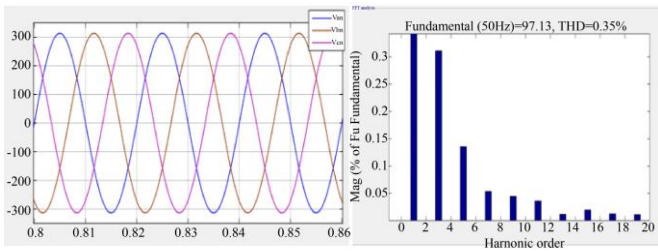

Fig. 10 Three-phase output voltage of filtered 21-level inverter with unequal sources(R-load)

The performance of the 21-level cascaded H-bridge multilevel inverter has been tested on pure resistive and R-L loads to study its performance for a complex nature of load conditions. (Figure 11) shows the output current of the filtered 21-level inverter powered by unequal DC sources and subjected to a 16.667 kVA per-phase R-L load. Due to the addition of the series LC filter, the THD of the current was reduced to 0.73%, showing that the filter has minimized the harmonic content even under an inductive load nature. (Figure 12) gives the corresponding three-phase voltages with a THD of 1.72%, slightly higher. The harmonic content in the voltage waveform increased compared to the current; however, the results are very low THD compared to an unfiltered operation. Under these conditions, the phase voltage and line current RMS values at an R-L load of 16.667 kVA per phase were measured to be 227.65V and 78.38A, respectively. These results confirm that the inverter can provide stable, high-quality power to both resistive and inductive loads with efficient harmonic suppression through the series LC filter.

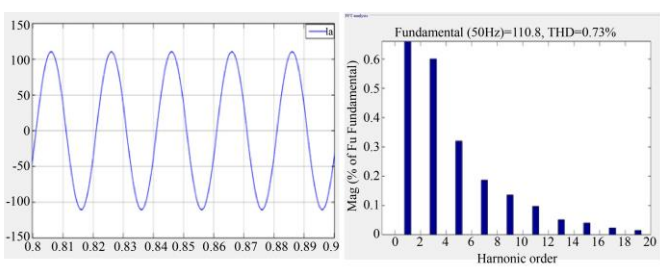

Fig. 11 The output current of a 21-level inverter with unequal DC sources with filter(R-L) load

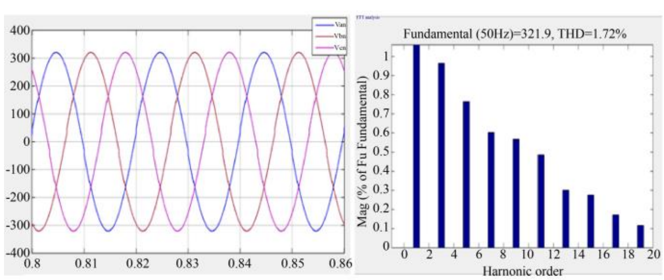

Fig. 12 Three-phase voltage of 21-level inverter with unequal DC sources with filter(R-L load)

A three-phase full-wave controlled rectifier circuit was also interfaced with the 21-level Cascaded H-Bridge Multilevel Inverter to check its performance with a rectifier load. Shown in (Figure 13) is the waveform of the output voltage of the inverter-controlled rectifier circuit at the condition of a resistive load of 15 kW, where the voltage THD is 2.89%. This shows that the voltage waveform contains a reasonable amount of harmonic content, which is expected from the combined effect of multilevel inverter switching characteristics and the controlled rectifier's operation. On the other hand, the output current of the inverter-controlled rectifier circuit, as obtained from (Figure 14), has a THD of 37.84%, which is significantly higher. It should be expected because such harmonic distortion in the current waveform would arise from the non-ideal nature of the rectifier and the interaction of switching harmonics contributed by both the inverter and the rectifier. Despite higher current THD, the system can feed a resistive load with an acceptable level of harmonic distortion in the voltage while the current distortion reflects the characteristics of the controlled rectifier. These results show the complication of harmonic interaction in systems that include inverters and rectifiers; hence, advanced filtering techniques are required in practical applications bound for high THD.

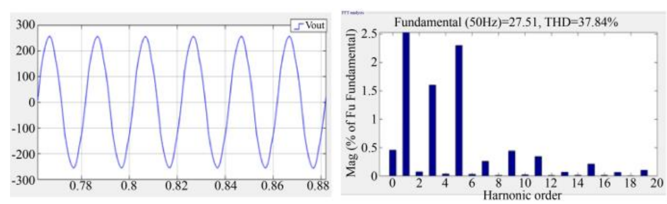

Fig. 13 The output voltage of an inverter with controlled rectifier circuit load

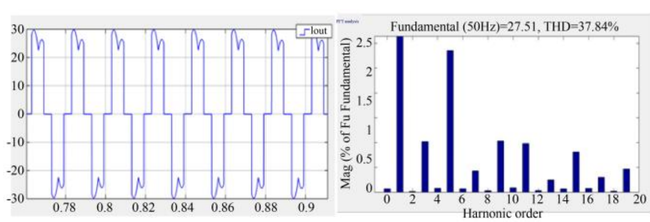

Fig. 14 The output current of an inverter with a controlled rectifier circuit load

9. Results Analysis

The outcomes presented in Table 1 indicate a significant reduction in Total Harmonic Distortion (THD) of the output phase voltage and line current of the 21-level Cascaded H-Bridge Multilevel Inverter (CHMLI) with low-frequency switching (50 Hz) and unequal DC sources and an L-C filter. These observations validate the superiority of the presented configuration in minimizing harmonic content and enhancing power quality.

Table 1. Tabulated values of inverter output phase voltage and current THD

Circuit Configuration	Voltage THD	Current THD
Without filter (R load)	12.75%	12.75%
With a filter (R load)	0.35%	0.35%
With a filter (R-L load)	1.72%	0.73%

Another distinguishing aspect of this work is the use of unequal DC sources, which plays a major role in improved harmonic performance. Traditional CHMLI implementations practically utilize equal DC sources, which are structurally simpler but result in higher harmonic content with fewer voltage-level synthesis degrees of freedom. Using unequal DC sources allows for better voltage level control accuracy, which helps reduce the harmonics content in the synthesized output waveform.

In earlier studies, it has been reported that equal DC source-based CHMLIs tend to have higher THD because of less than optimal voltage level generation, particularly in high-level inverters [1]. For example, in [2], a 15-level CHMLI with equal DC sources was taken into account, and the voltage THD reported was greater than 15%, significantly higher than the 12.75% obtained in our system in the absence of filtering. This suggests that the employment of unequal DC sources inherently maximizes voltage waveform generation with lower harmonic distortions even before using other filtering techniques.

Low-frequency switching (50 Hz) was specifically chosen in this work to reduce switching losses, thermal stress, and Electromagnetic Interference (EMI). High-frequency switching techniques, such as Sinusoidal Pulse Width Modulation (SPWM) and Space Vector PWM (SVPWM), while efficient in improving output waveform quality, are recognized to cause considerable switching losses [3]. This is because high-frequency switching-state changes increase power dissipation within semiconductor devices, thereby reducing system efficiency and reliability.

As demonstrated in this work, low-frequency switching eliminates these drawbacks with a high degree of efficiency while maintaining a good-quality output waveform. The results confirm that with a lower switching frequency, the output voltage and current are of higher quality due to the high-quality harmonic cancellation achieved through the chosen modulation technique and the utilization of unequal DC sources.

Incorporating an L-C filter further enhances waveform quality by eliminating residual harmonic components in the output. As illustrated in Table 1, phase voltage and current THD levels drop from 12.75% to 0.35% (for an R load) when incorporating the L-C filter. This represents an estimated 96% decrease in harmonic distortion, highlighting the effectiveness of filtering in offering near-ideal sinusoidal waveforms.

Moreover, under the application of an R-L load, the THD of current drops to 0.73%, which is still much smaller than in unfiltered configurations. This is consistent with findings in [4], where an L-C filter on a 17-level CHMLI reduced the THD of voltage to approximately 1.5%. Our observations demonstrate additional advancement in filtering quality, demonstrating the discussed system's effectiveness in delivering a purer power supply.

The findings of this work have far-reaching implications for future high-power inverter design, particularly for renewable energy and industrial drives. By demonstrating that a 21-level CHMLI with unbalanced DC sources and L-C filtering can achieve extremely low THD, this paper provides a realistic framework for designing more efficient and high-power multilevel inverters. The combination of low switching losses, enhanced waveform quality, and minimized harmonic distortion renders this technique applicable to applications requiring high power quality, such as grid-connected photovoltaic power systems, electric vehicle charging stations, and industrial motor drives.

10. Conclusion

Theoretical analysis is verified, and enhanced performance is presented for a 21-level cascaded H-bridge multilevel inverter under various loading conditions, such as pure resistive, R-L, and controlled rectifier configurations. Low-frequency modulation techniques used in this thesis unraveled crucial details regarding the impact of unequal DC sources and filtering schemes on harmonic distortion and general power quality at the inverter output.

First, when the system operated with equal DC sources, the THD was 61.94%, within the range expected for multilevel inverters operating at low switching frequencies. Although this follows the theoretical predictions obtained, it indicates that the system inherently possesses harmonics. This was considerably reduced when unequal DC sources were used to 12.75% THD in current and voltage. This big drop evidences the goodness of non-uniform DC sourcing: it optimizes the inverter output with a much smoother waveform, almost perfect sinusoid, at 15 kW per-phase resistive load.

The output quality improved by adding a series LC filter; the current THD fell to as low as 0.35% under resistive loads and 0.73% under R-L loads. This improvement underscores the importance of filtering techniques in mitigating high-frequency harmonics, which is crucial for applications requiring high power quality. After filtering, the phase voltage and current waveforms closely resembled ideal sinusoidal waveforms, indicating that the LC filter effectively attenuated the harmonic content and contributed to cleaner power delivery.

The evaluation of the system under an R-L load and in conjunction with a three-phase controlled rectifier showed the inverter's capability to handle more complex load conditions. While the current THD in the inverter-controlled rectifier system was higher, reaching 37.84%, the voltage waveform showed a moderate THD of 2.89%, showing that advanced filtering techniques must be employed in systems involving both inverters and rectifiers. This is expected due to the non-ideal nature of the rectifier and combined switching harmonics from both the inverter and rectifier.

In summary, it outlines the benefits that come along with the use of unequal DC sources and LC filtering techniques in multilevel inverter systems. Applying such methods allows for substantial reductions in harmonic distortions, thus ensuring more efficient and cleaner power delivery. These results underline the importance of harmonics management in improving the overall performance of CHMLI systems where low harmonic content, high efficiency, and robust power delivery are required. This research thus provides valuable insight into the optimization of multilevel inverter designs for a wide variety of power applications, extending further the prospect of clean and efficient energy conversion technologies.

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