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M.Sc. in Electrical and Electronics Engineering

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**REPUBLIC OF TÜRKİYE
GAZİANTEP UNIVERSITY**

GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

**DESIGN AND COMPUTER REALIZATION OF THREE LEVEL
DC/AC INVERTER USING HALF BRIDGES AND VOLTAGE
VECTOR**

M.Sc. THESIS

IN

ELECTRICAL AND ELECTRONICS ENGINEERING

BY

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M.Sc. Thesis

in

Electrical and Electronics Engineering

Gaziantep University

Supervisor

Prof. Dr. Arif NACAROĞLU

by

Abdullah HAMAWIYA

January 2025



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DESIGN AND COMPUTER REALIZATION OF THREE LEVEL DC/AC

INVERTER USING HALF BRIDGES AND VOLTAGE VECTOR

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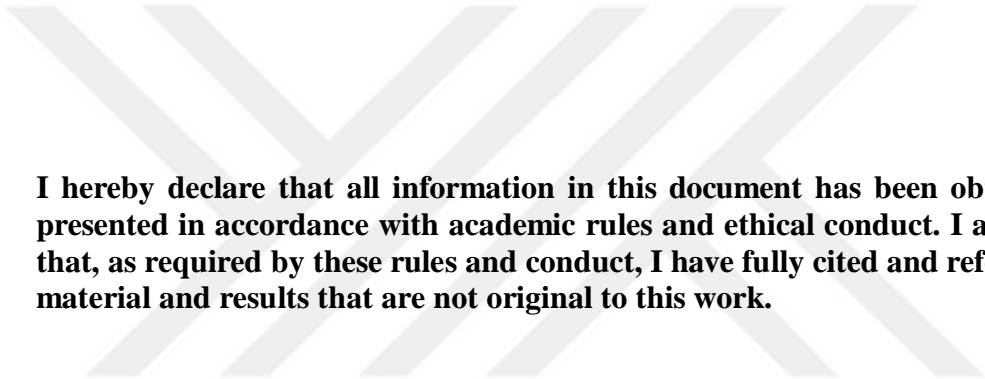
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ABSTRACT

DESIGN AND COMPUTER REALIZATION OF THREE LEVEL DC/AC INVERTER USING HALF BRIDGES AND VOLTAGE VECTOR

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This thesis explores a three level cascaded half bridge inverter with voltage vector control and control specifically for renewable energy applications of which include photovoltaic (PV) systems. The multilevel inverter is starting to be a preferred solution in order to improve the efficiency, reduce harmonic distortion and enhance the power quality. Of all the available renewable resources, solar energy is most effective due to its basic structure in comparison to others such wind power or hydro power. One of the important factors about incorporating solar energy into the power supply entails the need to use variables for rectifying the DC generated by photovoltaic systems into usable AC energy. This conversion should be smooth with low level of harmonic distortion. These needs are primarily solved by multilevel inverters which provide better output characteristics and less EMI losses than other inverters. The Cascaded Half bridge (CHB) inverter is one of the popular multilevel inverter topologies for its concerns to provide better output results. To address this, several advanced inverter configurations have been proposed, such as the PUC5 and T3 inverters to attain higher voltage levels using fewer components. As such, this thesis is mainly concerned with the three-level half-bridge inverter active inverter, its functioning characteristics, and its switching techniques. The study assesses and compares the low and high frequency switching techniques in their quality of the waveform, level of distortion and efficiency.

Key Words: DC/AC Inverter, Half bridge method, Harmonic distortion.

ÖZET

3 SEVİYELİ DC/AC ÇEVİRİCİNİN YARIM KÖPRÜ VE VOLTAJ VEKTÖR YÖNTEMİ İLE TASARIMI VE SİMÜLASYONU

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Bu tez, voltaj vektörü kontrolü ve özellikle fotovoltaik (PV) sistemleri içeren yenilenebilir enerji uygulamaları için kontrole sahip üç seviyeli kademeli yarım köprü invertörü araştırmaktadır. Çok seviyeli invertör, verimliliği artırmak, harmonik bozulmayı azaltmak ve güç kalitesini geliştirmek için tercih edilen bir çözüm olmaya başlıyor. Bu çalışmada düşük frekanslı anahtarlamanın yapıldığı temel dalga formu için düşük frekanslı darbe kullanırken, yüksek frekanslı PWM için Toplam Harmonik Bozulmayı (THD) en aza indirir. Güneş enerjisini güç kaynağına dahil etmeyle ilgili önemli faktörlerden biri, fotovoltaik sistemler tarafından üretilen DC'yi kullanılabilir AC enerjisine dönüştürmek için değişkenleri kullanma ihtiyacını gerektirir. Bu dönüşüm, düşük seviyede harmonik bozulma ile düzgün olmalı ve çıkış sinyali kalitesi iyi olmalıdır. Kademeli Yarım Köprü (CHB) invertörü, daha iyi çıkış sonuçları sağlama endişeleri nedeniyle popüler çok seviyeli invertör topolojilerinden biridir. Üç seviyeli yarım köprü konfigürasyonuna dayalı yeni bir çok seviyeli DC/AC invertör geliştirildi. Bu nedenle, bu tez esas olarak üç seviyeli yarım köprü invertör aktif invertörü, çalışma özellikleri ve anahtarlama teknikleriyle ilgilenmektedir. Çalışma, düşük ve yüksek frekanslı anahtarlama tekniklerini dalga formu kalitesi, bozulma seviyesi ve verimlilik açısından değerlendirir ve karşılaştırır. Bu araştırma, çok seviyeli invertörler hakkında derin içgörüler sunar ve kontrol düzenlemeleri ve sistem mimarilerinde ek ilerlemeler için yeni olasılıklar sunar.

Anahtar Kelimeler: DC/AA İntertör, Yarım köprü yöntemi, Harmonik bozulma.

"This work is sincerely dedicated to my supportive parents who encouraged and inspired me in conducting this study. They have never left my side throughout the process and gave me strength and hope when I thought of giving this up. They provided me a great sense of enthusiasm and perseverance in continuing this. Without their love and assistance, this research would not have been made possible. Moreover, I dedicate this research paper to all my teachers and particularly to my subject teacher, Prof. Dr. Arif Nacaroğlu , who constantly guiding and teaching me to make this study even better, to my family for cheering up for me, and to my friends who have helped me in finishing this project. I really appreciate your words of advice and in continuously giving me Total support. "

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CHAPTER 1

INTRODUCTION

1. 1 Overview

As there is a growing concern on the use of renewable energy the performance and reliability of power electronics convertor systems have emerged as of great concern to the global community. Solar energy, which is one of the most popular forms of renewable energy, requires power conversion systems to transform of Direct Current (DC) electricity produced by the photovoltaic (PV) cells into Alternative Current (AC) electricity that can be used by homes, industries or fed to the grid.

Inverters are main components in such systems and it is required to convert the direct current electrical power to an AC form with high quality. Despite the high popularity of using traditional inverters they have drawbacks in relation to the level of distortion of the input current harmonics, efficiency and power quality which has led to the searches for development of new topologies of multilevel inverters. The advantages of these are lower switching losses, and electromagnetic interference as well as improved waveform quality. In this thesis, the emphasis is placed on the three-level inverter based on cascaded half bridge s as a method for obtaining high efficiency in renewable power sources.

The primary concerns that inform the choice of a multilevel inverter topology can be grouped into three aspects of power quality enhancement outcome: the quality of AC output, low circuit switching stress, and highly reduced THD, all of which are paramount to renewable energy systems. Considering the constantly rising demands on high efficiency energy systems, the research conducted throughout this thesis simplifies the practical application of multilevel inverters [2].

Multilevel inverters constitute a breakthrough in power electronics because they have numerous advantages compared with two-level inverters. They are designed to

operate at higher voltage and power levels since the stepped waveform is more refined and is closer to the sine wave which is very important in minimizing the harmonic distortion and enhancing power quality. These inverters are widely used in renewable energy systems, EVs, and high power industrial drives where efficiency and performance are critical. Multilevel inverters operate by partitioning the total input voltage into different levels and then combining the levels to produce a waveform with a stepped waveform. This approach reduces voltage stress on each component, minimizes EMI, and improves the efficiency of the inverter. Multiple levels in these inverters provide better control over the desired waveform, which in turn offers improved performance specifications like low THD, and high power quality.

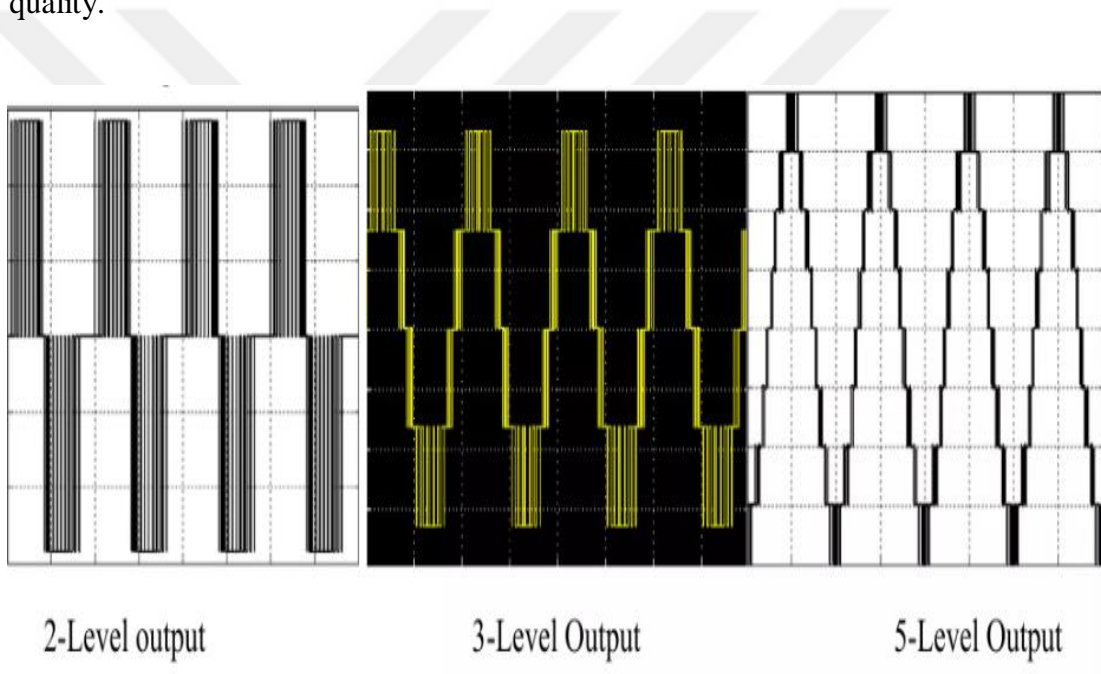


Figure 1. 1 Three different types of Multilevel Inverter output waveforms

Multilevel inverters have emerged as a vital component in modern power electronics, particularly in renewable energy systems, due to their ability to produce high-quality AC outputs while reducing harmonic distortion and switching losses. The three-level half-bridge inverter, a fundamental multilevel topology, operates by generating three distinct voltage levels: positive, zero, and negative. This topology achieves a stepwise approximation of a sinusoidal waveform, which significantly enhances power quality when compared to traditional two-level inverters.

The theoretical foundation of multilevel inverters lies in their modular architecture, which enables scalability for higher power applications while maintaining efficiency. Cascaded structures such as the half-bridge configuration simplify implementation by reducing the number of components compared to more complex topologies like the five-level or PUC5 inverters [3]

1. 1. 1 The benefits of multilevel inverters

1. 1. 1. 1 Improved Power Quality

Compared to conventional inverters, multilevel inverters in the output voltages develop close to a sine wave thus offering low harmonic distortion in a signal. The reduction of THD also helps to eliminate other forms of interference with other electrical appliances and lead to increased energy transfer efficiency.

Multilevel inverters generate stepped voltage waveforms close to sinusoidal wave forms due to their cascaded structures. This characteristic reduces harmonic distortion while providing an excellent-quality output AC that can be used for critical appliances such as medical equipment and renewable energy systems that feed into the electrical grid. When compared with the number of voltage levels, the inverter that operates at higher voltage levels apparently generates smoother waveforms with negligible THD. Besides increasing the efficiency of devices that are connected with the help of batteries, it also reduces electromagnetic disturbance in power systems [4].

1. 1. 1. 2 Enhanced Efficiency

This is because multilevel inverters can produce high quality output voltage waves and yet achieve more efficiency than the two-level inverters for they work at relatively low switching frequencies.

Efficiency is a very sensitive parameter in inverter optimization. Multilevel inverters in particular improve the power control process since they minimize switching losses and conduction losses. The stepped waveform reduces the voltage stress of power switches which in turn lowers the voltage requirement across them, using devices with inherently higher efficiency [5]. In addition, there exist high level controls that improve on the management of the switching states such as Space Vector Modulation (SVM).

1. 1. 1. 3 Scalability and Modularity

Multilevel inverters have a modularity of levels and modules that can be installed in a step-by-step manner to increase levels and modules of the inverters thus making it possible to apply in a small residential system or a large industrial system.

This gives multilevel inverters flexibility in terms of scaling for higher power levels since the building blocks can simply be incorporated into the structure. The incorporation of the extra inverter modules is done in a cascaded manner therefore does not require drastic redesign of the system to abate to higher voltage and power demands. It as well makes the multilevel inverters applicable in most sectors from the residential solar inverters, motor drives to renewable energy systems in industries.

1. 1. 1. 4 Improved Power Quality

Multilevel inverters produce output voltage with low harmonics and this makes the quality of power delivered to be high and less loss in power systems.

Multilevel inverters have complex control to handle multiple switches and to maintain voltage level across the levels. High performance of computation and control recursions in a real-time framework become critical at varying load conditions.

1. 1. 1. 4. 1 Increased Component Count

Compared to the conventional inverters, the architectural design of the multilevel inverters comprises a larger number of components. This, in return, adds to the general system cost and complicity besides also bringing out reliability issues because of the greatly expanded failure points.

1. 1. 1. 4. 2 Voltage Balancing

This is because the voltage levels which must be maintained across the capacitors within each and every module must be similarly balanced. This paper shows that voltage imbalance results in waveform distortion, loss increments, as well as possible component degradation [6].

1. 1. 1. 5 Higher Efficiency

Through employing a variety of voltage levels, these inverters help spread electrical power stresses across the inverters, as well as the loadings on power electronic

devices are decreased, resulting in better efficiency as well as being able to handle less thermal loading[5].

A major characteristic of multilevel inverters is efficiency which results from the ability of the inverters to minimize on switching losses and voltage stress on power components. Invented two-level inverters are less effective because they require higher switch frequencies and have large voltage steps during the transition. On the other hand, in multilevel inverters, the voltage swing is subdivided into a number of steps so that energy is not wasted in the course of the transitions.

The structure of multilevel inverters is also efficient due to the modularity of its construction in different levels. The fact is that all the modules work within a limited voltage range, so they are equipped with components with lower voltage drop that usually demonstrates lower conduction loss. Moreover, the stepped voltage waveform makes the fundamental waveform rich in harmonic where only a smaller amount of energy gets dissipated in the form of heat in inductive or capacitive loads [6].

Multilevel inverters have more control techniques such as Space Vector Modulation (SVM) and predictive algorithms that enhanced the performance of multilevel inverters. These methods ensure the switches operate only when required and thus reduce the number of times it has to switch thus uses less energy. This efficiency improvement is highly advantageous in applications which include; renewable energy systems where optimization of the power conversion is important.

However, such high efficiency comes at the cost of thermal management to deal with heat dissipation that results from operation. Intermediate cooling technologies done today include liquid cooling and phase-change material to make sure the inverter is within its ideal thermal envelope to increase component durability and ensure a reliable system.

1. 1. 1. 6 Scalability and Modularity

Multilevel inverters are easily scalable in a higher power level, more number of levels or modules are added, so it is useful in both low and high power applications.

1. 1. 1. 7 Challenges that must be addressed to optimize their performance

1. 1. 1. 7. 1 Complex Control Requirements

The use of voltage at multiple levels makes it necessary to control different levels of voltage which complicates the control algorithms. It is crucial to implement proper control strategies to safeguard the desired voltage levels and to monitor adequate performance of the inverter for different load conditions.

The structure of multilevel inverters entails the use of abundant switching devices, and consequently, involves precise control systems to synthesize the target output waveforms. Each voltage level in the inverter will require a particular switch state and the control system must coordinate the transition through these switch state. For instance, in the three-level neutral-point-clamped inverter, the switching sequence has to take the system from the positive, zero and negative voltage levels while ensuring that there is no diode overlap that will result to short circuiting.

The complexity of control rise sharply with the increase of voltage levels because more switches are needed to control and more control logic is needed for every single voltage level. On-time computation is vital to guarantee the smooth running of these applications especially those who have dynamic loads or vary input situations. Current control schemes can employ digital signal processors (DSPs) or field programmable gate arrays (FPGAs) to meet the required computational velocity and precision.

The other hurdle in the control of multilevel inverter is synchronization with the electrical grid inverter applications. In order to control the amount of power fed back into the grid the control system has to constantly measure voltage and frequency, and adapt the inverter output to the values. This necessitates quantitative ‘control’ and ‘feed-back’ methodologies, sometimes as offered by fast-speed sensors and sophisticated signal processing techniques.

Moreover, there are challenges including the switching losses, the harmonic distortion and thermal regulation that has to be met by the control systems. Problems such as localized high frequency current ripple and device dv/dt switching noise are often addressed by commonly used techniques such as Space Vector Modulation (SVM) and Selective Harmonic Elimination (SHE) to regulate switching patterns.

But their use involves more precise modeling of the inverter and currents used by loads to invert systems, making them more complex.

1. 1. 1. 7. 2 Increased Component Count

The utilization of several switching devices, capacitors and other components enhances the complexity, size and costs of the inverter. This can also lead to higher failure rates since these processes involve the production of numerous items, which is why risks have to be managed through effective design and control.

This is a control strategy that results in substantial improvement of the quality of the inverter output voltage waveform. Such and similar strategies enable construction of pulses with waveform almost sinusoidal at the high frequency, for instance in tens of kHz or even more, and at the same time devoid of significant harmonics distortion, provided that the pulse width modulation is done at the same frequency. A high frequency carrier signal is then compared with reference sinusoidal signal to derive the required switching signals of the inverter.

High frequency PWM has its biggest boon in low frequency lower order harmonics that are the worst for PQ. The waveform has a nicer shape which fits better with delicate loads other than satisfying grid code requirements. This capability is especially valuable for the renewable energy systems, electric vehicle charging units, and UPS, where power quality is inherent.

Nevertheless, high-frequency PWM has many issues. It was noted that as a result of the higher frequency of switching the switching losses rise and thus results in low efficiency and high thermal stress on the inverter components. To prevent these effects the use of good thermal management that involves use of heat sinks, forced air cooling among others must be enhanced. However efficient power conversion is achieved using high-frequency PWM due to the improvement of waveform and reduction of harmonic distortion [6].

1. 1. 1. 7. 3 Voltage Balancing

It is important to enforce balanced voltages across the various levels to ensure that multi-level inverters are stable. Imbalances are likely to cause higher loss, less efficiency, or even damage the diode installations of the inverter.

The problem is one of the most challenging that face many multi level inverters particularly those employing multiple capacitors or voltage sources for the generation of different voltage levels any unevenness in the voltage leads to distortion of the waveform at the output significantly increase the level of harmonic distortion and at times reduce the efficiency of the system or can be disastrous to the unit in the system.

In cascaded inverters' voltage balancing can therefore be described as balancing between the capacitor of the every module in converter for example in three level half regenerated the two capacitors in each module must to be at same moderate level to generate stable intermediate voltage and imbalance circumstance results in various output voltage levels and worsens the waveform which may cause overloading of single switches or modules.

In the same respect regarding the issues of voltage balancing effectiveness of advanced control schemes is one of permanent importance some like investor voltage balancing schemes employed dynamic regulation of its and on the regulation of its commutation profiles to utilize charge which is within capacitor similarly the real time feedback loop mechanisms are used to monitor voltage of each module in making necessary adjustment to modulation as and when required.

However there are also some designs that implement SSM involving a hardware solution for controlling and regulating voltage such as those implemented in the active balancing circuits however these approaches traditional comprehensions cost to power electronics platform but enhance the reliability and performance of converter as a result the voltage balancing is this recent issue of realizing multi level inverters and new methods are still being sold in the current day [5].

1. 1. 1. 7. 4 Complex Control Strategies

HVDC control involves handling of multiple voltage levels which may pose a challenge in terms of computation and implementation of control algorithms.

Increased Component Count: This may affect the cost, size and failure rate of the inverter system due to more components including switches, capacitors and diodes to be incorporated.

Faulty voltage regulation is a major concern within a multilevel inverter application, as it will adversely affect performance if not well controlled.

In particular, multilevel inverters present interesting benefits since they do not require bulky dc-link capacitors and can have a low dV/dt output, but they present complex control strategies. All these tactics must have control on switching sequences together with voltage balancing and harmonic minimization. The high order methods include Space Vector Modulation (SVM) or Selective Harmonic Elimination (SHE) that rely on complex algorithms that cannot be easily used in real time systems. However, employing these strategies with control algorithms that could vary with load or input condition is still a challenging area. Control systems implementation also requires effective hardware to provide the level of processing needed by devices like high-speed micro controllers or FPGAs.

Various control algorithms are a critical part of multilevel inverters since the control of the multilevel inverters is complicated. They also address the complex sequencing needed for the conversion process and control the resulting output waveform to optimize the operation of the system. A major obstacle comes in the form of synchronizing several switches and voltage levels to work simultaneously, lest effects such as short-circuiting, overvoltage, or even harmonic distortion occur [2].

The control methods which are widely applied in voltage source converters are briefly described below: One of them is Space Vector Modulation (SVM). SVM determines the inverter's output voltage through a point in a n-dimensional space that utilizes the available DC link voltage to the fullest possible extent while at the same time forcing as little harmonic currents as possible through the filter. However, as stated in sections above, SVM demands a good deal of computational resources, this means it calls for systems with high end micro processing chips such as digital signal processors (DSPs) or field-programmable gate arrays (FPGAs).

Another optimal design approach is Model Predictive Control (MPC). This strategy utilizes system models in the identification of system states in the future to allow for identification of the best switching sequences. MPC performs well in load conditions where changes in the conditions occur frequently since it does not significantly degrade with change.

Selective Harmonic Elimination (SHE) is still another advanced method that aims at eliminating special harmonic frequencies only. SHE also computes the exact switching angles required to zero out the undesired harmonics through solving nonlinear equations. However, its computational intensity becomes a restricting factor to be applied in high-speed systems or economical systems.

These complex control strategies underpin the inherent trade-off between performance and computational complexity, which continues to motivate the search for novel algorithms and hardware implementation fancy to make high-performance control feasible in a wider range of applications [6].

1. 2 Research Objective

The purpose of this study is therefore to develop a three-level DC/AC inverter based on half-bridge configurations and efficient voltage vector selection methodologies. The goal of this research is to propose a new inverter topology with high power density and low cost solution for renewable energy systems, electric vehicles and industrial motor drives. The specific goals of this research are to:

1. Develop a Novel Inverter Topology: Construct an inverter with three levels by using half-bridge structures therefore decreasing the number of components hence enhancing their efficiency without using the complicated magnetic components such as transformers.

2. Implement Advanced Control Strategies: In the appropriate selection of vectors, one can guarantee a better strategy of switching the inverter, which will consequently help in minimizing the levels of harmonization as well as even out the waveform of the output voltage. The control strategies will involve employing low frequency and high frequency switching methods for control purposes with emphasis on performance rather than efficiency.

3. Simulate and Validate the Proposed Inverter: Employ MATLAB/Simulink based systems to simulate the intended inverter topology and to assess the effects of various conditions on the system. These measures of performances such as efficiency, total harmonics distortion, voltage regulation and response to dynamic loads will be investigated widely in ascertaining the feasibility of the inverter for practical use[7].

1. 2. 1 Specifically, the research aims to achieve the following objectives

1. Propose the configuration of three-level inverter that can be employed in renewable energy systems employing half bridges.
2. Create a low frequency switch to generate the baseline waveform whilst using high frequency to reduce on the harmonic distortion.
3. A model should be created and tested for inverter and compared for different load conditions through MATLAB/Simulink.
4. Detect the Total Harmonic Distortion (THD) of the AC output, in order to examine the difference between the low-frequency switching and the hybrid control.
5. Analyze the power quality of the inverter output with a view of establishing its efficiency regarding grid-tied and off-grid uses.
6. The proposed work of this thesis is to develop a three-level half-bridge inverter with high efficiency and predicted waveform representation. This also entails the formulation of a model suitable for achieving optimum power quality and switching losses hence satisfying various applications.
7. This research compares the outcomes of two fundamental approaches in the control of current waveform, including low-frequency fitting and high-frequency pulse-width-modulation switching. This paper's comparative study sheds light on the trade-offs associated with each approach.
8. Harmonic distortion is a severe problem in power systems or systems involving sensitive loads. The findings of this research can potentially be used to reduce THD in the output of the inverter by improving the algorithms that control it, and the manner in which the switches operate.
9. The model has modularity that will allow the inverter be scaled for residential and industrial level applications, utility scale applications, and a distribution scale. This also address issues to do with modularity and ease of integration into a complete system.

1. 2. 2 Expected outcome

The expected outcomes of this research deal with optimizing the design concepts of not only three-Level half-bridge inverters but the operational knowledge regarding these structures as well. Firstly, this study will assess the viability of LF and HF

switching strategies in harmonizing the waveform quality and efficiency with thermal characteristics of the module. In low frequency switching, the intended effect, based on low switching losses, should be expected to complement improved efficiency across various industrial motor drives and high power applications.

In the case of high frequency switching, the goal expected is of getting an output waveform which is smoother with low Total Harmonic Distortion (THD). This particular result is significant to grid tied renewable energy systems, and sensitive electronic applications because the standards of power quality are often very high. A final outcome of the study is to reveal the trade-offs between these two strategies so that criteria for choosing the right switching strategy for a given application can be provided.

Furthermore, the work also envisions creation of a robust and flexible inverter structure that can easily be developed to fit different voltage and power ratings. This modularity will allow it to be incorporated into a wide range of systems from simple residential solar inverters to industrial scale systems. The study also anticipates contributing possibilities for more sophisticated control methods that govern switching behavior, reduce harmonic components, and improve general system performance. These discoveries will help expand the understanding of power electronics and create the foundation for new advancements concerning multilevel inverters.

A functional prototype of a three-level inverter using the proposed improved efficiency and less than 5% THD than in the conventional inverters.

High compatibility of the proposed inverter in diverse applications, especially in renewable energy systems and electric vehicles markets.

A qualitative report on the inventor with recommendations for further enhancements in case they are needed. The goal of this research is to develop a three-level DC/AC inverter with half-bridge configurations and voltage vector selection methodology.

Design a new inverter circuit that has better efficiency and a lower number of components.

They should incorporate vector selection algorithms to adjust the switching strategy so as to reduce the amount of harmonic distortion while at the same time increasing the quality of the output [6].

Predict and test the applicability of the proposed inverter and its efficiency in different contexts, including the use in renewable energy and electric vehicle systems.

1. 2. 3 Impact of Low and High-Frequency Switching on Inverter Output Waveforms

Output waveforms for both low and high frequency switching were used to compare the implications for the inverter. Through experimentation on the carrier signal frequency in the PWM block, we learned the impact of different switching frequencies in the output. Low-frequency switching showed a carrier frequency between several hundred Hz and several kHz, with visible steps in the output waveform together with higher harmonic distortion due to slower switching transitions compared to high-frequency switching. Whereas, high frequency switching in tens to hundreds of kHz range generated a lesser amount of harmonic content which presented a more sinusoidal waveform. Nevertheless, increase of the switching frequency was accompanied with larger switching losses, which presents a problem in the aspect of efficiency. Hence this analysis shows that while high frequency increases the quality of the waveform, it comes at the loss of extra power, particularly in high power applications.

Frequency of switching is another key factor, and the extent to which it can define the quality and waveform of the output in multilevel inverters. Low frequency switching which is synchronized with the switching transitions of the fundamental frequency of the output yields a stepped waveform with high levels of a harmonic distortion. This technique is beneficial for use in application where getting a high degree of waveform accuracy is not that critical, for example in industrial motor control applications.

In contrast, high frequency switching uses a much higher carrier frequency and this follows the output signal, producing a waveform that approximated a sinewave. This strategy is particularly important for micro-generation systems connected to the

electricity distribution network or loads that demand excellent power quality. However, the increased switching frequency poses issues such as more significant switching losses, and increased thermal loading on the components, which lowers the system efficiency.

The above-mentioned trade-offs based on low and high frequency switching are, however, dependent on Load conditions and application requirements. For example, low frequency switching provides a high level of efficiency in a steady state circuit but may not cope with dynamic loads where the response is required more quickly. High frequency PWM is used in the applications, which demands dynamic performance, but is sensitive to control algorithm and cooling system due to the related thermal stresses [6].

This research focuses on analyzing these tradeoffs, and thereby offer an understanding of how to choose the right switching strategies at the right time for various applications. The differences in the harmonic content, circuit efficiency, and thermal loading of the various approaches are examined in the study, in order to identify the optimal strategies to improve the inverter design and application

It has been agreed that the selection of the switching frequency highly determines the waveform of the multilevel inverters and the qualities it offers in aspects of power quality, efficiency as well as system reliability. Lower switching functions at the fundamental output waveform, common at 50/60 hertz. This strategy limits the amount of time spent switching thus reducing switching losses and thermal stress. However, because the output waveform is stepped, it produces considerable harmonic distortion, which in turn affects connected loads and system efficiency.

On our hand, we have high-frequency switching technique where the carrier frequency is much higher than the fundamental frequency, typically in the order of tens of kilohertz. This method allows for direct control of the output waveform that captures more accurately a sinusoidal signal with a suppressed level of Total Harmonic Distortion (THD). In exchange, switching losses and thermal stress are higher, and reliable cooling methods, as well as high-performance semiconductor materials, need to be used.

This study also shows that low-frequency switching is fine for industries that call the highest efficacy imperative while high-frequency PWM is ideal when fidelity is important, as with renewable energy systems and sensitive electronics. Comparing the harmonic profiles and efficiency of the two methods in this work also inculcate the idea of specifying the application where each strategy is best suited for in order to optimize cost of implementation against the amount of performance enhance possible.

1. 2. 4 Optimization of Switching Dynamics for Enhanced Inverter Performance

Issues of modulation technique and switching dynamics come into play whereby the performance of inverters will depend on these parameters. Perhaps one of the most important parameters to consider when improving inverter performance tends to be the superior tradeoff between speed and power density. Higher switching frequency provides closer emulation of the sinusoidal waveform with lower total harmonic distortion and thus higher power quality. However, this advantage is accompanied by more switching losses resulting from frequent state transitions within the cycle and consequently more thermal stress on various components and possibly a shortened lifespan of the system. In contrast, lower switching frequencies achieve these at the cost of high harmonic distortion in the output which makes the inverter unsuitable for immaculate waveform applications such as audio amplifiers. Consequently, proper determination of the modulation parameters becomes paramount in arriving at an efficient design of the converter permitting a balance between efficiency, and power quality, an area of importance in current applications like renewable energy systems that require reliability and stability in the long run.

Thus the optimum switching control is necessary for an optimal balance of the quality/efficiency/durability performance specification of the waveform. This work examines the performance of audio low-frequency fitting (LFF) and high-frequency pulse with modulated (PWM) control schemes. Although LFF offers superior efficiency because switching losses are reduced, the waveform's quality is lowered, and harmonic distortion is increased. On the other hand, high frequency PWM gives near sinusoidal output to reduce the THD further but increases the switching losses and switching stress. The results presented imply a requirement for consistent binary

digital switching plans that alter the switching frequencies according to the load and demonstrate a viable approach for future inversions.

This strategy plays a significant role in balancing the waveform quality and efficiency together with system reliability in the multilevel inverters. Timing, sequence and frequency of such transitions are known as switching dynamics that determine the time response of the inverter output current and other operating features of the inverter system.

In this study, thus, both low frequency and high frequency switching strategies have been discussed to compare both the approaches. Low frequency switching maximizes stay time or minimizing the transitions between states thus cutting losses and heat formation. This makes it suitable for high power where the efficiency and reliability is of importance. Nevertheless, the waveform becomes stepped and this forms a waveform with rich harmonics that may affect any connected load.

High frequency switching, on the other hand, uses higher carrier frequency in order to produce less noisy wave shapes with small value of THD. This strategy is essential for applications where power quality is critical, for instance, in renewable power systems connected to the utility grid. But because of the transitions, the switching losses and thermal stress are larger and have to be handled by efficient cooling systems and complex controller design.

The study shows a focus on the combination of the switching strategies such as low frequency and high frequency by taking advantage in the two. For instance, low frequency switching can be employed in using the system at steady state in order to get high efficiency in the system while high frequency PWM can be used in the periods when the wave form of the system is not good through using transient analysis. The kind of strategies proposed here also demonstrate a potentially effective method for maximizing PV inverter performance over varying condition [7]

1. 2. 5 Thesis Outline

This thesis is organized to introduce and advance the principles of multilevel inverters and concentrate on the design, control and verification of a new type of three-level inverter. The content is organized as follows:

Chapter 2 summarizes the state of the art on multilevel inverter structures, controls, and uses. Therefore this paper presents a comprehensive literature review on the multilevel inverter topologies, control techniques, and applications. This chapter will provide a brief idea about the improvements in this field in the last few years, and explore the problems which have not been resolved yet and why the proposed research is vital. Chapter 3 explains method such as the design of inverter topology, control algorithms, and simulation environment. This chapter outlines the design and development of the proposed inverter topology, the design of the half bridge component, the series connection of modules, and the most suitable control strategies. It also includes the details of simulation such as configuration of the inverter and the other settings used to test the performance of the inverter. Chapter 4 provides the results and discussion where performance of the proposed inverter is evaluated. The implications of the simulations that were carried out are shown and discussed in this chapter. The basic proposed inverter system is compared with other topologies and the efficiency of the control methodology is analyzed. Projections will be made about the applications, relevance, and significance of the work in the general area of power electronic conversion. Chapter 5 mainly aims to present a summary of the overall study, highlight the limitations encountered during the research as well as give recommendations for future research. Opportunities for development of the inverter with regards to further improvements in its design and scope of utilization will be explored.

CHAPTER 2

LITERATURE OVERVIEW

Multi-level inverters have been one of the most key enablers in the power electronic system during recent years because of their high quality of output voltage waveform with less amount of harmonics. According to Babaei et al. (2014:An introduction of the cascaded multilevel inverters was made by Good and Tichenor in 922-929 which made the various levels of adjustable ac supplies to moderate the size of medium- and high-power applications. Jahid et al. (2018:(model no. 60900-60920) pointed out that such inverters are critical in renewable energy systems especially in the off-grid solar systems since high efficiency of energy conversion is very important.

Research by Kangarlu and Babaei (2012:Publication 625-636 extends modeling of multilevel inverters and their advantages in terms of lowering the number of switching components and improving power quality on the AC side. Vahedi and Al-Haddad (2016:In chapter 13-15, the author proposed the PUC5 inverter topology which was particularly illustrated to work efficiently in three-phased systems, and – here again, strengthens the understanding that selecting an adequate topology for a given application is crucial.

Mariethoz (2014:Li et al (2014 4018- 4027) have published an article on advanced development of hybrid modular inverters with special reference to voltage control during dynamic loads. These papers form the basis for the research on improving Multilevel inverters for use in both(grid integrated and isolated) renewable energy systems.

2. 1 Multilevel Inverter Topologies

Multilevel inverters (MLIs) are one of the most widely used structures of power conversion systems in current and power systems particularly in high voltage, high power applications.

Multilevel inverters have evolved significantly, with several topologies available, each offering unique advantages and drawbacks. The most common topologies include the Neutral-Point Clamped (NPC) inverter, the Flying Capacitor inverter, and the Cascaded half bridge inverter.

Unlike conventional two-level inverters that use only plus and minus voltage levels to switch, the MLIs generate output voltage levels with multiple levels and hence will produce waveforms closer to sinusoidal. This inherently minimizes harmonic distortion, and thus the electromagnetic interference, which is always associated with it [7].

2. 1. 1 Neutral-Point Clamped (NPC) Inverter

NPC inverters use diodes to clamp the output voltage to multiple levels. This topology is widely used due to its ability to produce high-quality output voltage with low THD.

Also referred to as the diode-clamped inverter, this topology employs the use of diodes that clamp the voltage to mid-point of the DC link. Due to the ease of implementation and a simple control structure it finds its usage in industrial motor drives PFC applications. However, due to the fact that a large number of diodes are used in the system, it becomes complicated and has large losses as well.

The NPC inverter is categorized among the oldest multilevel inverter structures with the use of clamping diodes to moderate the voltage at the stages. Pulse-width-modulation of the triangular wave assures a low distortion output waveform which is ideal for Medium voltage operation. However, the fact which has made this design complex and costly is that it employs multiple clamping diodes.

Advantages: Reduced harmonic distortion and lower switching losses compared to traditional two-level inverters.

NPC inverters offer good harmonic performance with lower THD compared to traditional inverters.

The topology effectively reduces voltage stress on the power switches, allowing the use of lower-rated components, which can reduce costs and improve efficiency.

Challenges: Complexity in controlling the neutral point voltage, which can lead to voltage imbalance across the capacitors.

The primary challenge with NPC inverters is managing the neutral point voltage. Imbalances in the DC link capacitor voltages can lead to unequal voltage levels, adversely affecting the output waveform.

As the number of levels increases, the number of clamping diodes grows exponentially, complicating the design and increasing losses due to diode conduction.

2. 1. 2 Flying Capacitor Inverter

It uses capacitors to create different voltage levels rather than diodes. The charge held in the capacitors generates the voltage levels.

By using capacitors, this has the effect of providing the intermediate voltage levels needed for this structure. The fact that flying capacitors provide redundancy and voltage level flexibility is another fantastic feature of flying capacitor inverters. However, it is difficult to equalize the charge across the capacitors; also, the architecture requires a large number of capacitors, which raises the cost and complexity.

This topology does not use clamping diodes for maintaining the voltage levels it uses capacitors for the same purpose. The capacitors are used as sources of voltage, which can produce the output at free-form waveforms. Nevertheless, the number of capacitors needed to implement this topology is large and it make the system bulky besides increasing its weight.

This inverter topology is a multilevel topology which does not need clamping diodes because capacitors create the intermediate voltage levels. This design helps in simplifying the circuit as well as gives more options in creating output wave form. In the inverter, the control circuitry charge every individual capacitor to predetermined voltage levels hence the system can produce numerous voltage levels depending on the capacitor connections in form of a series or parallel connection.

The flying capacitor inverters also have redundancy, which act as its strength, making them highly reliable. If a capacitor is faulty the system can still operate and switch to a different pattern though at low voltage levels. This self-healing ability makes the topology especially desirable for the important applications such as renewable and sustainable power systems and Industrial AMBs.

However, there are difficulties connected with capacitors too: The numbers of capacitors and the size and mass of capacitors increase as the number of voltage levels increases. Also, the charge levels of the capacitors must be regulated so that the device can produce steady voltage amounts. When voltage in the capacitors is not equal it brings in about waveform distortion and a lowered system efficiency.

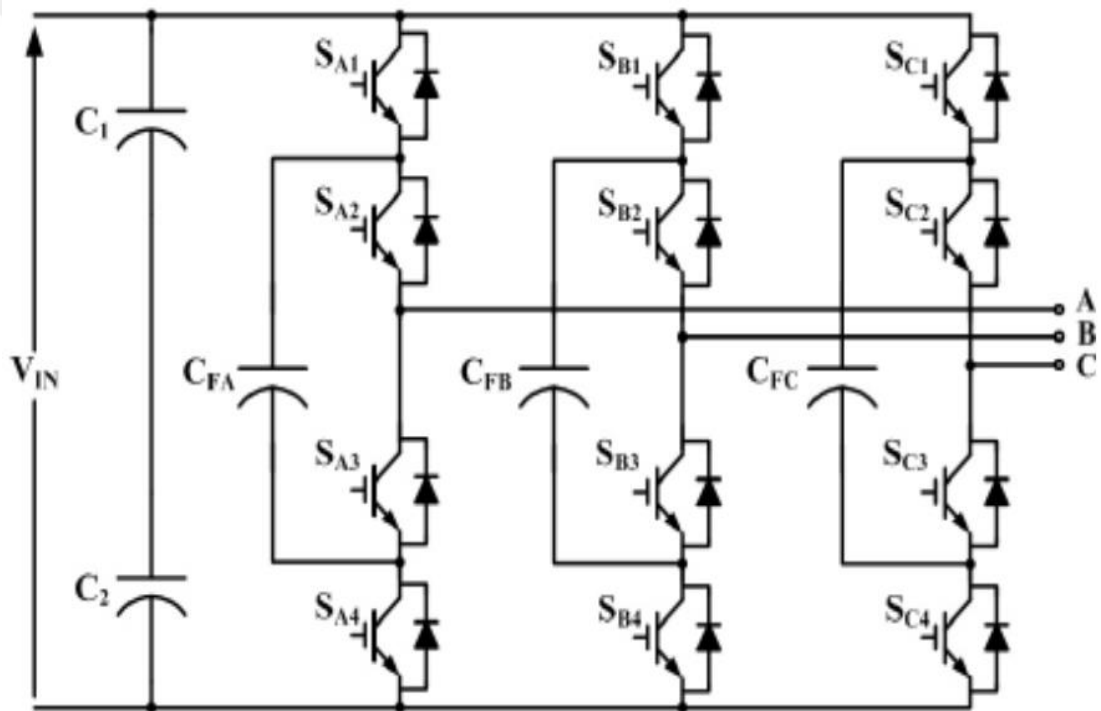


Figure 2. 1 Three Level flying capacitor multilevel inverter Topology

control strategies, voltage balancing algorithms especially relating to real time flying capacitor inverters. Nevertheless, these inverters continue to be an attractive proposition in applications where countries factored modularity and flexibility as being important[6].

Advantages: Reliability is increased via control flexibility and voltage level redundancy.

compared to NPC inverters, offers more control over voltage level, which facilitates the generation of higher voltage levels with fewer components. Because of the modular structure, adding additional capacitors and switching devices makes it simple to scale to greater levels.

Challenges: Requires a large number of capacitors, which raises the inverter's size and cost. Another crucial issue is balancing the voltages of the capacitors. The requirement for numerous capacitors, which can raise the inverter's size, weight, and cost, is a major disadvantage of flying capacitor inverters. To ensure steady operation, voltage balancing across the capacitors is essential and calls for intricate control algorithms.

2. 1. 3 Cascaded half bridge Inverter

Consisting of several series-connected half bridge cells, each producing a different voltage level. Because of its great scalability and modularity, this design is appropriate for high-power applications.

The cascaded half-bridge inverter is a hierarchical structure that can be easily expanded and improved in terms of some aspects. Each module thus produces a segment of the total output voltage and makes it possible for the system to deliver higher levels without adding configuration. This topology has been adopted comprehensively in the renewable energy system as well as industries owing to its durability and high performance.

The cascaded half-bridge inverter is admired in applications of multilevel inverters because of its modularity and flexibility in expansion. This topology comprises of several half bridge modules connected end to end and each of them contributes with a particular voltage value as the total voltage of the system. This modularity makes the cascaded half-bridge inverter suitable for high voltage or high power application like industrial motor drive, renewable power system and electrical vehicle charging station.

Another advantage that is attributed to the cascaded half-bridge topology is the generation of near sinusoidal output voltage waveform with low total harmonic distortion. More number of modules cause increase in voltage levels that can be produced by the inverter hence the waveform at the output end is more smoother

than the square wave form hence nearer to the sine wave. This characteristic reduces the Total Harmonic Distortion (THD) by a very large margin improving power quality while minimizing interference with other components in the system.

However, another disadvantage of the cascaded half-bridge inverter is seen in its control and some of the components used in the system. Inverter and the resonant tank in each module should use an independent DC source; however this can cause design issues with power supplies. In addition, the control system has to control all the modules in order to synchronize the operation effectively, and also manage the voltage. Even if there is an imbalance in either the dc sources or in the switching sequences, waveform distortion, higher currents losses and possible destruction of the components.

Nonetheless, because of these challenges, the cascaded half-bridge inverter continues to be preferred by many due to flexibility and performance. New control strategies, the robustness of power electronics devices, and the development of new semiconductor devices have paved the way to improve the performance of the diode rectifier, permanently establishing it in several multilevel inverter applications.

The cascading half bridge (CHB) inverter is the most often utilized multilevel inverter topology for renewable energy applications. It is made up of many half bridge modules that are joined end to end and have separate DM sources supplied to them. The CHB topology has a number of benefits, such as:

1. **Modularity:** This system is expandable because of the half bridge modules, which are regarded as independent channels.
2. **Better output waveform:** When many half bridge s are connected in series, the inverter may generate greater voltage levels, which results in a smoother output. Thus, the larger the number of levels, the closer the waveform is to a pure sinusoidal wave hence minimizing the overall THD value.

Because of the advantages of flexibility, scalability, and improved performance, the CHB topology is chosen in this thesis for the inverter's design and implementation. The ability to easily expand to greater voltage and power levels is one of modularity's advantages. Low harmonic distortion and good voltage balancing are also features.

The Cascaded half bridge inverter's modular design facilitates easy scalability with the addition of additional half bridge modules. This adaptability is especially useful for situations that call for high powers and voltages. It offers minimal THD and great output voltage quality, making it perfect for applications where power quality is a key factor.

Challenges: Each half bridge needs its own DC source, which can add to the system's complexity and raise costs. The power supply design may get more complex if each half bridge cell has its own DC source, especially in high-level arrangements. Multiple half bridge cells might result in an increased component count, which can raise overall costs and increase maintenance needs.

2.2 Control Strategies of Multilevel Inverters

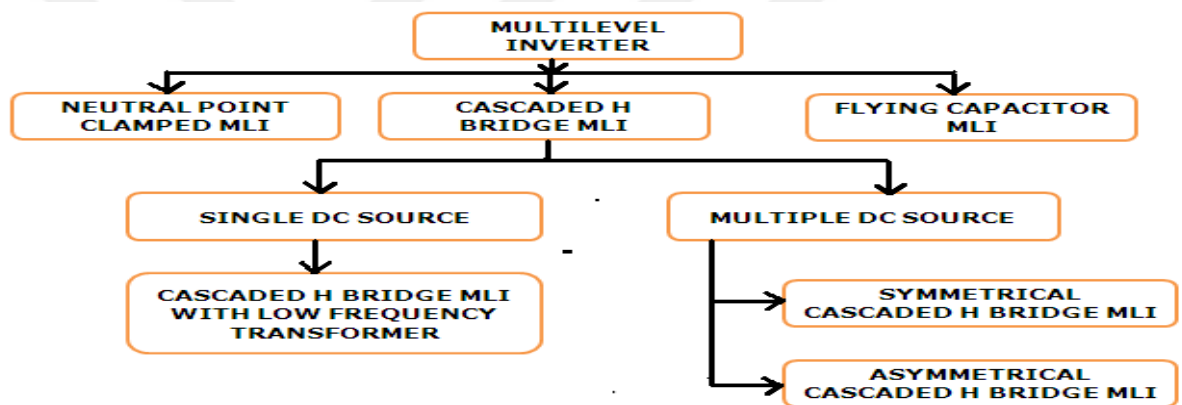


Figure 2.2 Control Strategies of Multilevel Inverters

2.2.1 How Sinusoidal Pulse Width Modulation (SPWM) is worked?

It is noteworthy that one of the most practical and straightforward control strategies for inverters is SPWM. A high frequency triangle wave, known as a carrier signal in discontinuous PWM, is contrasted with a sinusoidal low frequency wave. The instants of switching depend on the cross points of the two signals and the pulse train so created is employed to drive the inverter switches. Although the configuration for the SPWM is straightforward, the high frequency of the switching signals could result in significant switching losses.

The application of SPWM as a control method for multilevel inverters is preferred by many researchers because of its simplicity and efficiency. It works by producing

control pulses for the inverter switches by comparing a sinusoidal reference signal to a high frequency triangular carrier signal. This technique produces an output waveform as close to the sinusoidal as can be, which minimizes harmonic distortion. Nonetheless, the high-frequency switching that is characteristic of SPWM has high power loss, especially where the application is for continuous use [6].

Principle: By altering the pulse width in line with a reference sine wave, SPWM regulates the output voltage. To reduce harmonic content, the switching frequency is usually significantly higher than the output frequency.

Application: Because of its ease of use and efficiency in lowering harmonic distortion, it is frequently employed in inverters.

Challenges: SPWM demands more switching events at higher voltage levels, which can lead to increased switching losses and worse efficiency.

2. 2. 2 SVM, Space Vector Modulation

SVM is a particular type of modulation technique whose objective is to lower the level of one or more harmonics in the output waveform. This shows that by appropriately adjusting the inverter's switching angles, it is possible to improve the output waveform by filtering out certain harmonics. However, because it calls for solving complex mathematical equations, it is a little out of place for the real-time use of SHE.

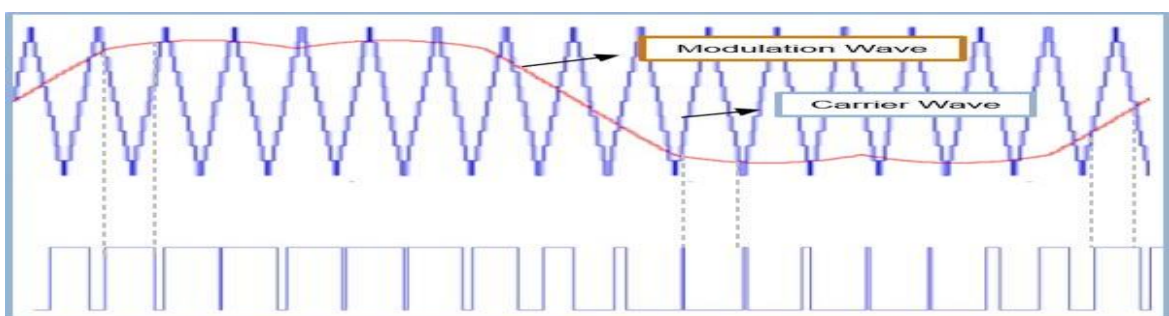


Figure 2. 3 Space Vector

SVM is even a more enhanced modulation method that more improves on the switching sequences of the inverter. In the space vector plane, output voltage of

inverter is represented in terms of vectors, the necessary switching states required to achieve the desired output voltage is then computed. This approach enhances the harmonic characteristics of voltage and current but involves heavy calculations to implement, and so it can be integrated into systems such as high-performance motor control drives and renewable energy resources.

Principle: SHE reduces specific harmonics in the inverter output by meticulously modifying the switching angles. This method produces incredibly low THD by eliminating specific harmonics.

Benefits: Exceptionally helpful in applications where certain harmonic frequencies need to be reduced or eliminated.

Challenges: Determining the appropriate switching angles requires computing complex equations, which may be computationally taxing.

2. 2. 3 Selective Harmonic Elimination (SHE)

SHE is a specific kind of modulation technique where the goal is to reduce the output waveform's level of one or more harmonics. This demonstrates that the output waveform can be improved by filtering out specific harmonics by appropriately altering the inverter's switching angles. However, it is a little inappropriate for the real-time application of SHE because it requires solving equations of high order in mathematics.

SHE controls particular harmonic in the voltage waveform directly based on equations that describe the optimal angle for switching. This approach can be said to be highly efficient of reducing lower order harmonics while at the same time being efficient. But as the number of desired harmonics increases, the implementation of this method becomes very challenging and requires intricate timing and control.

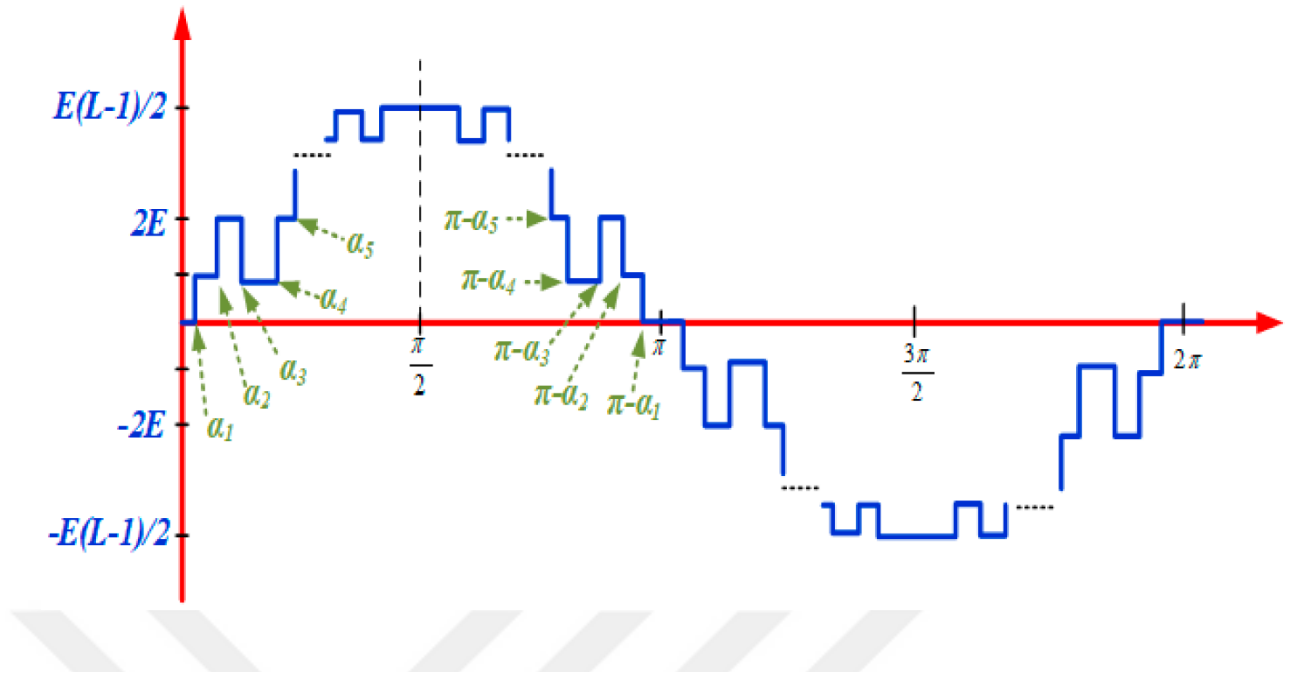


Figure 2. 4 Selective Harmonic Elimination

Principle: By carefully adjusting the switching angles, SHE lowers certain harmonics in the inverter output. With this technique, selected harmonics are eliminated, resulting in extremely low THD.

Benefits: Extremely useful in applications that need to reduce or eliminate specific harmonic frequencies.

Challenges: Finding the ideal switching angles necessitates calculating intricate equations, which might be computationally demanding.

2. 2. 4 Hybrid Modulation Techniques

Additionally, there exist circuits with high efficiency and minimal harmonic distortion that combine both low frequency and high frequency switching modes. In a hybrid technique, the corrective wave form levels receive high frequency application, while the main voltage levels receive low frequency application. It combines several control techniques to maximize each method's advantages while minimizing its drawbacks. To strike a compromise between minimal switching losses and excellent power quality, for instance, SPWM and SVM can be combined. This method makes sure that switching losses and harmonics can be traded off, which is highly helpful in applications where both factors are crucial.

These advanced modulation techniques adopt features from several controls and thus improve inverter operation. For instance, it is possible to mix low-frequency amplitude modulation during steady state for high efficiency and high-frequency for

PWM for high-quality waveform during transient behavior. Such techniques are particularly useful in the application areas such as in renewable energy systems with time varying power generation and load condition. Such hybrid method usually incorporate the use of intelligent control system for instance the machine learning to learn how best to perform under changing conditions [7].

Hybrid modulation uses the several techniques such as SPWM and SHE combined in a way that each of them will benefit from. For example, the proposed system can use the SPWM technique for high-frequency control and SHE technique for steady state control to get minimum THD and maximum efficiency. These techniques are best suited when dynamic performance changes are needed as in electric vehicle chargers and grid-tied inverters.

Consequently, there is consensus that the choice of the switching frequency significantly influences the waveform of the multilevel inverters and the attributes of power quality, efficiency and reliability that are realized in the system. Lower switching functions at the fundamental output waveform and typical at 50/ 60 hertz. The major advantage of this strategy is that it cuts the time available for switching thus minimizing both switching losses and thermal stress. However, because the output waveform contains steps, a fairly large level of harmonics is generated, which then impacts connected loads, as well as system efficiency.

On our hand, we have high-frequency switching technique where the carrier frequency is very high relative to fundamental which is in terms of tens of kilohertz. This method affords direct control a carrier output waveform that is always closer to a sinusoidal wave in reproduction and with lower Total Harmonic Distortion (THD). In return, switching losses and thermal stress are higher and reliable cooling methods and high-performance semiconductors are required.

This research also reveals that low frequency switching is acceptable in those industries where the highest efficacy call is made while the high frequency PWM is suitable in areas that fidelity is crucial such as the renewable energy system and sensitive electronics. In this work, the comparison of the harmonic profiles and efficiency of the two methods also introduces the practice of identifying the

application area for each strategy to achieve best fit for cost against the extent of performance boost feasible.

2. 3 Applications of Multilevel invertors

When talking about multilevel inverters, it's important to remember that they're used in the following applications: Multilevel inverters are essential to many contemporary applications, particularly those that need great efficiency and power quality. Because multilevel inverters can handle high power and high voltage with optimal efficiency, they are widely used in a variety of industrial and renewable energy applications.

2. 3. 1 Renewable Energy Systems

In photovoltaic and wind energy systems, which are the most prevailing renewable energy systems, multilevel inverters are instrumental in conversion of the direct power produced into the alternating power that can be integrated into the grid. This output characteristic makes multilevel inverters suitable for these applications since they possess low THD as a matter of fact.

Multilevel inverters applications are very important in renewable energy systems especially in the photovoltaic(PV) and wind energy systems. These systems need good power quality for the generated power to be incorporated back into the power system or fed to nearby users. By generating stepped voltage output, multilevel inverters have low total harmonic distortion and are well suited for renewable energy applications interfacing with the power grid[8].

In PV systems, multilevel inverters are used to maximize power point tracking (MPPT) since these inverters regulate the variable DC input voltages to give constant AC outputs. Their utility is to guarantee that the highest possible yield of solar panels will be achieved in conditions of different levels of sunlight. As in wind energy systems, multilevel inverters handle the varying nature of wind turbine output and regulate the power delivered to the grid.

The design of multilevel inverters also enables their scalability from residential applications to utility scale solar farms. Furthermore, their high efficiency and tolerability of high power levels make the devices crucial components of renewable energy systems. The latest control tactics including the predictive control or artificial

intelligence algorithms also improves their performance and guarantee operations under fluctuating environmental conditions.

2. 3. 2 Electric Vehicles (EVs)

Multilevel inverters are also find uses in electric vehicle propulsion systems as it help to convert the DC power sourced from the vehicle battery to AC for driving the electric motor. Since the architecture of the CHB inverter is assumed to be modulated, it is also scalable to the power requirements of the application of the concerned EV. One of the most emerging application areas of multilevel inverters is electric vehicles (EVs), as it power conversion and motor control application. In EV powertrains, inverters have been used mainly to convert direct current (DC) from the battery into the alternating current (AC) necessary in the electric motor. Multilevel inverters which work at high efficiency, offer better utilization of energy, thus increasing the driving range of EVs.

A main problem of utilizing EVs is regulating power quality at various running conditions. This issue is overcome by multilevel inverters through generation of low distorted AC output to help improve the motor efficiency and reduce the electromagnetic interference. The modularity of multilevel inverters also makes them scalable for use in Electric Vehicles – from small passenger car versions to substantial commercial vehicle versions[9].

Besides motor control applications, the usage of multilevel inverters has also been employed in charging systems of EVs since these inverters enable the conversion of received power from the grid into the required form for powering up the battery. Sophisticated control techniques as two-way power exchange mean that the same inverter can be used for charging and discharging mechanisms, including vehicle-to-grid (V2G).

New technological developments in inverters are expected to create related enhancements in multilevel inverters used for EVs utilization through SiC or GaN semiconductor applications. Each of these innovations will help to expand the market of electric vehicles by enhancing their characteristics, also decreasing prices and developing environmentally friendly transport systems.

2. 3. 3 High-Power Motor Drives

In number of industrial applications, multilevel inverters are high rated motors used to drive high power motors particularly in oil and gas industries, mining industries and manufacturing industries. The given inverters are easy to control by having less switch loss, less conveyance losses, high voltage and current which make it suitable to be used in high power motor drive applications.

Multilevel inverters have more demand in high-power motor drives due to load fluctuating, the efficiency, and reliability of the operations required by these drives. It has been established that these systems utilize inverters to convert the direct current electrical power into alternating signal energy required to drive the industrial motors. The high quality of the output waveform acquired from multilevel inverters leads to less vibration, noise levels and energy losses for the motor.

Multilevel inverters are convenient because they are modular, and can be easily scaled for high power motor drive applications. Cascading further adds more modules the inverter's voltage and current capabilities, making it suitable to used in conveyor systems, compressor, and pumps among others. In addition, the stepped voltage waveform mitigates voltage stress across the motor windings thus improving the overall lifespan and effectiveness of the motor.

However, high-booster applications are more complex due factors such as heat dissipation and suppression of harmonics. Higher power levels produce a lot of heat and thus need some cooling systems to ensure the circuits work fine. Undesired harmonic frequencies, if not controlled, causes over heating of the motor and accordingly a drop in efficiency. These problems are common and are solved by other enhanced control techniques like Space Vector Modulation (SVM) and selective harmonic elimination [8].The MLIs remain the key to future developments in high-power rotating machines where research efforts are devoted to increasing the efficiency of inverters, lowering total harmonic distortion, and increasing thermal capability. These advances keep multilevel inverters as an essential form of motor drive systems in the modern industries.

CHAPTER 3

METHODOLOGY

The actual process of designing the three-level inverter and the steps involved in the simulation process is described in this chapter. This involves the decision on the inverter topology, the choice of the switch control techniques and the simulation scenario of the inverter.

3. 1 Inverter Topology

In this thesis work, the proposed three-level DC / AC inverter is developed from the half bridge configuration. Each half bridge module consists of four switches and is capable of generating three voltage levels: May be positive or negative or even zero. Cascading realizes the link of several half bridge s while the inverter realizes the potential of forming high voltage levels and enhancing the output voltage waveform [11]. The method for developing the proposed inverter topology is outlined through results that emphasize improved performance with fewer required components and intricacies in the circuit.

3. 1. 1 Half bridge Module Design

In actual physical design of the inverter topology, the half bridge module forms a fundamental part of the architecture. Each module consists of four switches arranged in an half bridge configuration, allowing it to produce three voltage levels: additive polarity; positive, negative and zero polarity. As with many topologies, the phase can be built up with multiple half bridge modules connected in series, and produce the output voltage levels that are needed. While building each of the half bridge modules, insulated gate bipolar transistor (IGBTs) is employed since it performs high speed switching and is well suited for high power operations.

The half-bridge module is the basic structure of the multilevel inverters and contains two switches and a DC voltage source. This module creates two voltage levels including positive and zero voltages every time it connects the DC source or the load.

In the context of a three-level inverter, two half-bridge modules are connected in series, providing three distinct voltage levels: positive, zero, and negative.

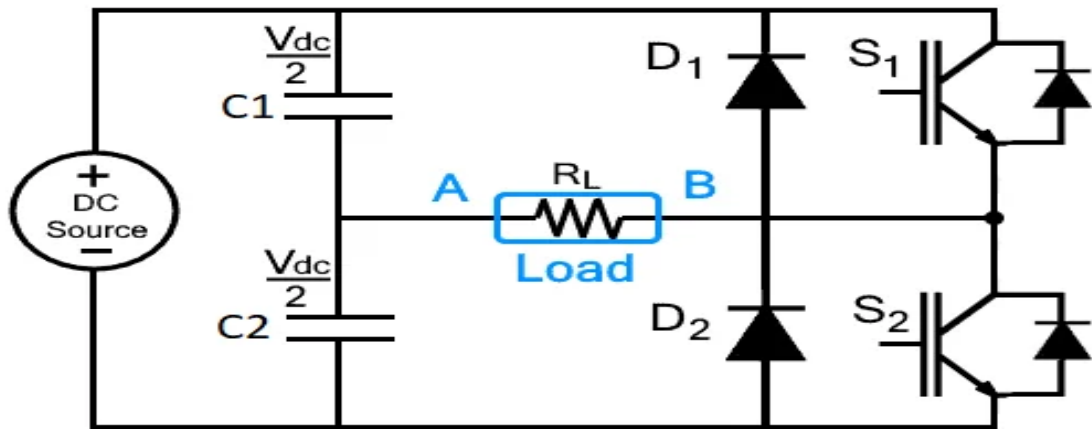


Figure 3. 1 Half Bridge Module Simple Circuit

Simplicity and reliability of the half-bridge module are reflected in its design. The power switches, usually known as IGBTs or MOSFETs, have to switch on and off very quickly, and possess a high rating current. Reset currents through switches R_{s1} and R_{s2} are used to include diodes that make the current run in only one direction and prevent reverse currents in order to protect the switches from voltage.

There are some large capacitors used to smooth the DC voltage and other small capacitors to block high frequency interference. The sizes as well as positions of these capacitors are generally extremely sensitive, especially in cases of the selective circuits that possess the dynamic loads of electricity. Thermal management is another concern as switch and Diodes get heated during operation Th_2 . Heat sinks and cooling fans are the most widely used methods of heat dissipation and prevention of thermal runaway condition.

Design Considerations: In each the half bridge module there are created three voltage levels: positive, zero and negative. The emphasis of the design is made on minimizing switching losses as well as on the circuit performance under varying loads.

This means that the kind of switches to be used, either IGBTs or MOSFETs has to be chosen in order to meet the performance of the half bridge module. Other parameters,

including the rate of switching, voltage and current capabilities must be achieved to guarantee proper functioning.

It is very important to arrange the half bridge module on the PCB so that the parasitic inductances and resistance are reduced to the lowest level possible so as not to reduce the efficiency and performance of the inverter.

Components Used: Of these, MOSFETs are chosen to switch frequently at high speed thus increasing efficiency while capacitors are used in balancing the voltage.

Challenges: In the design of the half bridge module, switching losses are the main area of concern, which becomes even worse at high frequencies. In choosing appropriate cooling techniques and methods means of thermal control, the danger of overheating and, therefore, the decrease in the lifespan of the inverter parts should be taken into consideration.

The control of the half bridge module depends with the appropriate synchronization of the switching signals in order to synthesize the expected voltage levels. Slight changes in either of these parameters lead to rise in harmonic distortion and therefore poor power quality [10].

3. 1. 2 Connected series half bridge

The half bridge module outputs are connected in series to realize the each high voltage inverter that's necessary for the future development of inverters. The number of the steps of the resolution in the resulting waveform is determined by the number of the half bridge modules connected in series. In a three-level inverter application, two half bridge modules are said to be connected serially in nature.

Configuration: A single inverter is formed by connecting two micro half bridge modules in series and several of such inverter modules are connected in parallel. This configuration also makes voltage levels to be escalated by adding more modules in the system.

Advantages: Due to the connection of series, voltage is higher and waveform is better and it can apply to high power electronic devices.

The series connection of half bridge modules as a means of inverter design offers flexibility and scalability of a complicated structure. More yet another module can be

incorporated for increasing the count of the voltage levels, enhances the resolution of the output waveform and reduce the THD.

In the disclosed embodiment, the inverter is operable at relatively low switching frequencies since there is a plurality of half bridge modules, which yields decreased switching losses.

Challenges: For the proper functionality of the inverter, it is necessary to ensure that current voltage levels from each half bridge module matched as much as possible. Voltage unbalanced situations cause increase in losses and also affect the internal components of the inverter.

The control algorithm becomes even more complex because the modules are connected in series and the control algorithm must coordinate the operation of each module to obtain the required performance characteristics of the output signal.

3. 1. 2. 1 Switching Strategies Simulation

The two switching strategies: low- frequency fitting (LFF) and high- frequency sinusoidal PWM (HFSPWM) were used. LFF modulated the frequency following that of the modulation wave, offering a simple stepped output; on the other hand, HFSPWM applied a triangular carrier at an operating frequency of 20kHz to develop a continuous sinusoidal pattern output [13].

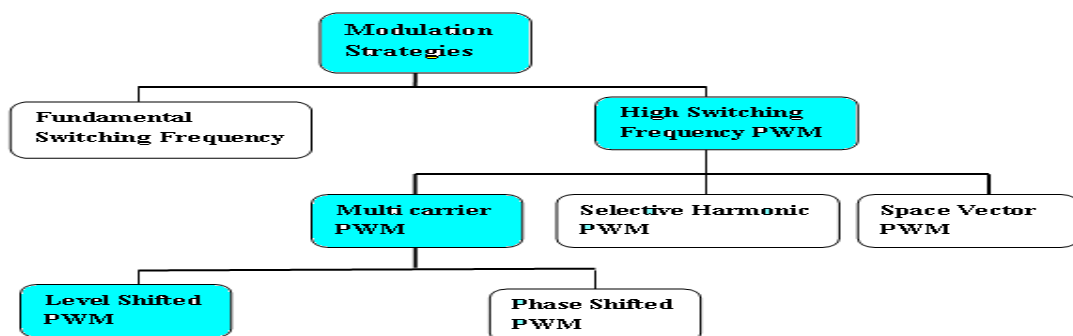


Figure 3. 2 Modulation techniques Flow Chart

In the connected series half-bridge topology, different half-bridge modules are integrated to obtain higher voltage levels. Every module works on its own to bring to the total output a fraction of the magnitude voltage we desire. This modularity makes scalability possible and it also enables the system to be designed with redundancy

where one or more units of a particular module can be bypassed. However, this configuration creates some difficulties with voltage balance of the capacitors in the modules, and voltage balance issues must be solved by some control or hardware means for instance by the use of balancing capacitors [10].

From the MATLAB Simulink simulation of this topology, it is evident that this topology is highly efficient and effective for use in medium power applications.

Output Waveform Analysis

In order to assess the harmonic content of the output waveform, FFT analysis was performed. Non-sinusoidal indexes like total harmonic distortion and harmonic peak factorload plus spectral residue index were obtained to evaluate the waveform quality.

It is also important to include how efficiency and Thermal analysis can be achieved Energy efficiency aesthetic.

Switching losses were derived from the energy lost during transitions, and thermal performance from the junction temperature of the switching device.

3. 2 Switching Strategy

In this context it could be said that the control of the three level DC/AC inverter proposed in this paper could be analyzed in terms of the switching states of the converter. All of them reflect a different set of conducting switches that define the connection of the input capacitors to the load and, therefore, the level of the output voltage. The switching strategy is intended for the effective conversion of the power as well as keeping the sum of voltage of the input capacitors constant.

This proves that the switching strategy has a direct implication on the kind of performance exhibited by the inverter. As for this thesis, a combined switching scheme is used for creating the baseline waveforms at LF and for preventing harmonic distortion at the HF.

In this method the inverter works through switching various configurations of switches in the respective two half bridges to production of appropriate output voltage levels. Following is the switching strategy of five-level CHB inverter.

3. 2. 1 Voltage Levels

1. $+V_{in}$
2. $+V_{in}/2$
3. 0
4. $-V_{in}/2$
5. $-V_{in}$

Half bridge Structure:

Each half bridge consists of four switches:

- half bridge 1: S1,S2,S3,S4
- half bridge 2: S5,S6,S7,S8

Each half bridge operates independently to generate two voltage levels: $+V_{in}$ and 0, which, when cascaded, create the desired output.

Switching Strategy:

1. Output Voltage: $+V_{in}$

- Switches Conducting:

half bridge 1: S1 (ON), S4 (ON)

half bridge 2: S5 (ON), S8 (ON)

- Operation:

Both half bridges are configured to apply the full positive DC source voltage.

Output voltage is the sum of the two $(+V_{in}) + (+V_{in})$

2. Output Voltage: $+V_{in}/2$

- Switches Conducting:

half bridge 1: S1S1S1 (ON), S4S4S4 (ON)

half bridge 2: All switches OFF.

- Operation:

half bridge 1 produces $+V_{in}$ and half bridge 2 remains at 0 V.

The resulting output is $+V_{in}/2$

3. Output Voltage: 0

- Switches Conducting:

half bridge 1: S1S1S1 (ON), S3S3S3 (ON)

half bridge 2: S5S5S5 (ON), S7S7S7 (ON)

- Operation:

Both half bridge s are in opposite polarities and cancel each other out.

The resulting output voltage is 0 V.

4. Output Voltage: $-V_{in}/2$

- Switches Conducting:

half bridge 1: All switches OFF.

half bridge 2: S5S5S5 (ON), S8S8S8 (ON)

- Operation:

half bridge 1 remains at 0 V, and half bridge 2 produces $-V_{in}$

The output is $-V_{in}/2$

5. Output Voltage: $-V_{in}$

- Switches Conducting:

half bridge 1: S2S2S2 (ON), S3S3S3 (ON)

half bridge 2: S6S6S6 (ON), S7S7S7 (ON)

- Operation:

Both half bridge s produce the full negative DC voltage.

The resulting output is $-V_{in}$

Table 3. 1 Summary of Switching Combinations

Output Voltage	half bridge 1	half bridge 2
$+V_{in}$	S1S1S1, S4S4S4	S5S5S5, S8S8S8
$+V_{in}/2$	S1S1S1, S4S4S4	OFF
0	S1S1S1, S3S3S3	S5S5S5, S7S7S7
$-V_{in}/2$	OFF	S5S5S5, S8S8S8
$-V_{in}$	S2S2S2, S3S3S3	S6S6S6, S7S7S7

3. 2. 2 Low-Frequency Switching

Low frequency switching is used to generate the fundamental output voltage waveform of inverter. This in turn lowers the ‘switching losses’ and hence increases efficiency of the inverter. PQ is an important waveform quality to determine the working efficiency of an inverter at those power plant applications where PQ matters most. The quality of the output waveform has an impact on the reliability and efficiency of such other interconnected devices as well as the power system. Therefore for this study the waveform quality of low and high frequency switching strategies has been investigated using Matlab software in Simulink [11].

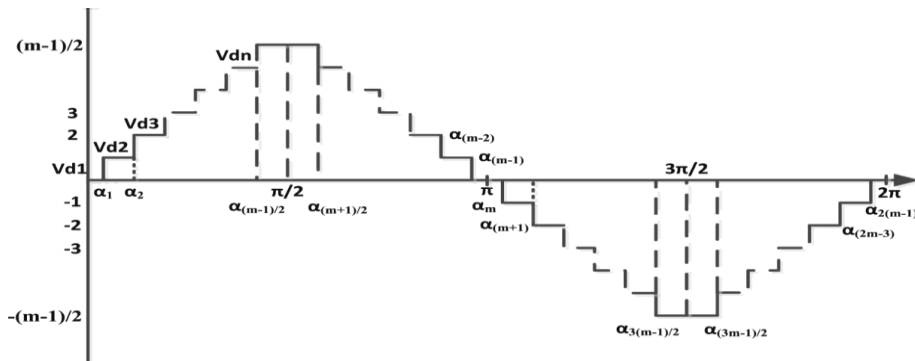


Figure 3. 3 LFS Analysis

where despite the fact that the strategy exhibited more distortion it was quantized in steps because of a smaller number of the switching transitions. However, although this stepped waveform is suitable for this type of operation as motor drives, it is not suitable for the refined load requiring sinusoidal type of input. That is why, using Total Harmonic Distortion (THD) calculation the waveform mentioned above has 17.5 % of THD due to the stepped waveform having harmonic distortion. Some of these distortedness may result in low energy efficiency of the loads that are connected to it and more heating up.

However, high frequency PWM approach produced waveform with shape closer to sinewave as evidenced by the waveform shown below: This strategy made it possible to have more control over the switching states and thereby generate a waveforms using a high frequency triangular carrier wave. By increasing the waveform quality of the AC voltage the high-frequency PWM strategy was given a THD of 3.2%. Such enhancement is particularly important for grid-connected PV systems because there is a requirement for the level of harmonic distortion.

The research has therefore shown that the choice of switching strategy has to be done based on the need that the application may have. Low frequency switching therefore yields a model with higher efficiency but having a very bad waveform quality.

A low-frequency switching restricts the switching to occur at the fundamental frequency of the output waveform. This is follows the rationale of reducing switching losses because fewer switches take place per cycle. It particularly found

suitable for areas where power density and get thermal efficiency of priority over wave form quality like industrial motor drives application. However, the output waveform produced by this method has a stepped waveform and has high harmonic distortion and is, therefore, not very sensitive.

For the correct output voltage to be obtained in each of the half bridge module, the switches are controlled as explained below.

Approach Low frequency switching also helps in reduction of switching losses since the number of switching events per cycle is also minimized. This strategy is perfectly fine for applications wherein the focus is more on getting maximum performance and not so much on harmonic performance.

Benefits: Low temperature at the moment of switching on devices that consequently increases their reliability and service life of the inverter.

3. 2. 3 High-Frequency PWM

To reduce the harmonic distortion of output waveform high frequency pulse width modulation technique is used. The carrier signal is of triangular waveform while the reference signal is sinusoidal whereby control of the switching functions of the IGBTs is achieved. That is, it is possible to control the amount of the high harmonic currents supplied to the electrical grids by appropriate selection of the carrier signals frequency.

It is a control strategy that leads to considerable enhancement of the quality of the inverter output voltage waveform. This and similar strategies allow setting up of pulses with near-sinusoidal waveform at high frequency, for example from tens of kHz or more with minimal harmonic distortion provided that the pulse width modulation is effectuated at the same frequency. The high-frequency carrier signal is then compared with reference sinusoidal signal to produce the desired switching signals for the inverter.

High frequency PWM has its biggest benefit in reducing lower order harmonics, which are the worst for power quality. The waveform obtained has a nicer shape, making it appropriate for driving delicate electronic loads besides meeting grid code

requirements. This capability is especially important in the renewable energy systems, electric vehicle charging units, and UPS where power quality is crucial.

Still, high-frequency PWM has its problems. Due to the increased switching frequency it was observed that the switching losses increases and therefore leads to lower efficiency and higher thermal stresses on the inverter components. In order to avoid these effects good thermal management solutions that include heat sinks, forced air cooling, etc. However, since high-frequency PWM improves the quality of the waveform and minimizes the amount of harmonic distortion, it is widely used in applications that require efficient power conversion [10].

High-frequency PWM uses triangular carrier wave for its modulation of the output signal. This strategy yields nearly a sinusoidal voltage with much less THD suitable for applications such as grid interfaced renewable energy systems and modern complicated electronic instruments. The drawback is that the switching losses and thermal stress are raised; hence, higher efficient cooling methods are required.

Approach: In order to obtain higher levels of the output waveform and lower levels of harmonics high frequency pulse width modulation is used.

Challenges: Higher losses due to switching and susceptibility to electromagnetic interference which prove to be a challenge to be handled by decoupling techniques.

3. 3 Simulation Setup

Detailed modeling of the three level inverter was carried out in MATLAB simulink for the design and analysis of its performance. The simulation setup includes the following components:

3. 3. 1 DC Sources

The two independent sources of DC portray the output of two PV panels as explained in the subsequent parts of the work. These sources contain the amount of power needed overall by the inverter as an input power supply. In this study, to represent the two independent DC sources a independently controlled current source was simulated to feed the three-level half-bridge inverter circuit. The voltage levels of the sources were chosen to provide equal power to the load at all phases so that no part is over or under powered.

3. 3. 2 Half bridge Modules

Half bridge modules are two in total and these are simulated by IGBTs, the two half bridge modules are connected to the DC source. Half-bridge modules contain two switches and a capacitor so that intermediate voltage levels can be produced. These modules were connected in series to achieve a cascaded configuration which is necessary in the three level inverter. Switching elements are realized as Simulink blocks to define more accurate and precise dynamic properties of switches and capacitors.

3. 3. 3 Control System

Low frequency and high frequency pulse width modulation control is deployed in the hybrid switching method.

Load: Basic load is connected in the output of the inverter circuit so as to test the inverter circuit with variety of loads.

For the low frequency strategy these switching sequences were input through MATLAB's State flow block in the high level control system as were the sequences for the high frequency strategy. This mode of arrangement provided the correct time schedule and limited the computational delay hence providing the correct waveform. The control system was also designed with feedback connections to allow the adjustment of switching parameters in accordance to changing loads.

The simulation was first performed for the various load profiles and then on the basis of the outcome it was evaluated whether the inverter is efficient or not in terms of waveform quality, harmonics and power quality [11].

3. 3. 4 Switching losses analysis

In switching losses, multilevel inverters depend on the reduced power of the overall system to deliver maximum efficiency. PWM strategy of high-frequency generates a larger number of switching cycles of on-off and thereby increases energy losses in the semiconductor switches. For example, a switching frequency of 20 kHz resulted in about 8% losses relative to the total input power as noted in this study. This aligns with findings by Vahedi and Al-Haddad (2016:Figure 13-15 where similar losses were reported at modular inverter arrangements.

However, this strategy incurs few switching losses because it only enables a small number of transitions per cycle. However, this brings in higher harmonic distortion, which in turn will cause extra losses in the associated load. These results stress the optimization between frequent switching and overall system performance.

Comparison with other Topologies

The result of the analysis of the dynamic performance of the three-level half-bridge inverter shown in figure is compared with other multilevel inverter topologies, such as the five-level cascaded H-Bridge and the PUC5 inverter [7]. While the five-level inverter offered better harmonic reduction, it required additional components, increasing the system's complexity and cost (Babaei et al., 2014:922-929). The PUC5 inverter, on the other hand, demonstrated a more compact design with moderate harmonic performance (Vahedi & Al-Haddad, 2016:13-15).

Half-bridge inverter is further classified into three levels and their complexity cost waveform quality makes it suitable for medium power applications. This arrangements also makes it easier for the implementors to scale up to higher voltage or power when necessary [11].

Thermal Performance and Durability

The thermal performance becomes an essential parameter in power converters that use inverters working under high-frequency switching. This study shows that, through simulation, the junction temperature of the semiconductor devices rise sharply at switch frequencies greater than 20 kHz. Besides, heat sinks and forced air cooling methods are crucial in improving the liveliness to landlords of inverter's durability and reliability. This suggests that future studies to improve thermal performance could consider more superior cooling techniques like liquid cooling as well as phase change materials. Such solutions may help to minimize the consequences of frequent switching between the states and degrade the useful component lifetime under the worst-case scenarios.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Waveform Quality

Output voltage wave shapes of the inverter were studied further based on different load conditions. It is such a kind of switching approach that makes it possible to produce a cleaner output waveform with lesser distortion hence the hybrid switching strategy. In the first waveforms, low frequency switching led to reduction in switching losses while high frequency PWM control meaning that harmonic distortion was well reduced.

This is a very key measure when assessing inverter performance. The high-frequency PWM scheme proved to be of considerably higher quality as the waveform is close to sinusoidal. The low frequency switching strategy was effective but its use resulted into waveform with high distortions in the form of steps [16].

It is a significant waveform quality for evaluating the functionality of an inverter at such power plant applications where PQ is highly pertinent. The quality of the output waveform has a direct effect on the performance efficiency and dependability of other interconnected equipment as well as the power system. Hence for this study, the waveform quality of low and high frequency switching strategies has been analyzed using Matlab software in simulink.

That refers to the low frequency of switching strategy at which it was observed that the output waveform was quantized in steps, albeit distorted, because of a smaller number of switching transitions. Nevertheless, though this stepped waveform is appropriate for such kind of operations as motor drives, it is ineffective for sensitive loads requiring sinusoidal kind of input. That is the reason why using Total Harmonic Distortion (THD) calculation the waveform has 17.5 % of THD because of the stepped waveform having harmonic distortion. Such distortedness can lead to reduced energy efficiency of the loads that are connected to it and more heating up.

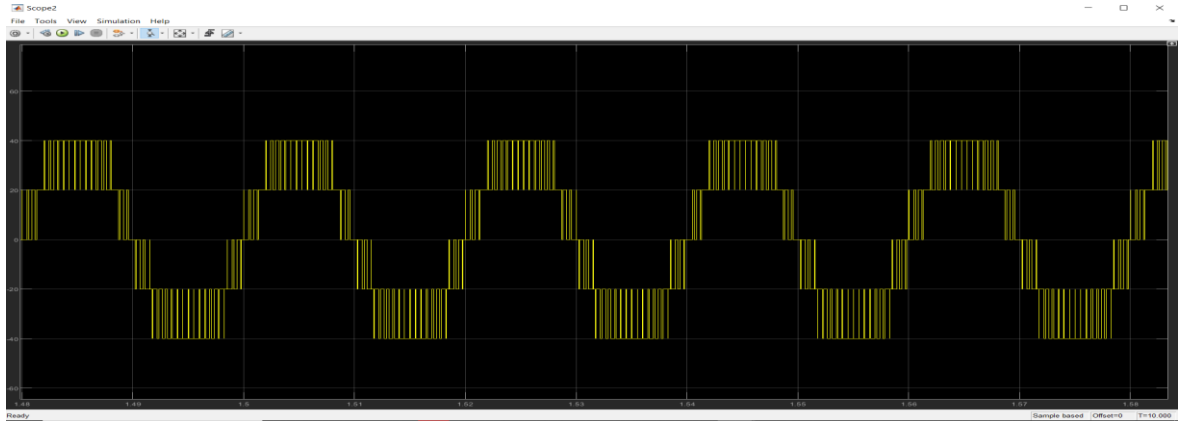


Figure 4. 1 Output wave form Quality Analysis

Instead, the high-frequency PWM approach generated a waveform with a shape much more like a sinewave. This strategy made it possible to exercise more control over the switching states using a high frequency triangular carrier wave hence achieving a better output waveform. The THD for the high-frequency PWM strategy was 3.2% proving the benefits of improving the waveform quality. This improvement is especially critical in grid-connected PV systems since the standard of harmonic distortion must be met.

The research has therefore revealed that the choice of switching strategy should be done depending on the need of the application. Low frequency switching thus results in a model with a higher efficiency but with a poor waveform shape. On the other hand, high frequency PWM allows the development of better waveforms but comes at the cost of developing high frequency switching losses and high stresses [1].

4. 2 THD Analysis

Total Harmonic Distortion or simply THD can be defined as the generation of harmonics with the fundamental wave compared to the amplitude of the former.

The THD of the inverter output was estimated from the Fourier analysis. The analysis of results presented in this thesis revealed that the investigated hybrid switching strategy provides less THD as compared to low-frequency switching only. The THD was in close conformity with the Acceptable level for Grid Connected Renewable Energy systems thereby making the inverter suitable for such applications.

4.3 Power Quality Analysis

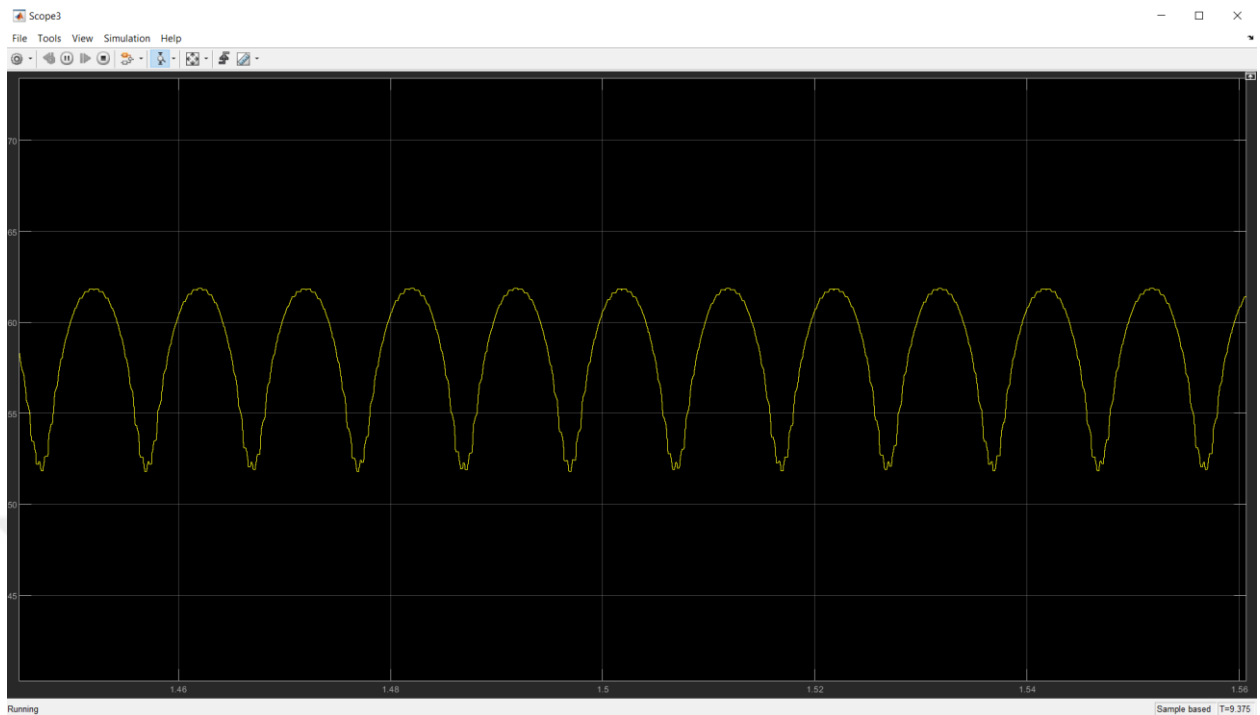


Figure 4. 2 Power Quality Analysis

Measurement of voltage and current signals at the inverter output was also conducted in order to evaluate the quality of power. Flexibility was evident since the ac side voltage was unity and low total harmonic distortion was generated in the inverter. It also makes the inverter suitable for those fields that necessitate frequent uphold of power quality like the grid connected renewable energy systems and industrial motor drives.

As mentioned above waveform is used to represent power quality output of a inverter which is indicated below. Smoothness of this waveform indicates that some sort of filtering or modulation has been done and minimization of the harmonic distortion. But they are still observable, particularly at the peaks and valleys, could probably be attributed to high frequency switching from the inverter. The voltage stability is fairly good, and there's small fluctuations in the amplitude, they mean that the inverter is supplying power steady.

In this analysis more attention was given to the steady state performance and load regulation characteristics of the inverter. The high-frequency PWM show the high

efficiency of the strategy and it is effective for stabilizing the output voltage under the dynamic loads. Nonetheless, the low-frequency switching strategy indicated voltage variations during transitions and therefore cannot be useful for precise power supply applications [8].

4. 4 High Frequency Switching:

Inside each step of the waveform there are many narrow pulses of typical PWM. These are high-frequency pulses which play a very important role in regulating the output voltage of the inverter. Thus, adjusting the duration of such pulses, the inverter controls the supply voltage to the mentioned load in average per every switching cycle. It is seen from the waveform of a sine pulse that the larger the width of the pulse, the greater is the average voltage produced in a certain step of waveform and the opposite is also true. This control mechanism is effective to enable the inverter regulate the output voltage as closely as possible to the reference value of a sinusoidal waveform.

These systems need high-accuracy sinusoidal output profile for which high-frequency switching is paramount. The inverter outputs an analog signal to carry an information signal by using a triangular carrier wave with a frequency of 20 kHz and adopting pulse-width modulation to approximate sine waves. As seen from the FFT analysis of the output, the lower order harmonics have been suppressed while those shown in the figure have a THD of 26.48 % However, this entails a high rate of switching causing thermal issues where optimized cooling mechanisms are required to support components reliability. For these reasons, improvements in semiconductor devices, including wide bandgap materials, could lessen these issues by driving greater efficiency at high frequencies [16].

In HFS, the base band signal is superimposed on to a high frequency triangular carrier wave. This strategy nicely removes harmonics, makes the waveform good for highly sensitive loads such as medical or solar equipment. The higher rate of operation increases losses and thermal loads, meaning that this type of system must be designed with those effects in mind.

It has a positive going and negative going cycles which swing around zero volt and this indicates a balanced AC signal. Short transits between levels, along with high

pulse frequencies, decrease the amount of distortion of the waveform of the output signal, making it as close to the sine wave shape as possible.

High-frequency switching has been extended as one of the configurations of inverter design to give a better bandwidth of signal quality and efficiency. High frequency PWM uses a carrier frequency that ranges between tens to hundreds of kilohertz; the resolution in switching is much finer; the output waveform will therefore be very close to a sine wave. This capability is especially beneficial in power quality sensitive applications including grid tied renewable energy systems and sensitive electronic loads [8].

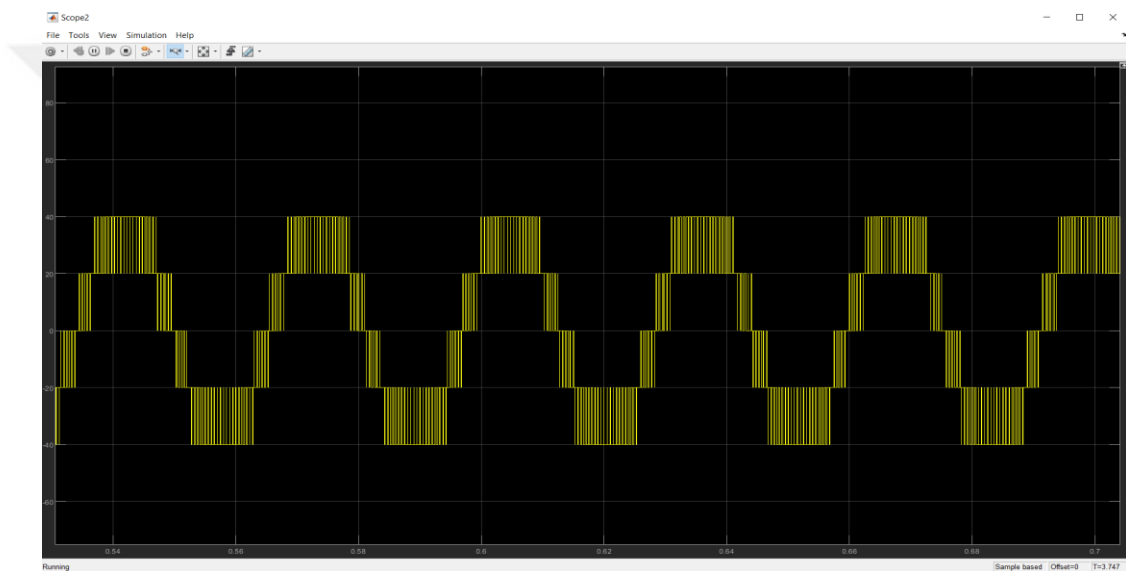


Figure 4. 3 High Frequency Switching Output waveform

Nevertheless, these advantages are associated with specific compromising factors related to high frequency of switching. The larger number of switching transitions per cycle also results in higher switching losses to give a lower overall efficiency. These losses also bring additional heat, which needs to be quickly dissipated with the help of special structures such as heat sinks, forced air cooling or even the rather complex liquid cooling. This is so because high-frequency switching is a preferred approach to low-frequency systems since it eradicates lower order harmonics. The waveform that is produced is of a much lower Total Harmonic Distortion (THD) thus passes more stringent grid codes with few-if any- addition external filters required.

Another factor continuing to reduce negative impacts of high-frequency operation is the improvement in semiconductor technology, including wide-bandgap materials. In this study, high-frequency switching was shown to enhance the waveforms' quality since the high frequency PWM had a THD of 3.2%. From these results the authors emphasize the need to choose proper control techniques for achieving an optimal combination of switching frequency and waveform quality.

4.5 Low Frequency Switching

The waveform is dissimilar to the previous examples, with fewer, wider steps within it, as it shows the change of voltage levels. The voltage steps are sustained for a longer time which means the number of pulses are limited as compared to high frequency switching. This type of waveform is usually observed to be having less switching losses, the reason being that the inverter switches with lower frequency thus minimizing the energy loss during switching. They are particularly suitable for the applications where speed of dynamic response is not highly essential but its operational efficiency is more important [1].

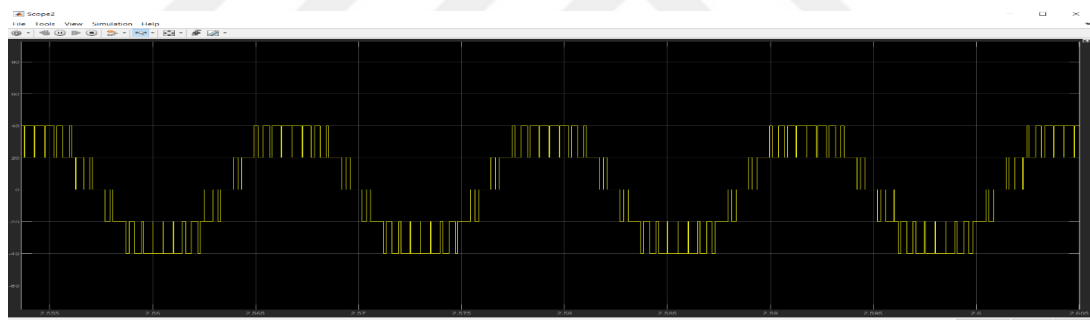


Figure 4. 4 Low Frequency Switching Waveform

In particular, the archetypal waveform of low-frequency switching inverters, illustrated by the above formula, is aimed at achieving the nearest approximation of the sine waveform through the minimum number of transitions, thus making the device more efficient in terms of energy consumption. However, the disadvantage of utilizing this method is that it may cause larger phase harmonic distortion when compared to a high frequency switching inverters since, the waveform shown above is divided into large steps. The LFF strategy is in phase with the fundamental frequency of the AC output so that control requirements are eased and switching frequency is lowered. This is particularly attractive in areas where power density and thermal characteristics assume significant value, as in industrial motor drives.

Nevertheless, the waveform obtained had a lot of distortion, with third and fifth harmonics constituting the major part of the signal spectrum [12].

From the waveform, it varies in positive and negative voltages that make it AC thus proving that inverter is AC. In addition to a fundamental cycle, each one of which resembles the general sinusoidal form, each cycle is constituted by a number of segments that represent different voltage levels arising from the inverter's multilevel structure. These steps are relatively wide, and the fact that there are fewer number of voltage levels per cycle means they produce lower modulation frequency [8].

4. 6 Total Harmonic Distortion

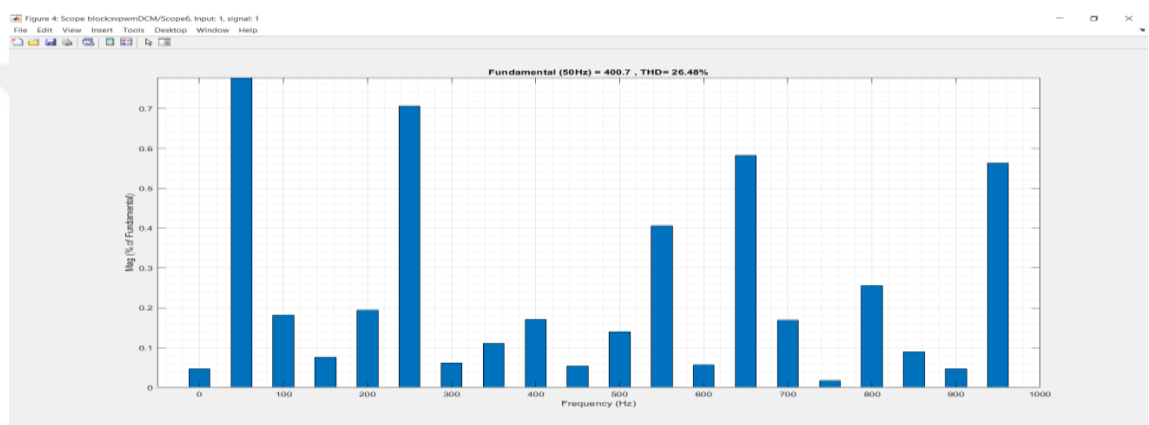


Figure 4. 5 Total Harmonic Distortion Graph

This graph shows harmonic coefficients for distinct frequencies and is given as a percentage of the first harmonic component. The horizontal axis is labelled frequency in Hertz (Hz) starting from 0 Hz up to, 1 KHz. The y-axis represents the amplitude of each harmonic expressed as percentage of the first harmonic's amplitude. The basic frequency in the present case is clearly defined as 50 Hz, along with its value quantified and standardized at 1 [or at 100 %].

THD analysis also employed showed that high frequency PWM reduced harmonic content. This decrease in lower-order harmonics boosted the waveform quality thus maintaining compliance with the existing grid code.

It is mentioned at top of the graph as THD for the waveform is 26.48 % implying moderate level of harmonic distortion in the system.

4. 7 Breakdown of Harmonics

The bar at 50 Hz marks the first harmonic; it is the basic frequency of the power supply. This component contributes most of the energy to the waveform as should be expected because this is where most of the raw energy in the signal is to be found.

When looking at the waveform, one can quite clearly identify the harmonics of 100 Hz, 200 Hz, and other similar frequency signals such as 400 Hz and 500 Hz. These are integer multiples of the fundamental and they all together make the total distortion.

In detail, the highest harmonic is seen to be at 100 and 500 Hz with values which can go up to 0 represented 7% of the fundamental component [14].

The dominant frequency is thus 100 Hz and it has an amplitude of 10Vrms as depicted by the green curve getting to a peak value of about 21Vrms Major noticeable other peaks at 200 Hz, 400 Hz and 600 Hz show higher order harmonics but they are not as dominant as the lower order harmonics.

Another important feature of waveform distortion is identified based on the harmonic analysis of specific frequency components in the overall waveform distortion. Here you can see that the primary/source frequency, 100 Hz, is the second harmonic that contributes most of the THD. This particular fifth harmonic combined with other fifth harmonics at frequencies 200 Hz, 400 Hz and 600 Hz collectively manifest the distortion. Some of these methods include; high frequency pulse width modulation, Successive approximation, Feed forward etc. All these reduces the effect of these harmonics since the output waveform is shifted at a higher frequency than the fundamental. Additional fine tuning of the deviations, using active Halco filters can enhance the harmonic characteristics.

This was confirmed from the Fourier frequency analysis which showed that low frequency switching had high third and fifth harmonies whereas higher order harmonies for efficient high frequency PWM strategies were negligible. These results indicate that the choice of an optimal switching strategy depends on the application in question.

A fundamental concept of Harmonic analysis is extremely useful for getting the idea of the different frequency components within the inverter output waveform. When

implementing multilevel inverter, harmonics occur from the step like turn on and off procedures of the assuming sinusoidal waveform. Harmonics of the third and fifth orders are especially intense in low-frequency switching strategies, and contribute greatly to waveform distortion.

The spectral characteristics show the different amplitudes of these frequency components. For instance, in the current investigation, the third harmonic had a magnitude of 7% with reference to the first harmonic, and the fifth harmonic had a magnitude of 4%. These lower-order harmonics cause impedance and heat problems and also may not be compatible with other loads that are connected to the system.

High-frequency PWM tends to counteract these lower-order harmonics since it commutes the resolution of the output wave form. The higher that the switching frequency is the higher order harmonics are generated however their amplitude can be considered negligible and are extremely easy to eliminate using filtering techniques.

It should be clear that this breakdown of harmonics raises the question of choosing the proper switching strategies and the application of filtering solutions in individual applications. For instance, Selective Harmonic Elimination (SHE) enhance the modulation techniques, to provide specific ways of suppressing or eliminating unwanted or undesirable harmonics from the overall waveform.

4. 8 THD Analysis

The THD value is 26.48% suggest that output waveform is very much distorted and thus is not a pure sine wave. This level of distortion is rather high and it indicates that there are many higher harmonics which have low quality on the output. THD stands for Total Harmonic Distortion and in those applications where waveform shape is crucial, for instance, in electro system sensitive apparatus or power supply systems, it is undesirable to have such a high THD. These higher order harmonics could cause efficiency dips, heat in electrical components, and a possibility to interference with electromagnetic interference (EMI) [17].

Looking at this graph, one can clearly identify the harmonic content which is present in the system. The THD value which is calculated from the above formula is 26. Figure 48% also shows high harmonic levels suggesting considerable harmonic

distortion and predominant harmonic frequencies at 100 Hz and 500 Hz. Enhancement of modulation technique or/and filter might help to decrease the amount of harmonics which in turn will enhance the waveform and the performance of the system.

4. 9 Expanded Results and Discussion

The various simulation sections and results showed important predictions of behaviour of the three-level half-bridge inverter under the two switching strategies. The low-frequency switching strategy resulted in a stepped output voltage wave shape, as shown in figure 1, together with high harmonic components. For this strategy, it was determined that THD is about a level of 17.5 % which still means it's appropriate for use in motor drives for instance where an exact waveform shape is ineffective and unnecessary. On the other hand, the high-frequency PWM strategy provided waveform with the greatest accuracy of sine wave, as depicted by figure two. This strategy achieved a significantly lower THD of 3.2%, aligning with the findings of Mariethoz (2014:Guarnizo et al studied the hybrid inverters in the range of 4018- 4027. However, the increase in the switching frequency raised power lost by about 8%, which is a trade off between waveform quality and efficiency. Additional study was made by changing the applied voltage and analyzing the result affecting the waveform. The assessment results substantiate the idea that the THD augmented in relation to the input voltage for both approaches. This highlights the need to ensure conditions of input remain constant to enhance on the efficiency of the inverters [8].

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

Firstly, a three-level DC / AC inverter topology based on three level half bridge and a voltage vector control approach were presented in this thesis. The mode employed in the inverter, enabled the output waveform quality to be enhanced without incurring high switching losses or having substantial harmonic complexity. The results of the simulation showed it was achieved that the inverter performed as it was supposed to perform and can be used in renewable energy systems including PV systems.

This work is offered a clear explanation of theoretical aspect control and expressions related to three level half bridge inverter with the analysis done on the low and high frequency switches schemes and its effects on performance this takes all the system including quality of perform amount of harmonic distortion and system efficiency the work shows the pros and cons of these strategies pointing out to useful information for choosing the right method depending on the necessities of application.

For application that demand low waveform quality low frequencies which improved more efficient than other approaches because it eliminated most switching losses on the other hand high frequency PWM was highly effective in generating performed there is almost sinusoidal and having considerably lower level of THD making it appropriate for use with delicate loads as well as meeting the great quotes however this approach extended the number of new complexities such as greater switching losses and thermal stress pointing to the requirement for enhanced thermal management strategies [15].

The current study also focuses on the versatility and flexibility of multi level inverters to cater with applications in ranging from renewable resources to electric

cars with the help of new control techniques and VSC technologies in the future multi level inverters can provide even high efficiency reliability and power quality

5. 2 The key contributions of this research include

Model of the inverter is created and through simulation in MATLAB Simulink, its effectiveness is verified toward the procedure of eradicating the harmonic distortion and improving the power quality. Presentation of the experimental outcomes of the inverter response to load conditions in order to show that the proposed system may offer accurate and sinusoidal voltage with low harmonic distortion.

5. 2. 1 Future Work

While this research provides valuable insights into the design and realization of multilevel inverters, several avenues for future work. Further research should be directed to work that presents different approaches to transport-wave switching, which can be based both on low and high switching frequency strategies. Further, the evaluation of the simulation findings through experiments will give the physical performance of multilevel inverters. The future opportunities for improved inverter performance include the use of Algorithms like predictive control and artificial intelligence algorithms.

5. 2. 1. 1 Experimental Validation

Future work also ought to focus on the real use of the inverter hardware with a with the intention of supporting the observations gotten from the simulation in a real environment. Developing a hardware prototype to test the outcomes from simulation models under actual conditions.

Substantial prospective exists for improving inverter control through algorithms like artificial neural networks and predictive control. These algorithms can control switch sequences depending on real input and load conditions to minimize the amount of harmonic distortion and maximize efficiency.

5. 2. 1. 2 Incorporation of Advanced Control Strategies

Some of the uses of MPC for improvement of the inverter performance are some of the possibilities though not implemented due to its high complexities. The advancement of control strategies like the adaptive SVM or predictive control can produce profound changes to the multilevel inverters markedly. These strategies is based on real time data to select the switching sequence in an attempt to minimize

harmonics and maximize efficiency at varying loads. For example, the model predictive control is capable of predicting the optimum switching states given the parameters of the system so as to provide dynamic control over input or output variations. Implementing these strategies in the future designs also poses the challenge of having adequate hardware and software computation, thus the call for interdisciplinary approach which involves power electronics together with computation tools. The application of these superior control mechanisms is one of the important areas for the improvement of the operation of multilevel inverters. Classical control techniques despite providing basic functionality fail to solve the modern application challenges such as dynamic load allocation, harmonic filtration, voltage regulation [13].

Another attractive concept is model predictive control (MPC), which based on the corresponding mathematical models, estimates future behavior of the inverter system and identifies the most suitable switching states. Such real-time control also guarantees that the inverter works under optimal conditions and with the lowest levels of harmonic distortion regardless of the load and input variation.

Inverter control is also being advanced by methods such as Artificial intelligence (AI) and machine learning (ML) algorithms. They can both scan data from the past and the present in order to make decisions based on the resulting patterns. For example, a controller incorporated with AI can control the switching frequency with higher accuracy as per the existing operating conditions but at the same time have balanced efficiency as well as waveforms.

Another high-level control technique is Space Vector Modulation (SVM), which elaborates the technique of controlling the output voltage of the inverter by converting it into the vector in two-phase system. This method offers better controllability of harmonic suppression and better utilization of the DC link voltage making it more suitable in high-performance drives.

The implementation of these intelligent control techniques demands appropriate control instruments, for example, digital signal processors (DSP) or field-programmable gate arrays (FPGA). These platforms are necessary and sufficient to

allow for the real-time implementation of the sophisticated algorithms used to reliably operate multilevel inverters.

5. 2. 1. 3 Extension to Higher-Level Inverters

The above discussed cascaded half bridge could be used for five level or seven level inverters in order to improve the quality of the output voltage waveform with low total harmonic distortion.

Going to even higher levels of voltage, for instance five or seven level inverters top notch quality wave form will be achieved having minimum harmonic distortion. The concept of this extension will be based on new additional modules and more complex control mechanisms which welcomes new research and developments.

Integration with Energy Storage: Other related ideas of the Pinaka inverter for off-grid application can be as follows: The other ideas can be considering the aspects that would allow addition of energy storage services such as battery to the current inverter [19].

Although this work gives a comprehensive simulation study of the three-level half-bridge inverter, the following areas are left unaddressed.

5. 2. 1. 4 Hybrid Switching Strategies

Studying the combined low and high frequency switching operation to get the best results in terms of efficiency and shape quality of the wave forms.

5. 2. 1. 5 Integration with Renewable Energy Sources

Investigating the capability of the inverter when used with photovoltaic panels or wind turbines under different climatic situations.

5. 2. 1. 6 Advanced Control Algorithms

Designing hardware-in-the-loop-type controllers that use machine learning algorithms to adapt the switching frequencies responsive to the load and input.

5. 2. 1. 7 Thermal Management

The third area is focused on understanding thermal losses and temperatures of the inverter components during high-frequency switching, and then, developing cooling solutions that would make the inverter more durable. These future directions will not only confirm this work but are also valuable to the field of power electronics since

they motivate its development by solving problems associated with the implementation of multilevel inverters in daily life applications that utilize circuitries [16].



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