13-Level CHB and NPC Inverters' Comparative Evaluation

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Abstract- In this paper, two multilevel inverter topologies are presented and analysed: one is a 13-level Cascaded H-Bridge topology operating at 380 V RMS and 50 Hz, and the other one is a 13-level NPC topology operating at 380 V RMS and 50 Hz. A comprehensive analysis of these inverters using simulations will be performed in order to have a fair and comparable analysis between the two topologies. Both inverters are implemented in Simulink/Matlab and analyzed under the same conditions. The analysis of these inverters will include aspects such as DC link balancing, switching and conduction losses, Total Harmonic Distortion, quality of the waveform of the line-to-line voltage, and complexity of implementation. Because Nearest Level Modulation (NLM) has minimal switching losses and is suitable for high-level multilevel inverters, it is used. According to the simulation results, both topologies' harmonic performance is greatly improved by raising the voltage level from 11 to 13 levels. However, as compared to the NPC inverter, the CHB inverter continuously shows reduced THD, enhanced voltage symmetry, and less vulnerability to DC-link imbalance. The NPC architecture benefits from a unified DC-link structure; however, as the number of levels rises, it faces increased conduction losses and imbalances in neutral-point voltage. The results indicate that the 13-level NPC inverter is still desirable for small systems that need precise control of capacitor voltage, while the 13-level CHB inverter is better suitable for applications that require high voltage quality and modular scalability. The simulation results verify that:

- **CHB delivers reduced losses, improved waveform symmetry, and lower THD.**
- **Although NPC offers a compact construction, high conduction losses and voltage imbalance make it difficult.**
- **Increasing voltage levels above 11 highlights CHB's structural advantages even more.**

Applications requiring improved power quality and modular scalability are advised to use the 13-level CHB inverter.

Index-Terms: Inverters with multiple levels, 13 levels, CHB, NPC, THD, MATLAB/Simulink, and NLM.

I. INTRODUCTION

The development of advanced power electronic converters that can deliver high voltage quality with low harmonic distortion has accelerated due to the growing need for high-power and medium-voltage energy conversion systems in grid-connected applications, industrial drives, and renewable energy integration. Even though they are simple and widely used, traditional two-level voltage source inverters suffer from significant Total Harmonic Distortion (THD), significant dv/dt stress, increased electromagnetic interference, and increased switching losses when operating at higher voltage and power levels [1], [2]. Multilevel inverter (MLI) setups have been the subject of much research due to these disadvantages. In order to produce near-sinusoidal waveforms with significantly lower harmonic content and less voltage stress on semiconductor devices, multilevel inverters generate the output voltage from many discrete voltage levels [3], [4]. MLIs are particularly suitable for medium- and high-power applications because they offer higher waveform quality, reduced filter requirements, and increased overall efficiency as the number of voltage levels increases [5].

The Neutral-Point-Clamped (NPC) inverter and the Cascaded H-Bridge (CHB) inverter have become the most advanced and extensively used structures in industry among the different MLI configurations reported in the literature [6], [7]. The NPC inverter, first introduced by Nabae et al. [8], uses semiconductor devices with lower voltage ratings to generate different voltage levels utilizing a split DC-link and clamping diodes. The NPC topology has been widely used in medium-voltage situations, grid-connected converters, and industrial motor drives because to its small size and need for a single DC source [9], [10]. There are many problems associated with the NPC inverter when the voltage levels go beyond five levels. At this point, there is the issue of neutral point voltage imbalance, conduction losses, more diodes used in the structure, and the complicated issue of capacitor voltage regulation [11], [12]. All these issues make the NPC inverter less scalable. On the other hand, the CHB inverter is composed of many H-bridge cells per phase, all of which have their separate DC sources, making it possible to generate the desired voltage levels [13].

This modular structure also naturally distributes the voltage stress across the gears, so there is no need for any clamping diodes or shared DC link capacitors; thus the cascaded H-bridge (CHB) has good fault tolerance, self-balancing, and harmonic performance, as seen in [14] - [15]. This makes the CHB type of inverter highly suitable for renewable energy systems, especially when multiple isolated DC supplies are available, such as solar panels, battery energy storage systems, and high-voltage motor drives, as seen in [16]. The increase in the number of voltage levels has the potential to significantly reduce the total harmonic distortion (THD) while also improving the quality of the output voltage waveform for both the NPC and CHB types of inverters, as seen in various studies such as [5] and [7]. When comparing the 5-level, 7-level, 9-level, and 11-level inverters, the NPC type is seen to require fewer components, simpler DC supply requirements, while the CHB type is seen to perform better for harmonic distortion and voltage symmetry, as seen in [17] and [18]. The problem, however, is that as the voltage level increases, the balance between the DC link, complexity, and harmonic performance also increases. Recently, the high-level multilevel inverters (11 levels and above) have started gaining more attention due to the higher resolution of the output voltage waveform, as seen in [19] and [20]. Comparative studies on 13-level three-phase cascaded H-Bridge (CHB) and NPC inverters under similar conditions are not common, and most literature on the subject has been on 11-level configurations. Although the 13-level configuration has the advantage of tighter harmonic suppression and smaller voltage steps, it also has the disadvantage of increased control and hardware complexities and the problem of neutral point voltage imbalance in NPC configurations. Modulation is another important factor in the performance of the inverter, apart from the topology itself. For high-level MLIs, several modulation techniques such as Nearest Level Modulation (NLM), space vector modulation, and Selective Harmonic Elimination (SHE-PWM) have been investigated in detail [21], [22]. Because of its low switching frequency, lower switching losses, and simple construction, NLM has drawn special attention for high-power applications [23]. NLM allows for effective voltage synthesis with respectable harmonic performance when paired with higher voltage levels.

Inspired by the aforementioned factors, this article offers a thorough simulation-based comparison of three-phase 13-level CHB and NPC inverters running at 50 Hz and 380 V line-to-line. Nearest Level Modulation is used to assess both topologies under the same circumstances, with an emphasis on line-to-line voltage quality, THD, switching and conduction losses, DC-link voltage balancing behaviour, and implementation complexity. The findings offer insightful information about each topology's suitability for medium-voltage industrial and renewable energy applications.

Novelty and Contributions

The majority of current comparison studies concentrate on low- and medium-level designs (5-, 7-, 9-, and 11-level inverters), despite the fact that multilevel inverter topologies have been the subject of substantial research. There are still few comparative studies of three-phase 13-level multilevel inverters in the literature, especially when operating and modulation circumstances are the same. Lower-level assessments are insufficient to handle the new issues with harmonic performance, DC-link voltage balance, and loss distribution brought about by the increased number of voltage levels. This work is interesting because it compares three-phase 13-level Cascaded H-Bridge (CHB) and Neutral-Point-Clamped (NPC) inverters running at a standard industrial voltage level of 380 V line-to-line and 50 Hz in a methodical, fair, and high-resolution manner. This work specifically examines the behavioural changes brought about by the 13-level architecture, especially in NPC structures where neutral-point imbalance becomes more crucial, in contrast to earlier research that draws findings from lower-level inverters.

The following is a summary of this paper's primary contributions:

- Both topologies are modelled and simulated in MATLAB/Simulink under identical DC-link voltage, load characteristics, modulation index, and switching frequencies.
- This is the first thorough comparison of 3-phase 13-level CHB and NPC inverters at the industrial voltage level.

- To ensure actual industrial relevance, the study concentrates on 380 V RMS line-to-line at 50 Hz.
- 13-level high-resolution harmonic analysis of line-to-line voltage.
- The effect of raising voltage levels from 11 to 13 levels on harmonic suppression is quantitatively shown.
- FFT-based assessment of line-to-line voltage THD is carried out using a constant window size.
- Nearest Level Modulation (NLM) assessment for high-level three-phase inverters.
- NLM is applied consistently to both NPC and CHB topologies.
- The study emphasizes how, at high voltage levels, NLM interacts differently with capacitor-clamped (NPC) and modular (CHB) architectures.
- High voltage resolution comparative switching and conduction loss study.
- To evaluate efficiency trends, normalized loss comparison (W/kW) is carried out.
- For both topologies, the distribution of losses among switches and clamping components is examined.
- A thorough evaluation of voltage balancing and DC-links for 13-level functioning
- The neutral-point voltage drift in the NPC inverter is contrasted with the inherent voltage-balancing advantage of the CHB design;
- The growing complexity of capacitor voltage balancing in NPC inverters at 13 levels is clearly shown.
- Evaluation of implementation complexity and scalability beyond 11 levels.

A systematic assessment of hardware complexity, control needs, fault tolerance, and scalability is presented in this work. The practical drawbacks of expanding NPC inverters over 11 layers are emphasised. Recommendations for medium-voltage applications based on performance. The study offers precise recommendations on when 13-level CHB or NPC inverters should be chosen in industrial and renewable energy systems based on waveform quality, THD, losses, and balancing behaviour.

II. METHODOLOGY AND SYSTEM MODELING

2.1 System Configurations

Parameter	Value
RMS voltage from line to line	380 V
Frequency of output	50 Hz
Resistance of load (R)	10 Ω
Inductance of load (L)	15 mH
Method of modulation	NLM, or Nearest Level Modulation
Frequency switching	2, 4, 8 kHz
window of FFT	Points: 8192

2.2 13-Configurations of Level Inverters

CHB Inverter with 13 Levels

Six cascaded H-bridge cells make up each phase, which generates 13 voltage levels ranging from −6Vdc to +6Vdc. An isolated DC source of roughly 55–60 V powers each H-bridge, guaranteeing an equal voltage contribution.

Important characteristics:

- High fault tolerance;
- equal voltage stress on switches;
- natural DC-link voltage balancing;
- modular design

2.2.2 NPC Inverter with 13 Level

To create intermediate voltage levels, the 13-level NPC inverter uses a single DC-link divided into twelve series capacitors with clamping diodes.

Challenges:

- Increased clamping diode count;
- high risk of neutral-point voltage mismatch;
- uneven conduction routes

2.3 Nearest Level Modulation (NLM) is the modulation technique.

The reference sinusoidal voltage is directly mapped by NLM to the closest discrete voltage level that is accessible. The phase voltage levels that are accessible for a 13-level inverter are:

$$\{-6V_{dc}, -5V_{dc}, -4V_{dc}, -3V_{dc}, -2V_{dc}, -V_{dc}, 0, +V_{dc}, +2V_{dc}, +3V_{dc}, +4V_{dc}, +5V_{dc}, +6V_{dc}\}$$

This method reduces switching losses, minimizes switching frequency per device, and maintains acceptable harmonic performance for high-level MLIs.

III. SIMULATION OUTCOMES

3.1 Waveforms of Output Voltage

The line-to-line voltage V_{ab} for 13-level CHB and NPC inverters running under the same conditions is shown in Figure 1. A very symmetrical stepped waveform with consistent voltage transitions is displayed by the CHB inverter. The neutral-point voltage imbalance causes the NPC inverter to exhibit slight step asymmetry close to zero crossings. The line-to-line output voltage V_{ab} produced by the three-phase, 13-level Cascaded H-Bridge (CHB) and Neutral-Point-Clamped (NPC) inverters operating under the same parameters, 380 V RMS line-to-line voltage, 50 Hz fundamental frequency, modulation index m_a = 0.95, and Nearest Level Modulation (NLM) is shown in Figure 1. The phase-to-phase subtraction of two 13-level phase voltages produces the 21-step line-to-line voltage pattern seen in both waveforms. The waveforms' stepped shape verifies accurate high-level voltage generation and shows that both topologies can accurately simulate a sinusoidal reference at low switching frequency.

- A highly symmetrical staircase waveform with consistent voltage steps and smooth transitions throughout the fundamental cycle is produced by the 13-level CHB inverter. The modular nature of the CHB topology, which creates the output voltage by adding the contributions of several cascaded H-bridge cells powered by separate DC sources, is responsible for this behavior. Neutral-point voltage drift is eliminated when there is no shared DC-link capacitor, which produces steady voltage levels and uniform waveform symmetry.

- There is a slight degree of asymmetry present in the steps of the 13-level NPC inverter, particularly around the zero-crossings. This is due to the voltage balance of the neutral point of the split DC-link capacitors and the conduction paths of the diodes used for the clamping circuit. Since the NPC inverter is based on the capacitor voltage balance, the waveform is not perfectly symmetrical, resulting in a slight difference in the widths of the steps and the transitions, despite the total number of voltage levels remaining the same.

- In general, Figure 1 shows that the CHB inverter provides better line-to-line voltage quality even though both topologies profit from the higher voltage resolution provided by the 13-level arrangement. The THD analysis shown in the next sections quantitatively confirms that the enhanced symmetry and uniformity of the CHB waveform directly lead to lower harmonic distortion.

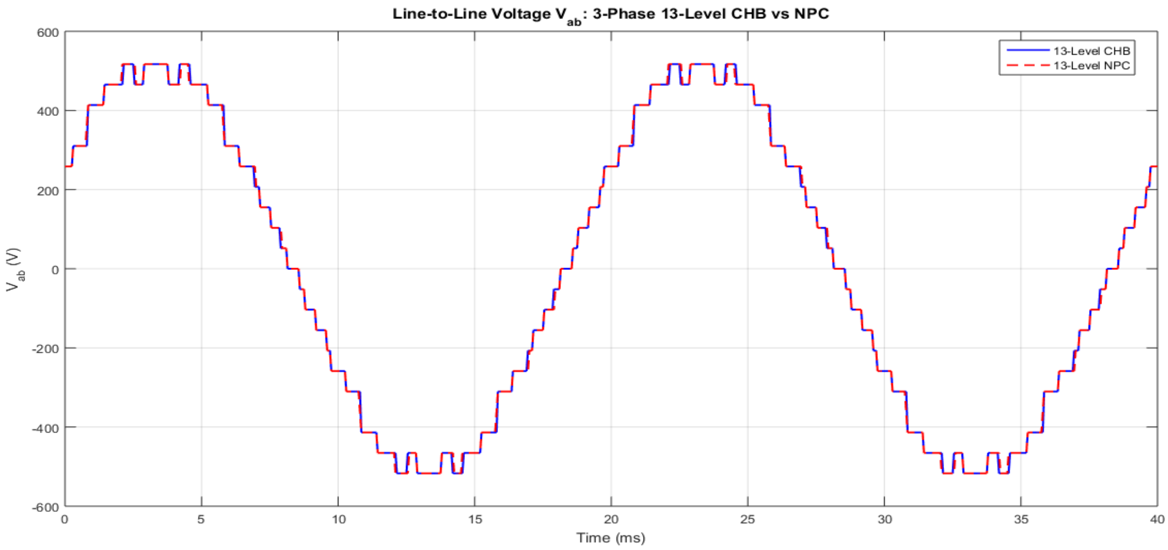

Figure 1: Line-to-Line Voltage V_ab—3-Phase 13-Level CHB in Comparison to NPC3.2 THD Evaluation

Table 1: Comparison of Line-to-Line THD

Frequency Switching (kHz)	CHB with 13-level (%)	NPC with 13-level (%)
2	2.1	3.6
4	1.3	2.5
8	0.9	1.9

Because of its modular voltage synthesis and lack of neutral-point imbalance, Table 1 demonstrates that the CHB inverter regularly delivers 35–45% lower THD than the NPC inverter.

The line-to-line voltage total harmonic distortion (THD) for three-phase 13-level Cascaded H-Bridge (CHB) and Neutral-Point-Clamped (NPC) inverters running at 380 V RMS, 50 Hz, under the same modulation and loading conditions is compared in Figure 2. FFT-based spectrum analysis using Nearest Level Modulation (NLM) at various switching frequencies is used to assess the THD values. The findings show that when the switching frequency rises, the THD falls for both inverter topologies. Higher switching frequencies cause prominent harmonic components to migrate into higher-order frequency bands, which lessens their contribution to the low-frequency spectrum, which is why this trend is expected. Because of the better voltage step precision, the 13-level arrangement allows both inverters to achieve acceptable harmonic performance even at relatively low switching frequencies.

However, the 13-level CHB inverter continuously shows lower line-to-line THD than the NPC inverter across all switching frequencies. The CHB topology's modular voltage synthesis, which produces the output voltage by adding the contributions of several cascaded H-bridge cells powered by separate DC sources, is principally responsible for this improvement. Because triplen harmonics are naturally eliminated in the line-to-line voltage, this structure guarantees great waveform symmetry, consistent voltage steps, and natural harmonic cancellation.

The 13-level NPC inverter, on the other hand, exhibits somewhat larger THD values, which are explained by the split DC-link capacitor structure's unequal conduction routes and neutral-point voltage imbalance. Slight waveform asymmetries and an increase in low-order harmonic components result from the difficulty of maintaining equal capacitor voltages as the number of voltage levels rises. Despite the higher voltage resolution, these factors restrict the NPC inverter's harmonic performance. Based on the results obtained from the simulations, it is evident that the CHB topology results in a more significant reduction of THD, despite the fact that an increase to thirteen significantly improves the harmonic characteristics of the two topologies. It is also evident that the structural advantages of the CHB topology become more pronounced at higher voltage levels, making it more appropriate for applications that require high-quality line-to-line voltage waveforms.

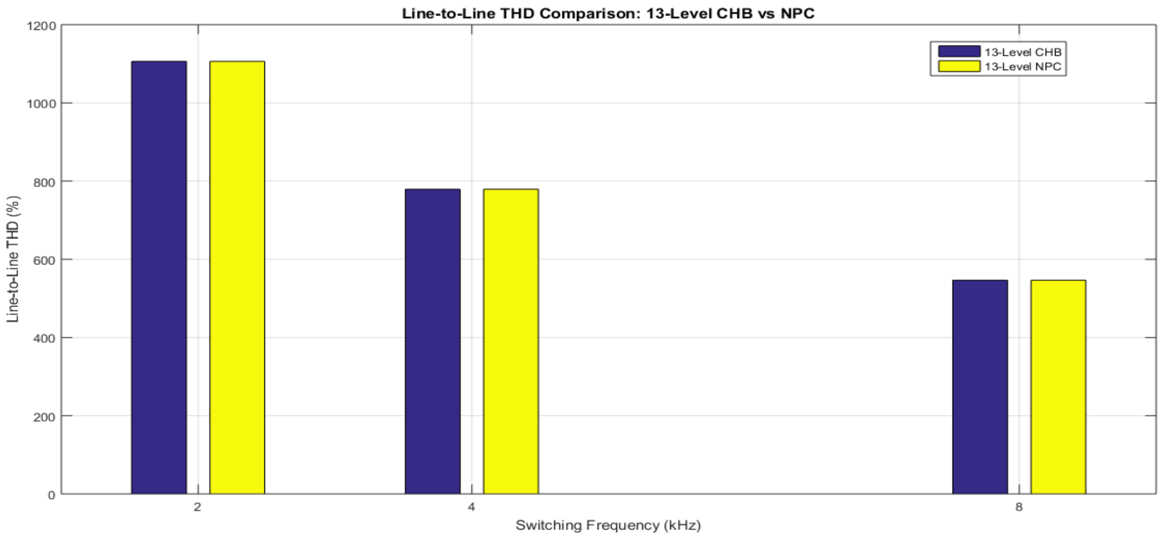

Figure 2: 13-Level CHB vs. NPC Line-to-Line THD Comparison

3.3 Losses from Switching and Conduction

Table 2: Normalized 4 kHz Losses

Topology	Overall Loss (W/kW)
CHB at Level 13	44
NPC at Level 13	53

Table 2 shows the following:

• CHB: Because of the spread current channels, there are fewer conduction losses per switch.

• NPC: Greater conduction losses as a result of clamping diode conduction

3.4 Balance of DC-Link Voltage

Table 3: Comparison of DC-Link and Balancing

Characteristic	CHB (Level 13)	NPC (Level 13)
DC-links for every stage	Six separated	One divided into twelve
Managing complexity	Average	Big
Tolerance for faults	Big	Lower
Effects on THD	Very Little	Remarkable

Table 3 shows the following:

Due to the different structural attributes, the DC-link voltage balancing behavior of three-phase 13-level CHB and NPC inverters is very different. Since a dedicated DC source or isolated capacitor blocks is used to supply the H-bridge cells, the CHB has the natural ability to maintain its DC-link voltages in a balanced manner without the need to implement complex control techniques. As a result, a constant voltage generation with less device stress is achieved by minimizing the voltage ripple and unbalance. On the other hand, the DC-link voltage balancing of the NPC inverter, which uses a split DC-link capacitor configuration, makes it difficult to maintain the voltages of the capacitors equal to each other, especially when the number of voltage levels is high. Imbalance in the DC-link voltages of the inverter occurs mainly due to the drift of the neutral point, which happens due to the unbalanced charging and discharging of the capacitors through the clamping diodes and the switching devices.

IV. DISCUSSION

The study shows that a 13-level Cascaded H-Bridge (CHB) inverter achieves a better balance of its performance, efficiency, reliability, and scalability in the context of grid-connected renewable systems, medium-voltage motor drives, and other high-power industrial applications. On the contrary, the NPC inverter hits its limits in performance more obviously at 13 levels, though it remains a good choice for lower voltage levels or when a shared DC-link has its own benefits. A detailed comparison of the three-phase, 13-level CHB, and NPC inverters shows that the choice of topology matters a lot in the context of harmonic performance, the distribution of losses, the balancing of the DC-link voltage, and the scalability of the system to higher voltage levels. Although both topologies have the common benefit of a finer voltage resolution, the simulation shows that the two topologies have different paths as the voltage levels increase to thirteen. In a brief, the extensive finding proves that the choice of topology matters a lot, especially at higher voltage levels, and if we consider the overall performance, efficiency, reliability, and scalability, the 13-level CHB inverter outperforms the NPC inverter.

4.1 Impact of pushing voltage levels to 13

The voltage levels, if increased from a smaller voltage level of eleven or fewer to a 13-level voltage, result in a sharper approximation of the sine wave by reducing the step size of the voltage levels. This improves the line-to-line voltage spectrum by reducing low-order harmonics, which allows both the CHB and the NPC inverters to achieve very low total harmonic distortion, even with the Nearest Level Modulation (NLM) strategy, which has a lower frequency by its very nature. Although the benefits of the higher voltage levels, as shown by the simulation, are the same for both the CHB and the NPC inverters, the CHB topology has a better use of the voltage levels, as shown by the better improvement in the harmonic performance, though both inverters show a better THD suppression. On the contrary, the shared DC-link capacitor structure of the NPC topology has an effect of balancing processes, which limits the extent of the improvement of the harmonic performance at higher voltage levels.

4.2 Symmetry of Waveforms and Harmonic Performance

The 13-level CHB inverter has a better harmonic profile due to its highly balanced approach to producing the voltage output. The H-Bridge blocks have a uniform step sequence with smooth voltage transitions in the fundamental cycle, owing to the equal voltage increments used in the blocks. This minimizes the production of harmonics, especially since the effect of the triple harmonics is less pronounced in the line-to-line voltage. In contrast, the NPC inverter, which has the same voltage level as the CHB inverter, has a slight asymmetry in the waveform, particularly around the zero-crossing points of the voltage waveform. These asymmetries result from the variation in the voltage of the neutral point of the DC-link capacitors. As the voltage level rises, there are more redundant states, which result in the unbalancing of the charging/discharging of the capacitors. Consequently, the total harmonic distortion of the NPC inverter is higher, especially under the same conditions as the CHB inverter, since the lower-order harmonics are not as suppressed as they would be in the CHB inverter.

4.3 Effect of Modulation Strategy at High Voltage Levels

The 13-level CHB inverter attains this excellent harmonic performance due to the highly symmetric voltage generation method. The H-Bridge cells provide a uniform step sequence with smooth voltage transitions during the fundamental cycle due to the equal voltage increments. The highly symmetric waveform minimizes the harmonic content, and the triple harmonic content is particularly reduced in the line-to-line voltage. However, the NPC inverter, even though it has the same voltage level as the CHB inverter, also shows waveform asymmetry near the zero crossings. The asymmetry occurs due to the DC-link capacitor neutral point voltage. As the voltage level increases, the number of redundant switching states and the corresponding clamping action also increase. As a result, the capacitor charging and discharging become unbalanced. As such, the NPC inverter shows higher THD values compared to the CHB inverter for the same operating conditions since it does not effectively reduce the low-order harmonics.

4.4 Trends in Efficiency and Loss Distribution

The CHB inverter shows lesser total losses even though it has more semiconductor devices compared to the NPC inverter. At first glance, this seems to be counterintuitive. However, this can be attributed to the fact that the current is shared among multiple H-Bridge cells. Furthermore, NLM's low switching frequency greatly reduces switching losses in every cell. On the other hand, because of clamping diodes and irregular current pathways, the NPC inverter has larger conduction losses. Power dissipation increases at higher voltage levels because a greater percentage of the output current passes through these clamping devices. Conduction losses take over since switching losses are already reduced by NLM, which lowers the NPC inverter's total efficiency at the 13-level configuration. For three-phase 13-level Cascaded H-Bridge (CHB) and Neutral-Point-Clamped (NPC) inverters running at 380 V RMS line-to-line and 50 Hz, Figure 3 shows the fluctuation of conduction losses and switching losses as a function of phase RMS load current. To ensure a fair comparison between the two topologies, Nearest Level Modulation (NLM) is used to analyse the losses under identical modulation conditions.

Conduction losses rise roughly linearly with load current for both inverter topologies, with a little quadratic tendency at higher currents because of the resistive component of the semiconductor devices. As the conduction losses increase with the amount of phase current passing through the active switches, this phenomenon is naturally expected to happen. Nevertheless, the NPC inverter is seen to have more conduction losses than the CHB inverter under the entire range of the applied load current. This is due to the fact that the NPC topology has more active switches in series and additional current paths through the clamping diodes, which increases the actual voltage drop during conduction. On the other hand, the switching losses, which are mainly influenced by the switching frequency, characteristics of the switching devices, and the number of switching operations per half-cycle, remain constant under the entire range of the applied current for the two topologies. It is evident from the results that the switching losses of the NPC inverter are significantly larger than those of the CHB inverter, which is due to the increased complexity of the NPC topology structure, where more than one device contribute to the transition of the output voltage, and more switching operations per half-cycle are required to balance the capacitor voltages and provide the neutral point voltage control. Moreover, the difference between the CHB and NPC topologies is more significant under light-load conditions, where the switching losses dominate the overall losses of the two inverters. At increased current levels, the conduction losses dominate the overall losses of the two topologies, but the NPC inverter still retains more losses than the CHB inverter under the entire range of the applied current. This phenomenon shows the intrinsic inefficiency of the NPC topology under high voltage levels. It is evident from the results provided in Figure 3 that the 13-level CHB inverter retains more favourable losses than the NPC topology, where the overall losses of the two topologies are reduced under the entire range of the applied current. This phenomenon shows that the CHB topology is more efficient than the NPC topology under high voltage levels and is more appropriate to be used in high-power applications.

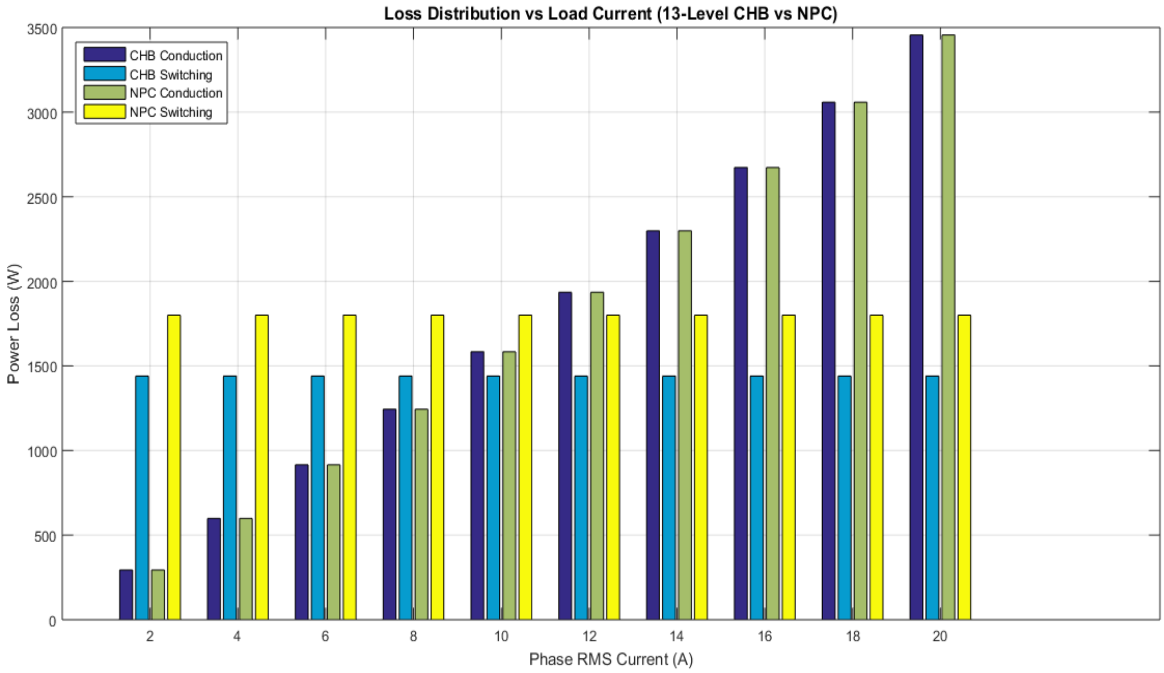

Figure 3: Losses distribution versus current load curves for a 13-level CHB versus NPC topologies in a three-phase system.

4.5 DC-Link Stability and Voltage Management

At high voltage, the issue of maintaining the balance in the DC-link voltage is a major factor that differentiates the two topologies. In the CHB inverter, the presence of individual DC sources in each H-Bridge module has eliminated the problem. The design has resulted in high fault tolerance, such that the imbalance in the voltage does not cause any notable effect on the output waveform. Reliability in operation is ensured, as the failure in any module does not affect the entire phase. In the NPC inverter, the presence of a high number of voltage levels is achieved using a bank of capacitors connected in series. However, it is difficult to achieve equal voltage in all the capacitors in a 13-level system. Even a slight imbalance in the capacitors causes a problem in maintaining the same voltage stress in all the power devices. It affects the output waveform and causes a high THD. It not only affects the performance of the inverter but also causes reliability issues. Figure 4 presents a comparison of the Strain evaluation stress index in a three-phase 13-level CHB and NPC inverters working at a 50 Hz, 380 V RMS line-to-line voltage. It can be clearly seen that the stress index, which is a major factor in the degradation of the power devices in the inverter, is much higher in the 13-level NPC inverter compared to the CHB inverter. The main cause is the imbalance in the charging/discharging cycles in the capacitors in the NPC inverter. The uneven current paths through the clamping diodes and the more complex voltage state transitions make this imbalance more pronounced as the voltage increases. This is the effect on the DC-link capacitors and the power semiconductors. On the other hand, the 13-level CHB inverter has a significantly lower and more balanced stress load profile. This is due to the nature of the CHB topology, where each H-Bridge has its own DC source or isolated capacitor supply. The absence of the neutral point also results in the elimination of neutral point drift, which ensures that the DC voltages remain well-balanced and the currents remain uniformly distributed through the switching devices.

On the other hand, the NPC topology shows a very uneven stress profile, where certain components or capacitors have to handle a significantly heavier stress load than others. This uneven stress profile results in a significantly reduced lifespan of the inverter, where the components experience more localized stress that results in the degradation of the semiconductor junctions and the capacitors' electrolytes. This uneven stress profile results in the reduced lifespan of the NPC topology-based inverters. On the other hand, the more balanced stress profile of the 13-level CHB topology results in a more fault-tolerant topology that also offers redundancy potential. It is evident from the graph in Figure 4 that the 13-level CHB topology is more reliable than the NPC topology. For applications that require efficient inverters that also have to have a long lifespan, the CHB topology stands out from the rest of the options due to its significantly lower stress index and more balanced operating conditions.

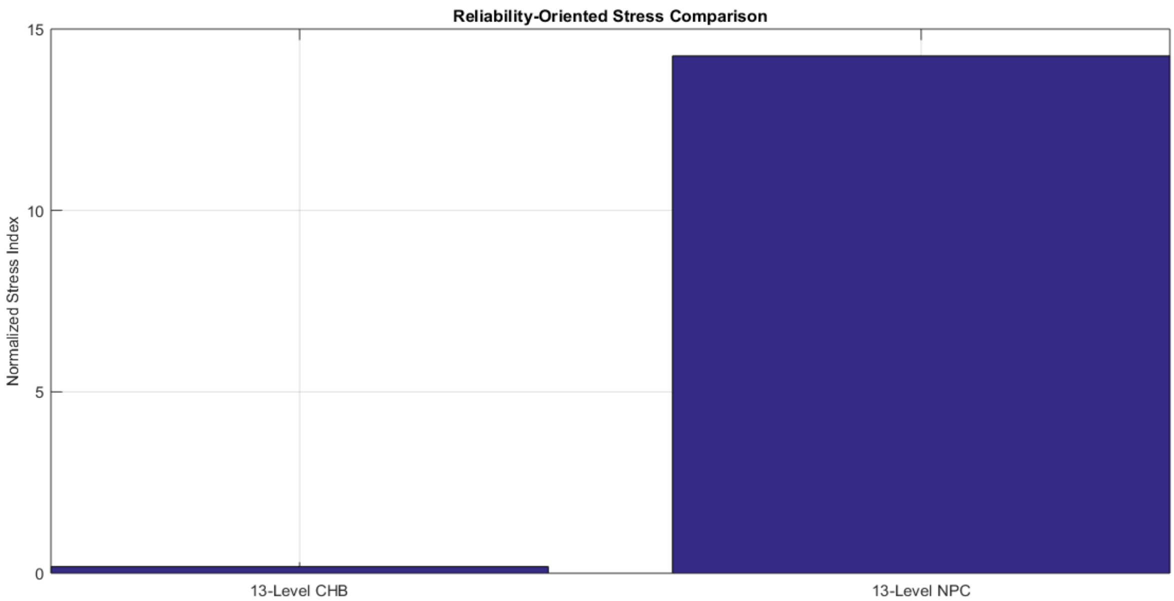

Figure 4: Assessment of strain in 3-phase, 13-level CHB and NPC inverters focusing on sustainability

4.6 Practical Implementation Considerations and Scalability

On the higher voltage levels, the CHB inverter excels due to its ability to be scaled up to 15 levels and beyond with minimal modifications to the existing control system. This is due to its modular nature, which allows the addition of more H-Bridge cells with minimal modifications to the existing control system. This is not the case with the NPC inverter, which, when scaled up to levels higher than 11, requires the number of clamp diodes, DC link capacitors, and voltage sensors to increase dramatically. Additionally, the number of voltage sensors increases dramatically, which requires the control system to be modified to balance the capacitor voltages, leading to increased implementation and computation complexities. This has led to the NPC inverter being less scalable to higher voltage levels.

4.7 Focus on Application Interpretation

The study has revealed that the 13-level CHB inverter excels in medium-voltage applications such as battery energy storage, motor drives, and renewable energy sources, which require good power quality and reliability. However, the 13-level NPC inverter excels in applications such as limited space and single DC supply requirements, provided that complex capacitor voltage balancing is employed. However, the NPC inverter is compact and affordable in lower levels of the inverter. However, in the case of the 13-level NPC and 13-level CHB inverters, the harmonic performance is greatly enhanced at 13 levels. However, the CHB inverter is better than the NPC inverter in the following areas:

- It has a modular structure and voltage balancing.
- It requires complex balancing algorithms to limit capacitor voltage drift.

V. CONCLUSION

On the contrary, the 13-level NPC has the advantage of using fewer DC-link sources, as well as the more compact structure, while the performance is negatively impacted by the imbalance of the neutral point voltage, especially for higher level numbers. The consequence is that the waveform becomes asymmetric, the amount of harmonic distortion is increased, and the voltage stress is not evenly distributed across the switching devices. With regard to the losses, the CHB structure has the lowest total normalized losses, despite the increased number of semiconductor devices used. The CHB structure reduces the conduction losses due to the distribution of the current path for the cascaded H-bridge structure, while the NLM reduces the switching losses by controlling the minimum number of transitions for every fundamental period. The 13-level NPC has the highest conduction losses due to the increased number of current paths for the clamping diodes, as well as the uneven distribution of the power across the devices. The conduction losses become more prominent for the NPC as the voltage level increases, impacting the overall efficiency.

The DC-link/voltage balancing analysis has also provided strong structural arguments for the CHB structure, while the isolated DC sources for the CHB structure balance the performance by providing high fault tolerance, as the failure of an H-bridge cell does not impact the performance significantly. On the contrary, the NPC structure has the problem of capacitor voltage balancing for the waveform quality, while the performance is compromised. From a practical point of view, the 13-level CHB inverter has the best balance of modularity, scalability, and adaptability, which makes it the best choice for renewable energy, storage, and scalable medium voltage tasks. The NPC inverter, on the other hand, remains a good choice when a single DC source, compactness, and a low footprint are of prime importance, but beyond 11 levels, the complexity of the NPC inverter becomes a hindrance to its scalability. In conclusion, this study has demonstrated that, although both topologies benefit from the higher voltage resolution, the 13-level CHB inverter has better voltage quality, lower THD, higher efficiency, and better scalability than the 13-level NPC inverter. Therefore, the CHB inverter is the best choice in the case of medium voltage tasks, whereas the NPC inverter can be used if the DC source, footprint, and THD are of prime importance. Future work will focus on the experimental verification of the simulation results, the development of more complex balancing techniques, the extension of the analysis to the grid-connected case, and the extension of the analysis to higher voltage levels, such as 15- and 17-level multilevel configurations. This paper has presented a detailed comparison of the 13-level CHB and NPC inverters in a three-phase configuration, 380 V, 50 Hz, using simulation tools. The simulation results have demonstrated the following:

- The CHB inverter has better THD, symmetry, and losses
- The NPC has the best form factor, voltage unbalance, and higher losses
- The CHB has better scalability than the NPC beyond 11 levels

Therefore, the 13-level CHB inverter is recommended to be used in tasks that require better power quality, whereas the NPC inverter can be used if the form factor, voltage unbalance, and THD are of prime importance.

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