INVESTIGATION ON THE IMPACT OF DIFFERENT VERTICAL AND HORIZONTAL RESOLUTIONS ON THE APPLICABILITY OF LINEAR HYBRID INVERTER

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Examiner: asoc.prof Pasi Paltoneimi

ABSTRACT

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In the given thesis we studied the impact of different vertical and horizontal resolutions on the applicability of linear hybrid inverter. Available techniques and models are investigated, and best solution is nominated. Different methods are examined and simulated by MATLAB Simulink and new operational modes are introduced as solutions to the subject.

Inhaltsverzeichnis

Abbildungsverzeichnis

Tabellenverzeichnis

Formelzeichenkonvention

$PAPR$	Peak To Average Power Ratio
PA	Power Amplifier
ET	Envelope Tracking
V	Voltage
I	Current
S	Power
Eff	Efficiency
AC	Alternating current
DC	Direct current
RF	Radio frequency
1	Input
2	Output
PK	Peak value
RMS	Root-Mean-Squared
LTE	Long Term Evolution
$UMTS$	Universal Mobile Telecommunications System
$HSPA$	high-speed packet access
dB	decibel
PS	Power source
PDF	probability density distribution
$SMPS$	Switch mode power supplies
VLA	Voltage controlled linear amplifier
VSC	Voltage-controlled switched mode converter
m	Magnitude
N_L	Number of Voltage levels

1 Introduction

The advent of technology and the rapid increase in population in recent times has brought about a requirement for accurate energy generation. To fulfill increased energy demands, new techniques and utilities have been introduced to provide efficient and sufficient electricity management. Since the 20th century, power electronics have played a vital role in fulfills the various requirement of electrical power transmission.
Inverters were introduced for converting a DC signal to an AC signal. Several designs and techniques were invented for DC to AC conversion process. Improved sinusoidal voltage generation is typically achieved by using inverters that are based on standard power electronic components. However, the usage of these types of inverters are limited and can be problematic when higher frequencies are required in the output signal waveform. The fast switching process adds a significant amount of harmonics and distortion to the output signal waveform and filtering the harmonics and distortion requires considerably complex and bulky filter design. Conventionally, filter elements are typically employed to smooth the rectangular output voltage of switching elements. By managing filter designs, the overall cost and size of the inverters can be scaled down enormously.
As an alternative approach, the difference between a non-sinusoidal output voltage of the switching elements and the desired smooth output voltage can be reduced by resistive losses with a transistor in linear operation mode. While this can lead to reduced efficiency, the overall system volume and complexity can be reduced. In addition to higher frequency requirements to obtain output signal horizontal resolution improvement, multi-level inverters with fixed output voltage levels can be used for escalating the vertical resolution of the output signal. In this thesis, fundamental ideas and suitable parameters for linear Hybrid inverters are evaluated and the suggested models are simulated and compared in detail via MATLAB Simulink software.

2 Literature Review

This section investigates and explains three primary themes based on references, and the main idea of each method and technique is stated.
The primary idea and explanation of the envelope tracking method as a power amplifier supplying methodology is first discovered and stated, followed by the working principle of multi-level converters and a detailed examination of the chosen model, Cascade H-bridge converter. Finally, power amplifiers and different classes are examined and discussed in detail in this section.

2.1 Envelope Tracking

Envelope tracking approach is a well-established technique for improving the efficiency of power amplifiers. The Envelope Tracking (ET) technique significantly improves the efficiency of power amplifiers (PAs) when used in conjunction with traditional class AB- or class B operation to amplify signals having a time-varying envelope, such as the majority of those utilized in modern wireless communication systems [6].In mobile communication systems, around 50% of the power loss is dissipated in power amplifiers, and these losses are wasted as heat, which requires determining the amount of energy for the cool down process of the system. Therefore, increasing the efficiency of the power amplifier plays a vital role in the reduction of overall power consumption of the system [2]. Envelope tracking technology was invented in the 1930s to address energy concerns connected with high-power amplitude modulated broadcast transmitters. In the May 1930 issue of the University of Arkansas Bulletin, Loy E Barton disclosed a technique for high-level modulation. The concept faded in usage and was not widely utilized until the late 1990s when makers of cellular base stations began investigating its application in 3G technology. Due to the modulation style employed in 3G, the efficiency of the RF amplifier was lower than that of 2G systems, which primarily used a modulation style with no amplitude content. However, it was not until around 2008 that the first base stations equipped with envelope tracking were introduced. The technology faced numerous challenges because of the requirement for huge modulation bandwidths. It was also considered for use within the phones themselves, and Samsung unveiled the first of these phones in September 2014, and it is currently found in a wide variety of smartphones.

Envelope tracking background

Radio frequency amplifiers amplify the input signal to a higher or lower level signal output of the amplifier by using DC voltage as a supply voltage for the amplification process. The efficiency of any amplifier is the ratio between the output signal power to the input DC power and can be calculated by Equation 2.1.

$$Eff = \frac{P_{RF2}}{P_{DC1}} \cdot 100\% \tag{2.1}$$

From Equation 2.1, it is seen that the efficiency of a power amplifier could be increased either by increasing the output power or by decreasing the input DC power of the amplifier[7][8]. From Equation 2.1, It can also be observed that DC voltage supply for the power amplifiers should always be higher than the peak value of the input signal to be able to amplify the input signal to a higher output signal.As shown in Figure 2.1, the amplification process in linear mode is limited by two boundaries (voltage rail) which are defined by the input DC voltage of the system [9].

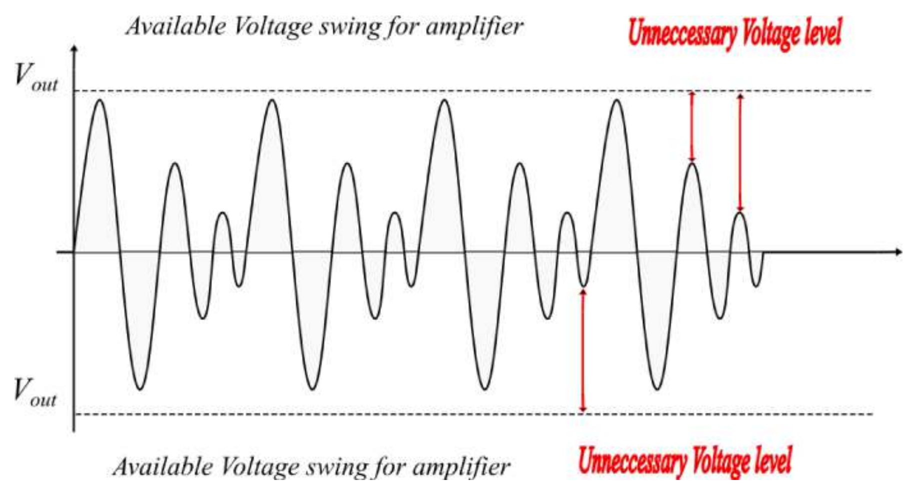

Abbildung 2.1: Power Amplifier without Envelope Tracking

The efficiency of an amplifier also depends on other factors like the shape of the waveform and the amplifier operation mode [10]. Peak to average power ratio(PAPR) definition was introduced for comparing the signals waveforms. From literature,the PAPR value is determined as shown in Equations2.2 & 2.3:

$$PAPR = \frac{|x_{pk}|^2}{x_{rms}} \tag{2.2}$$

$$PAPR_{dB} = 10log_{10}\frac{|x_{pk}|^2}{x_{rms}} \tag{2.3}$$

Thus, if the PAPR of a signal increases, it indicates that the signal's peak value has increased proportionately. As a result, the amplification procedure for that signal demands a larger DC voltage supply value. Higher PAPR signals are commonly used in cellular telecommunication systems such as 3G, LTE and 5G technologies.Thus, the transmission and the amplification process of these signals can be complicated[11][12]. New technologies for data transmission systems such as UMTS,HSPA,4G LTE have been introduced utilizing radio frequency waveforms. Radio Frequency waveforms incorporate an amplitude component in addition to the phase elements, and thus, these technologies require linear amplifiers from different class types[13]. In linear amplifiers,[1] often class A, the efficiency of amplifiers is around 50% .The main reason for the low efficiency of these type of amplifiers is the mentioned voltage rail.In linear amplifiers, the DC input voltage should always be constant and higher than the signal for the amplification process as is observed in Figure 2.1. The unnecessary voltage level marked in red is the source of the unused energy and is dissipated as heat. Therefore, different methods are introduced to maintain and manage the consumption of linear amplifiers. The following sections elaborate on the Envelope Tracking method for linear amplifiers.

Envelope tracking basic concept

Envelope Tracking method could be implemented in power amplifiers to boost the overall efficiency of the designed system.The power supply for the amplifier is continuously adjusted to ensure the peak-efficiency operation of the amplifier. This process is referred to as envelope tracking as it uses the envelope of the RF signal to adjust the power supply.
Envelope tracking systems considers the envelope appearing at the input of the power amplifier and then utilizes this envelope to drive the power supply providing the line voltage for the RF power amplifier. This is modulated to ensure that it correctly tracks the amplitude of the signal.
The supply has to be sufficient to meet the needs of the RF amplifier and should be slightly higher than the RF signal peak value at the input of the amplifier. It must track the voltage required so that the amplifier does not

[1] Deeply explained in 2.3

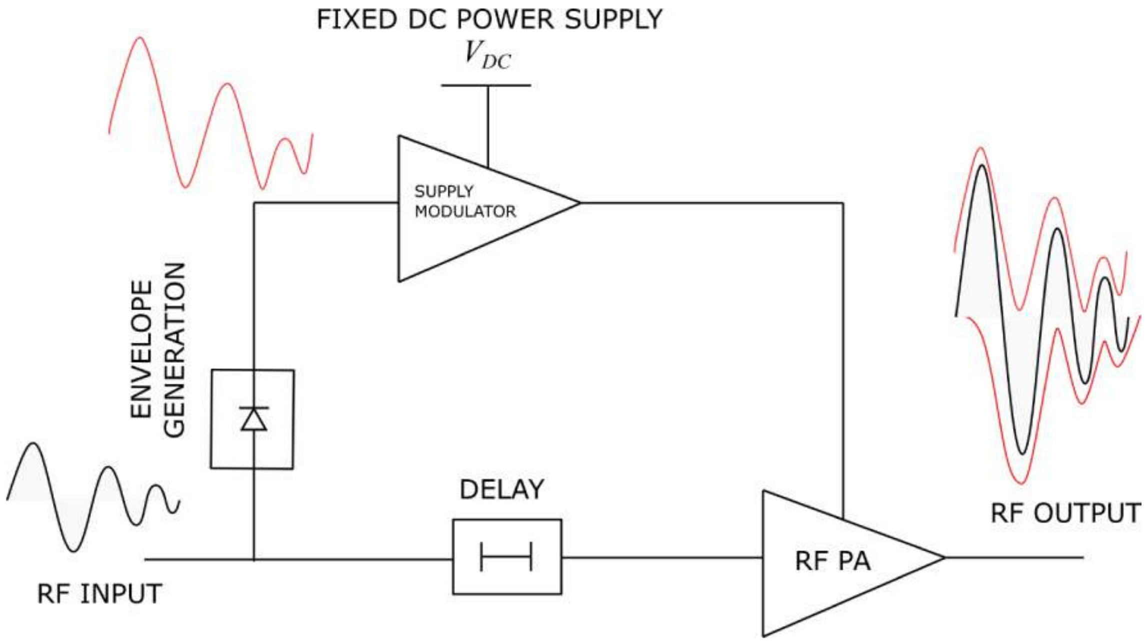

Abbildung 2.2: Schematic of Envelope Tracking,[1]

enter compression and distort the signal.In this manner, the final amplifier will be able to dissipate much less heat and consequently, consume much less power[1].

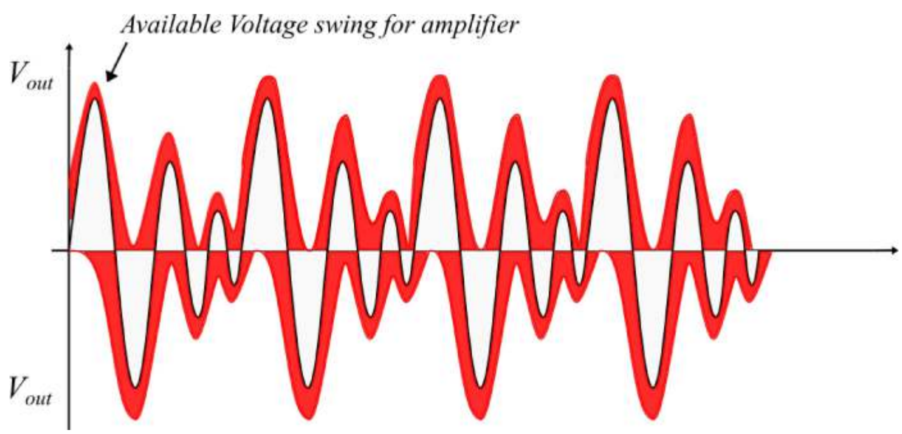

Abbildung 2.3: Amplifier with Envelope Tracking

Envelope Tracking Power Supply/DC Modulator

The DC modulator of the the power amplifier provides the required power for the amplification process and therefore, the DC modulator should be selected carefully so as to be able to overcome the peak values of the input signal while also considering the nadir values of the input signal.
DC supply selection must also be prudently chosen to provide a little bit more than the required power. Proper selection is vital in reducing the dissipated

power as heat in amplifiers and in increasing the efficiency of the amplifier and consequently, the efficiency of the system.
Design of the DC modulator varies according to the specific requirement, and several methods exist to overcome the above-mentioned problem.

Envelope tracking power supply basics

In Envelope tracking technique, the power supply should be able to trace the signal envelope and supply the amplifier with the required voltage. This process is problematic and the requirements and details are more exacting than may be seen at first look.The main requirements of the supply of the envelope tracking technique could be listed as[14]:

- **Bandwidth:**
  The envelope tracking only functions properly when the supply modulator follows the input signal precisely. The supply modulator should be able to overcome and follow the input signal (RF signal) at higher frequencies. The accuracy of the system can be improved by adding the DC supply modulator which would make it atleast two to three time faster or in better words, two to three times higher frequency than the input signal[14].

- **Efficiency:**
  The efficiency of the amplifier relies on the DC supply efficiency. Improving the DC supply modulator and using the Envelope tracking method is observed in literature to increase the efficiency of the amplifier. Therefore, selection of the DC supply should be done delicately [15].

- **Noise:**
  Switching mode power supplies are widely used in industries due to their higher efficiency. However, the switching process is usually a source of distortion and noise to the signal. Therefore, the switching process should also be considered in DC supply selection, and if the switching power supply is chosen, the filter design and the output signal and voltage should meet the criteria and requirements of the system.

- **No decoupling capacitors:**
  Traditionally, a decoupling capacitor is connected to the supply to ensure that the noise and voltage ripple and other factors is minimised. However in envelope tracking, due to the high frequency range

in the DC supply, adding a decoupling capacitor to the supply could be counter-productive.

- **Very low output impedance:**
  As in the design of the DC supply modulator, the decoupling capacitor should be omitted and the envelope tracking supply should have a low inductance in its output in order to meet the high frequency criteria.Thus, noise at the output of the DC supply/modulator could be manageable and could become more reliable.

- **Supply capability:**
  The envelope tracking supply modulator should be able to fully supply the required current, voltage and power for the amplification process in the amplifier and is an important consideration in the design of the system.

Envelope Tracking supply connection to Power Amplifier

As the bandwidth modulation of the power supply of the envelope tracking should be high, the traditional supply configuration with the decoupling capacitor for ensuring minimum noise at the output of the supply does not function as intended and the decoupled capacitor should be omitted to meet the high frequency requirement. The above- mentioned problem should be considered for the supply as well as the connection with the supply and amplifier[2]. Connection of the supply and the amplifier should meet certain criteria such as:

- **Low resistance:**
  To ensure that there is no voltage drop in the connection between the supply and modulator, the connection should always have the shortest connection possible and should have the least resistance possible in the connection.

- **Low inductance:**
  Similarly, the inductance of the connection should be mentioned in the design to meet the criteria for the envelope tracking method and to avoid to develop the voltage across the inductive element.This is potentially disadvantageous when the measurement and current sensing is required for the system.

- **Low capacitance:** While it may be tempting to make the link between the envelope tracking supply and the PA as wide as possible, this may increase the capacitance to ground, reducing tracking performance. The capacitance must be kept as low as possible. Removing the ground plane beneath this track on the circuit board could be one way to accomplish this.

One of the greatest obstacles to the concept's earlier adoption has been the inability to meet all of the requirements for the envelope tracking power supply. Now that firms have successfully implemented the envelope tracking power supply, the technology may be included into a wide range of devices, from broadcast transmitters to cellphones, where battery capacity is a concern.
Because of the significant design challenges on the supply, many patents are linked with these circuits and the technologies utilized, and as a result, firms are reluctant to divulge the exact methodologies, circuits, and technologies used.

Envelope tracking supply approaches

When it comes to designing an envelope tracking power supply or modulator, there are a few options. The technique taken in each specific design is determined by a variety of criteria such as the applications, performance requirements, costs, and so on.The efficiency of the envelope tracking approach is determined by the power supply efficiency, which may be computed using Equation 2.4 :

$$\eta_{ET} = \eta_{PS} * \eta_{PA} \tag{2.4}$$

There are three basic methods that can be employed[2]:

- **linear amplifier structure** The envelope tracking technique's supply is similar to that of ordinary linear regulators in this collective. This method allows for both series and shunt connection setups. However, connecting in series is a more common and efficient configuration. The supply's efficiency decreases as the difference between the output and input voltage levels increases.
  One of the primary advantages of linear amplifier structures is that they provide a very clean RF signal output voltage, which is important since voltage supply noise should not be introduced to the RF signal.
  Figure 2.4 shows typical linear amplifiers[2].Since the LPA can be equal to a constant resistor when powered by the ET power source, it is represented by R_{Ld} in the shown Figure[16].

[2]Linear amplifiers are deeply explained in 2.3

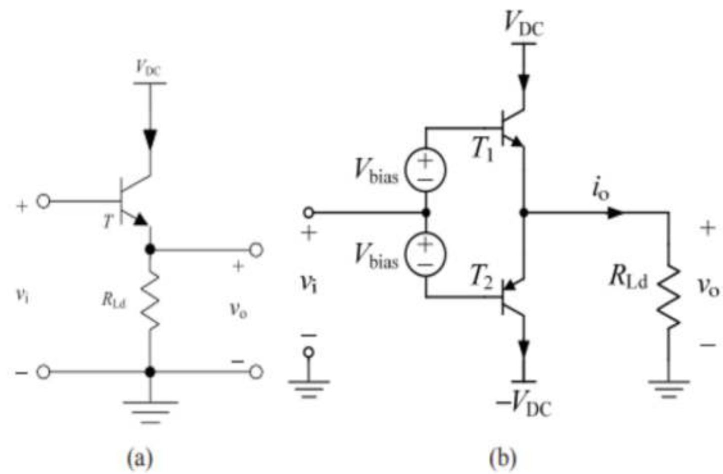

Abbildung 2.4: Typical Linear Amplifiers,(a) Class A, (b) Class AB, [2]

The efficiency curve of linear amplifiers and the probability density distribution(PDF) [3] of the envelope signal with 8.5 dB PAPR is shown in Figure 2.5

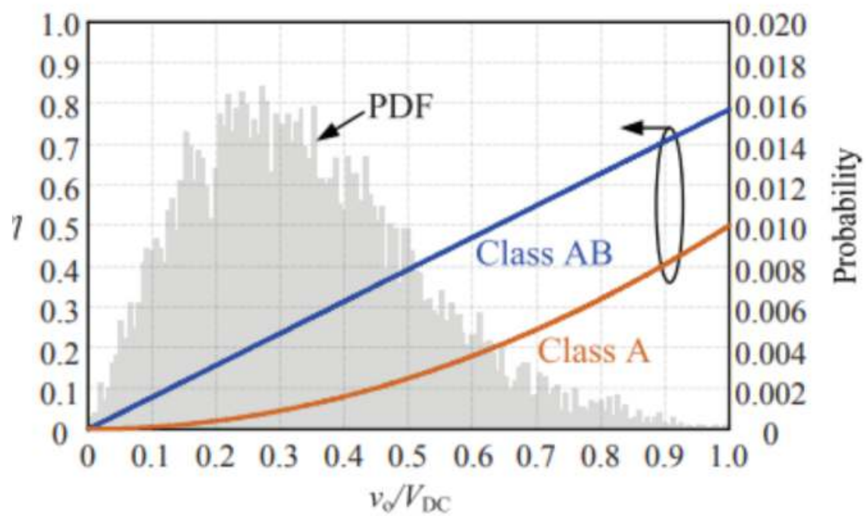

Abbildung 2.5: Efficiency curve of linear amplifiers and the PDF of a envelope with 8.5 dB PAPR signal,[3]

From Figure 2.5 that can be said "the efficiencies of the linear amplifiers decrease with the output voltage. Referring to the PDF curve, there is a large probability that the envelope signal lies in the low amplitude region, where the linear amplifier is less efficient. More than that, the PDF would move left if the PAPR of the envelope signal becomes higher, and this would further worse the efficiency of the linear amplifiers."[2]. In future the PAPR of the signals will increased and this structure will not be efficient enough for further technologies such as 5G in mobile communication systems.[17][18][19][20].

- **Switched mode converter structure** Switch-mode power supplies (SMPS) are mentioned and recommended in some cases according to their higher efficiency voltage conversion process instead of linear ones. Switched networks are classified based on the number of power switches that are used in the structure of the system. Two main networks are Single switch (SS) and multiple-switch (MS)network.
  Clean voltage production in term of noise and spike in the switched mode converters are consider as complex design process and in some points even impossible process.Another difficulty with this structure is its application in envelope tracking techniques. Because ET necessitates a high switching frequency (usually five times the signal bandwidth), the efficiency of the switched mode converter structure may be lower than that of switching supplies[21].

- **Switch-Linear hybrid** The combination of those strategies has piqued the interest of researchers based on the benefits and drawbacks of the aforementioned supply systems. A switch-mode converter is utilized in the switch-linear hybrid structure for low-frequency power with great efficiency, while a linear amplifier is used for the remaining little fraction with high-frequency power. So,the SLH structure can achieve both high efficiency and high bandwidth.[22][23].
  The switch-linear hybrid structure has been divided into three categories depending on its connections as:

  – *Serial hybrid* In this arrangement, a voltage-controlled switched-mode (VSC) and a voltage-controlled linear amplifier (VLA) are linked in series as shown in Figure 2.6. A VSC source is a multilevel converter that provides a stepped waveform voltage to reduce the voltage swing for the linear amplifier. The link significantly improves the switch-linear hybrid structure's efficiency. However,on the other hand, the linear amplifier's output current is still the load current, resulting in relatively high losses.[24][25].

  – *Parallel hybrid:* In this arrangement, a current controlled switched mode converter (CSC) and a linear amplifier are connecting in parallel form, Shown in Figure 2.7.The load current is tracked by the CSC, and the ripple current between the load current and the CSC's output current is compensated by the linear amplifier. The linear amplifier's loss is decreased, and the ET's efficiency

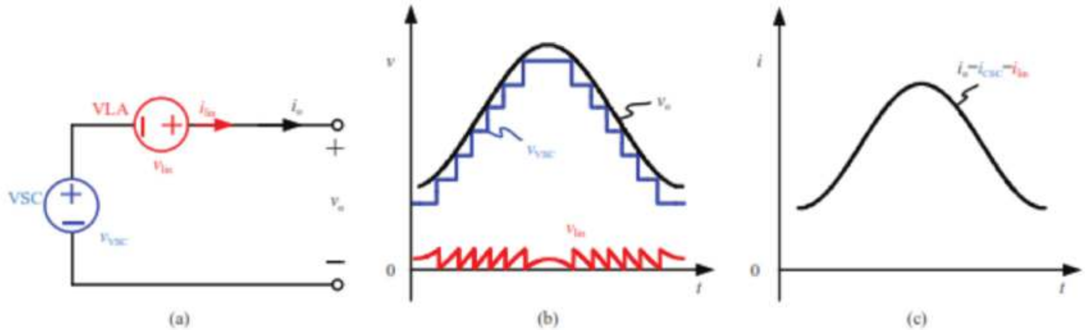

Abbildung 2.6: a)Serial hybrid connection schematic, b)key voltage wave form, c) key current wave form ,[2]

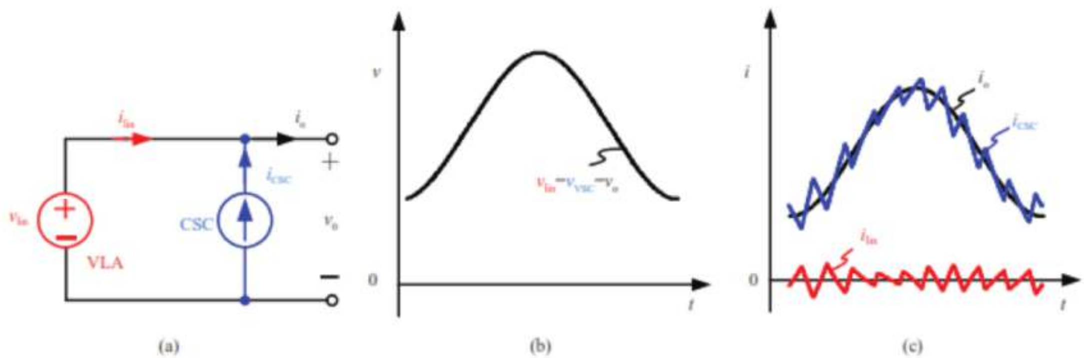

Abbildung 2.7: a)Parallel hybrid connection schematic diagram,b) key voltages wave form, c)key currents wave form,[2]

can be increased in this arrangement. Even if the VSC's output current is small, the load voltage is still high, which can result in large losses in high-power applications[26][27].

– *Combined hybrid:*The combined hybrid method achieves higher efficiency than either serial or parallel approaches can achieve on their own. Two switching elements and a single linear element are used. In the parallel hybrid design, one switch mode supply is utilized with a linear modulator linked in a parallel configuration, as stated above. This enables high-speed, high-efficiency broadband. In the case of the serial hybrid, the second switching supply is added into the circuit in cascade to provide the linear modulator with a bandwidth decreased variable supply, further reducing power loss. Both serial and parallel methods are utilized in this way to achieve the best results. efficiency[28][27][29].

Each type of envelope tracking supply has its own advantages and disadvantages. The actual type used depend upon the particular application required.However a brief comparison of the mentioned structures can be seen in Table2.1.

Tabelle 2.1: Comparison of the supply techniques for Envelope tracking method,[2]

Structure	Linear amplifier		Switched-mode converter		SLH structure		
Topology	Class A	Class AB	SS	MS	Serial hybrid form	Parallel hybrid form	Serial -parallel-form
Efficiency	Low		High		High		Higher
Linearity	Good		Medium		Good		Good
Bandwidth	Wide		Narrow	Medium	Wide		Wide
Complexity	Simple		Simple	Medium	Medium		Complex

2.2 Cascaded H bridge inverters (CHB)

Multi level converters are one method for generating stepped wave forms in power electronics. The AC output is generated by using several DC input signals in this technique[30]. DC input signals in multi level converters can be mentioned as an output of rectifiers, generation of photovoltaic panels,capacitors,etc. Multi-level converters are divided into three major categories: diode-clamped or neutral point clamped (NPC), flying capacitors(FC) and Cascade H-bridge (CHB)converters[31][32]. The cascaded H-bridge converters are mainly covered in this section,
The Cascade H-bridge converters (CHB) have become seen widespread usage due to their higher conversion efficiency, excellent output waveform and the possibility to reduce switching voltage stress. However the CHB converters are designed based on H-bridges and isolated DC sources which upscales the price. In literature, different methods have been introduced to overcome the problem and one of these methods can be mentioned as Hybrid Cascade H-bridge converters. In this section, the multilevel Cascade H-bridge converters are explored in detail. The working principle and circuit diagrams are listed and finally, the Hybrid cascade H-bridge is closely analysed with respect to efficiency and the available technologies for the CHB converters have been described.

2.2.1 Operation Principle

Cascaded H-bridge converters, abbreviated CHB, are multilevel H-bridges that are linked in series. In CHB converters, the H-bridge cell is the basic and main building block for modulation and converting process. As a reference and explanation, a H-bridge block diagram can be seen in Figure 2.8.In this figure, the input DC voltage, which is abbreviated as V_{dc}, can be replaced by a capacitor, the output of a rectifier or as the output voltage of a photovoltaic panel. CHB converters are separated into two groups based on the working principle. The CHB converters is referred to as symmetric configuration if all the input DC sources are equal in magnitudes, which provides better modularity to the typologies[33]. Additionally, the output voltage level can be boosted by using different DC sources as in the Asymmetric CHB converters' working principle. [34].The generic switches are implemented in the block diagram where each switch represents a transistor, and an anti-parallel diode for the switching processes.By evaluating all switching possibilities for a H-bridge block, it is observed the switching process in a H-bridge module should be performed in the diagonal direction. If S_1& S_3 or S_2 & S_4 are turned on, the output voltage of the H-bridge between $A\&B$ is 0V. If the switches turned on in the manner of $S_1\&S_2$, the voltage source will be short circuited and a fault will occur. Therefore, diagonal switching is the best possible option for a H-bridge module.

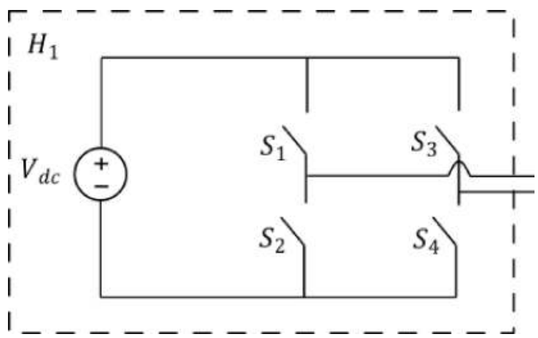

Abbildung 2.8: Basic H-bridge circuit

The complete H-bridge building block is sometimes referred to as a cell or modules in literature. Therefore, based on the H-bridge working and switching principle, the outcome of each cells can produce three distinct magnitudes of voltages- $0, V_{dc}, -V_{dc}$. The cascade H-bridge converters contain several H-bridge cells which are connected in series,or in other words, the H-bridge cells are cascaded together. In the following two cells, H-bridge are connected in series and the circuit diagram of the block can be seen in Figure 2.9 and the possible output voltage magnitudes can be calculated as the sum of the output voltage of each cell as shown in equation 2.5 and all possible voltage levels are shown in Table 2.2:

$$V_m = V_{H1} + V_{H2} \tag{2.5}$$

Based on the basic sample that can be driven, the number of voltage levels in the symmetrical CHB can be calculated with Equation2.6

$$N_L = 2 \cdot (n+1) \tag{2.6}$$

The total number of voltage levels for the asymmetrical topology depends on

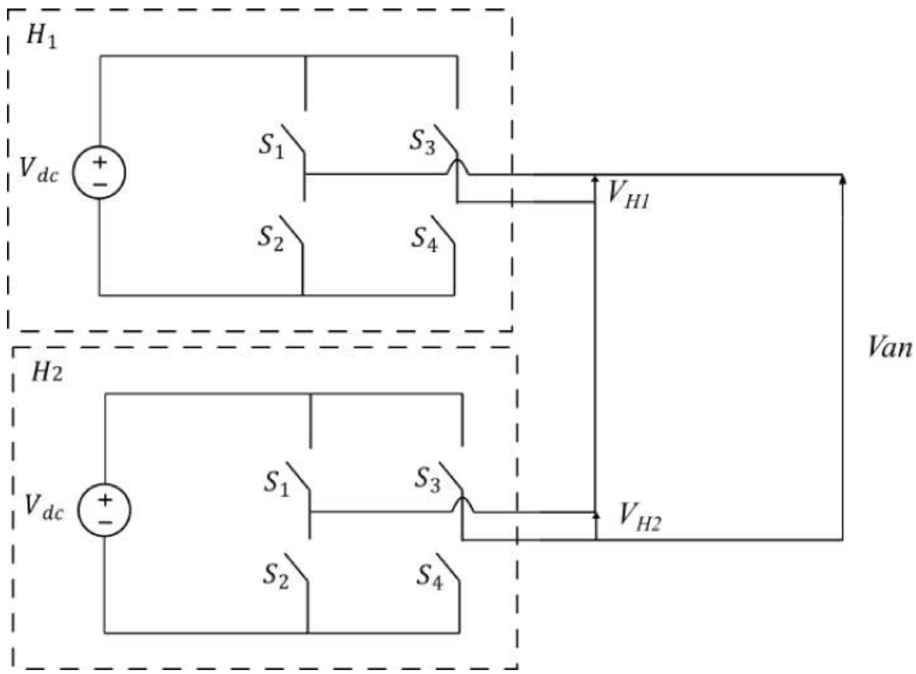

Abbildung 2.9: Two cells connected in series

the magnitude of DC sources[35].In this scenario, two methods for determination of DC sources are introduced:

- Binary
- Trinary

In the binary method,a DC source for one cell is different from other cells and the number of voltage levels can be calculated by using Equation2.7

$$N_L = 2^{(n+1)} - 1 \tag{2.7}$$

In the trinary method,DC source for at least two cells are different form other cells and the number of voltage levels are determined by Equation 2.8

$$N_L = 3^n \tag{2.8}$$

The number of voltage levels and switching states for a three cells in a series connection for symmetrical case are calculated to elucidate the concept better.

A. 7-level Symmetrical CHB Converter

- A. 7-level Symmetrical CHB converter is shown in Figure 2.10. In this figure, the CHB converter contains three cells with the same magnitude of input DC voltage and they are connected in series. The output

Tabelle 2.2: Possible voltage levels and switching states for two cell CHB

V_m	V_{H1}	V_{H2}	S_1H_1	S_3H_1	S_1H_2	S_3H_2	Multiplicity
$2V_{dc}$	V_{dc}	V_{dc}	1	0	1	0	1
V_{dc}	V_{dc}	0	1	0	0	0	4
			1	0	1	1	
	0	V_{dc}	0	0	1	0	
			1	1	1	0	
0	0	0	1	1	0	0	6
			1	1	1	1	
			0	0	1	1	
			0	0	0	0	
	V_{dc}	$-V_{dc}$	1	0	0	1	
	$-V_{dc}$	V_{dc}	0	1	1	0	
$-V_{dc}$	$-V_{dc}$	0	0	1	0	0	4
			0	1	1	1	
	0	$-V_{dc}$	0	0	0	1	
			1	1	0	1	
$-2V_{dc}$	$-V_{dc}$	$-V_{dc}$	0	1	0	1	1

voltage of the CHB can be calculated via the basic KVL method for the right-side closed circuit. Therefore, the output voltage of the CHB converter should be sum of the each cell's output voltage. According to equation 2.6,the number of voltage levels is 7 . A 7-level CHB has 64 switching states and these switching states are listed as shown in Table 2.11

B. 15-level and 27-level Asymmetrical CHB Converters

- If three cells of H-bridges are connected in series and the input DC voltage of each cells varies, the CHB converter is considered as an asymmetrical CHB converter. If the DC voltage of one cell varies from the others, it is referred to as a Binary Asymmetrical CHB. If the input DC voltage of more than one cell varies from the others, the CHB converter is referred to as a Trinary Asymmetrical CHB converter. The voltage levels for these converters can be calculated as shown in equations 2.7 2.8. The Asymmetrical CHB converter can generate 15-levels and 27-levels.
  Asymmetrical CHB converters are used rarely due to their complexi-

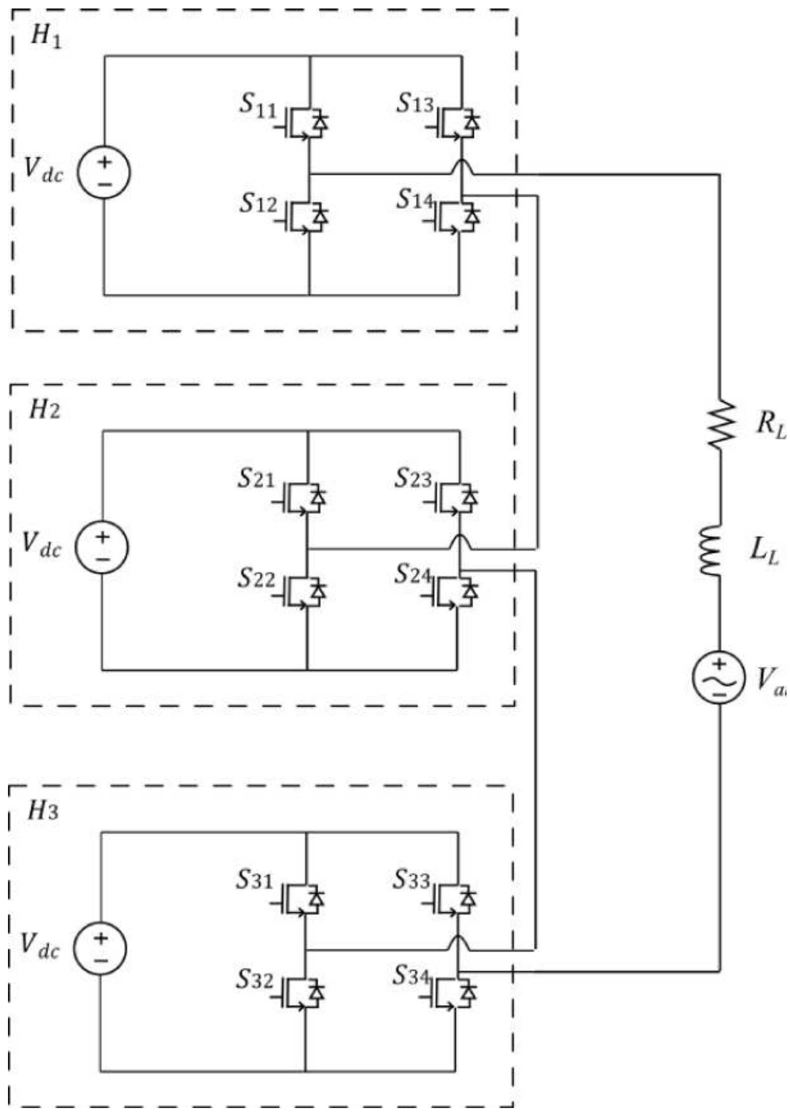

Abbildung 2.10: Symmetrical topology of CHB grid connection

ty and the requirement for different voltage rating components in their design which hinders mass production of these converters.

2.2.2 Comparison of CHB converters with Conventional VSC

Traditional inverters or two level inverters are used commonly in basic inverter. The basic circuit diagram of a voltage source converter (VSC) can be seen in Figure 2.13. The working principle of VSC converters is similar to CHB converters, and relies on the switching process. Nowadays multi-level converters ,especially CHB,are used for better output wave-form quality.If we are assuming the desired output peak voltage value of the converter is equal to $\frac{E}{2}$. The short comparison of two level three phase traditional con-

TABLE II: All Possible Switching States of a Cascaded H-bridge converter

States	S_{11}	S_{21}	S_{31}	S_{41}	S_{12}	S_{22}	S_{32}	S_{42}	S_{13}	S_{23}	S_{33}	S_{43}
1	1	0	1	0	1	0	1	0	1	0	1	0
2	1	0	1	0	1	0	1	0	0	1	0	1
3	1	0	1	0	0	1	0	1	1	0	1	0
4	1	0	1	0	0	1	0	1	0	1	0	1
5	0	1	0	1	1	0	0	1	1	0	1	0
6	0	1	0	1	1	0	0	1	0	1	0	1
7	0	1	0	1	0	1	0	1	1	0	1	0
8	0	1	0	1	0	1	0	1	0	1	0	1
9	1	0	0	1	1	0	1	0	0	1	1	0
10	1	0	0	1	0	1	1	0	1	0	1	0
11	1	0	1	0	1	0	0	1	0	1	1	0
12	1	0	1	0	0	1	1	0	1	0	0	1
13	0	1	1	0	1	0	0	1	1	0	1	1
14	0	1	1	0	1	0	0	1	0	1	0	1
15	0	1	1	0	1	0	1	0	1	0	0	1
16	0	1	1	0	1	0	1	0	1	0	0	1
17	0	1	1	0	0	1	0	1	1	0	0	1
18	0	1	0	1	1	0	0	1	0	1	1	0
19	0	1	0	1	0	1	1	0	1	0	0	1
20	0	1	0	1	0	1	1	0	1	0	1	0
21	0	1	0	1	0	1	1	0	0	1	0	1
22	1	0	0	1	0	1	0	1	0	1	1	0
23	1	0	0	1	1	0	0	1	0	1	1	0
24	1	0	0	1	1	0	1	0	1	0	1	0
25	1	0	0	1	1	0	1	0	0	1	0	1
26	1	0	0	1	0	1	1	0	1	0	0	1
27	1	0	1	0	1	0	0	1	1	0	1	0
28	1	0	1	0	1	0	0	1	0	1	0	1
29	1	0	1	0	1	0	1	0	1	0	0	1
30	0	1	1	0	1	0	0	1	1	0	0	1
31	0	1	0	1	1	0	0	1	0	1	0	1
32	0	1	0	1	1	0	0	1	1	0	1	0
33	0	1	0	1	0	1	0	1	1	0	0	1
34	0	1	0	1	1	0	1	0	1	0	0	1
35	1	0	0	1	0	1	0	1	1	0	1	0
36	1	0	0	1	0	1	0	1	0	1	0	1
37	1	0	1	0	0	1	0	1	1	0	0	1

Abbildung 2.11: Possible switching states of a Cascade H-bridge converter

verters and 5-level three phase Cascade H-bridge converters is made below:

- A. A two level three phase Conventional Voltage Source converter:
  Generation of the peak value as $\frac{E}{2}$ at the output of a VSC requires E as a DC voltage source for supplying the VSC converter.Additionally, switching components should be considered with the voltage rating for working under the E condition. As is seen in Figure 2.13, the VSC converters are engaged with 6 switching devices in total. These type of converters can generate $\frac{E}{2}$ in the peak value of the AC voltage at the output of the converter.

- B.5-level three phase Cascade H-bridge Converter:
  The generation of the same peak magnitude of AC voltage in 5-level three phase CHB demands six isolated DC voltage source with a magnitude of $\frac{E}{4}$ for each source. Therefore, the voltage rating for each of the switching components becomes become $\frac{E}{4}$ and each switching

TABLE III: Switching States of 15-Level Cascaded H-bridge Converter

States	S_{11}	S_{21}	S_{31}	S_{41}	S_{12}	S_{22}	S_{32}	S_{42}	S_{13}	S_{23}	S_{33}	S_{43}
38	1	0	0	1	0	1	1	0	0	1	1	0
39	1	0	1	0	1	0	1	0	0	1	1	0
40	1	0	1	0	0	1	1	0	1	0	1	0
41	1	0	1	0	0	1	1	0	0	1	0	1
42	0	1	1	0	1	0	0	1	0	1	1	0
43	1	0	0	1	1	0	1	0	1	0	1	0
44	0	1	1	0	1	0	1	0	0	1	0	1
45	0	1	1	0	0	1	1	0	1	0	0	1
46	0	1	1	0	0	1	0	1	1	0	1	0
47	0	1	0	1	1	0	1	0	0	1	1	0
48	0	1	0	1	0	1	0	1	0	1	1	0
49	1	0	1	0	0	1	0	1	0	1	1	0
50	0	1	1	0	0	1	0	1	1	0	1	0
51	1	0	0	1	1	0	0	1	1	0	1	0
52	1	0	0	1	1	0	0	1	0	1	0	1
53	1	0	0	1	1	0	1	0	1	0	0	1
54	1	0	1	0	1	0	0	1	1	0	0	1
55	0	1	0	1	1	0	0	1	1	0	0	1
56	1	0	0	1	0	1	0	1	1	0	0	1
57	1	0	1	0	0	1	1	0	0	1	1	0
58	0	1	1	0	1	0	1	0	0	1	1	0
59	0	1	1	0	0	1	1	0	1	0	1	0
60	0	1	1	0	0	1	1	0	0	1	0	1
61	0	1	1	0	0	1	0	1	0	1	1	0
62	0	1	0	1	0	1	1	0	0	1	1	0
63	1	0	0	1	0	0	0	1	1	0	0	1
64	0	1	1	0	0	1	1	0	0	1	1	0

Abbildung 2.12: Possible switching states of a Cascade H-bridge converter

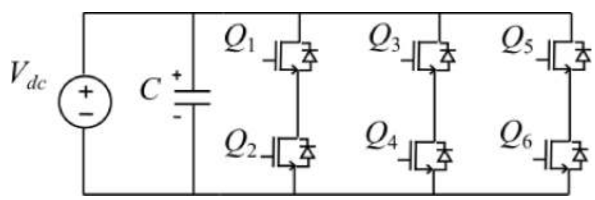

Abbildung 2.13: Conventional Voltage Source converter

components should be able to withstand $\frac{E}{4}$ DC voltage. This type of converter requires 24 switching devices in total.

To summarize these considerations, both converters have their merits and downsides. Traditional converters are adequate for basic inverters and they are designed for low voltage sources, while CHB converters are the optimal solution for high voltage and more complex inverters, because they can divide the input voltage to a smaller amount, thereby increasing the isolation and voltage rating of the switching components of the converters and decreasing the stress and switching losses of the inverter.Based on their operating principle, it can be stated that the size of the heat sink for the CHB converters has decreased and that they are more compact. It should be noted that while a greater output voltage may be reached with a CHB converter, the losses for each cell are not identical since the output voltage of each cell has a distinct waveform, as seen in Figure 2.14.[36].

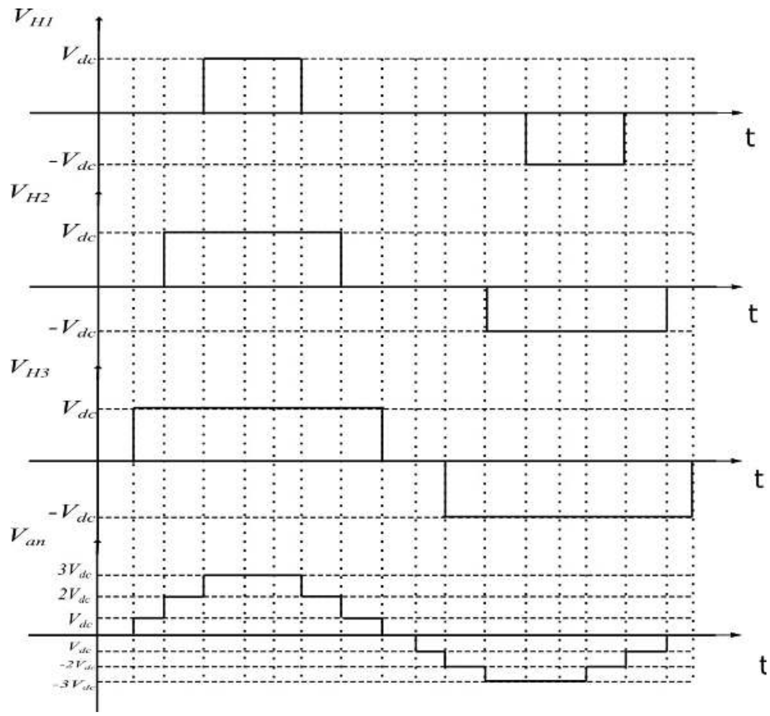

Abbildung 2.14: Three-cell Cascade H-bridge converter output wave form

2.3 Power Amplifiers

Power amplifiers are utilized for the amplification process. The input signal is always connected to the amplifier, and the output signal can be increased or decreased in peak values but most commonly, the wave-form is seen and desired to be same as input signal wave-form. Power amplifiers are named and divided into different classes based on their operational mode.
Power amplifiers elevate the signal levels mostly based on the working principle of transistors. Power amplifiers are divided into two main groups:

- Linear Amplifiers
- Non-Linear Amplifiers

These two groups are divided based on the linearity of the output signal after the amplification process. If the transistors are working or turned on all the time, the distortion at the output signal is insignificant enough such that output wave form can be considered the same as the input signal but with a higher value. These groups traditionally have a lower efficiency. As the transistor is switched on for the entire working duration, the unused power is mostly emitted as heat which leads to the decrease in efficiency [37].
New techniques have been introduced to overcome the low efficiency in linear amplifiers. The transistors or the overall amplifier is turned on based on the

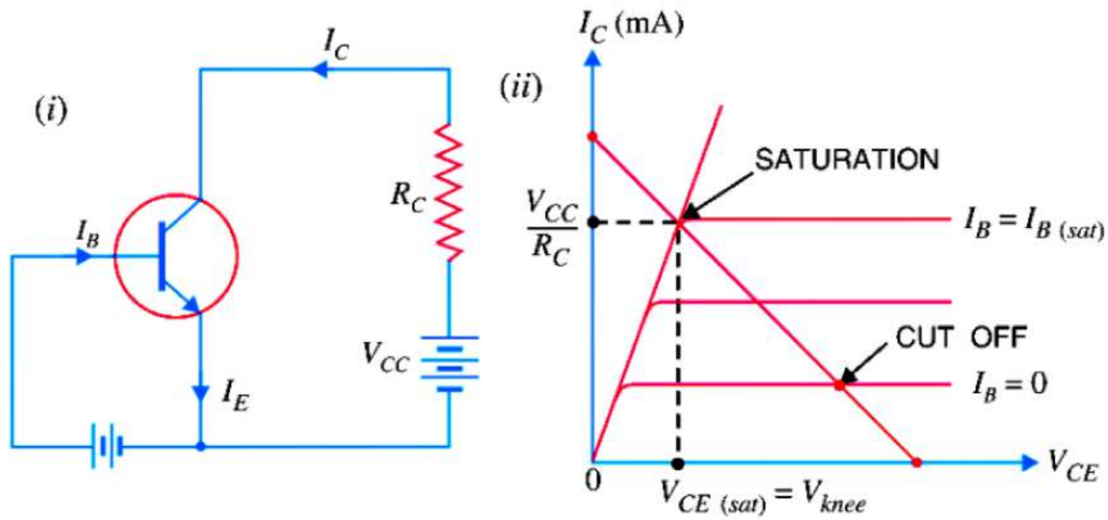

Abbildung 2.15: Example of bipolar transistor working region,[4]

input signal value. The main problem of these amplifiers is the harmonic distortion at the output signal based on the switching process in the amplifiers. However, because supplying the amplifier is happening mostly efficiently , the efficiency of these type are quite good in comparison to when they are turned on for the entire working duration value[38].
Base on these two main groups and their combinations,different classes are introduced for working in different ways and optimal solutions can be chosen based on individual requirements.

2.3.1 Linear Amplifiers

Linear class amplifiers such as Class A,B,C and AB typologies are quite similar to each other and different classes are named based on different regions of the usage of the transistors in the circuit. In electronics, transistors work in three different regions: Cut off, Active and Saturation.These working regions can be seen in Figure 2.15 The cut-off region is the part of the transistor operation where the Base and Emitter (in NPN transistors) are not conducting and the supply voltage of the collector is the same as the input value to collector. By increasing the base voltage up to the starting limit of voltage for the working region of transistor(differs from different models,around 0.6 mV), the transistor starts conducting current and collector voltage decreases and this region is called the active region of the transistor. By increasing the base voltage until the limit of the active region of transistor,the transistor is said to be in saturation and the collector voltage starts to increase again. Therefore, based on the transistor working region, different linear classes are

shortly defined as:
Class A: Device is on or active during the entire waveform.
Class B: Device is on for $\frac{1}{2}$cycle (180°)
Class C: Device is on for $< \frac{1}{2}$ cycle (180°)
Class AB: Between AB and working on (180° –360°)
Based on the biasing methods, different circuit diagram models are introduced but the basic model of each mentioned classes is as seen in Figure 2.16

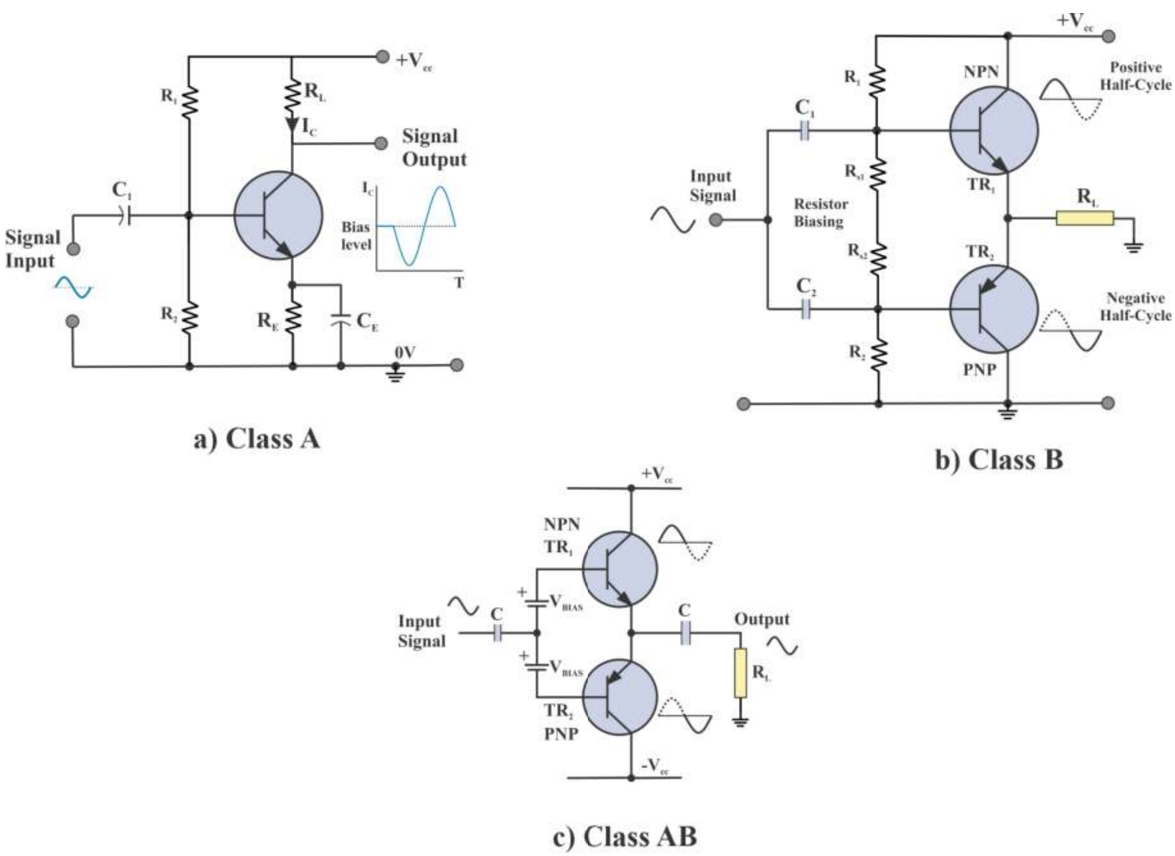

Abbildung 2.16: Basic model of linear amplifier

Class A amplifier

For a better understanding and comparison of these classes, it is assumed that the circuit schematic is as seen in Figure 2.17 and all initial values for this circuit are as listed as shown in Table 2.3
By referring to Figure2.17, it is seen that the R1 value is not defined and it acts as an adjustable resistor which allows control of the base voltage of the transistor via voltage divider method. By setting the R1 to 6.5k OHMS, the input signal is always higher than 600 mV which allows the transistor to operate in the active region and transistor is always is on and the circuit is

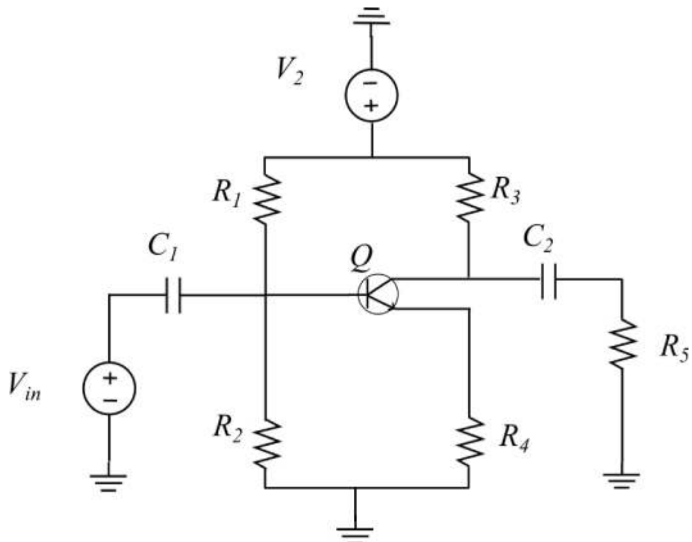

Abbildung 2.17: Simple Example of linear classes working regions

Components	Frequency (Hz)	Value	Unit
R_1	Adjustable		Ohm
R_2	2.7		KOhm
R_3	680		Ohm
R_4	680		Ohm
R_5	100		KOhm
C_1	470		nF
C_2	470		nF
V_{in}	10 Khz	20 (Peak)	Volt
V_2	DC	5	Volt
Q	2N2222		

Tabelle 2.3: Initial values for amplifier sample

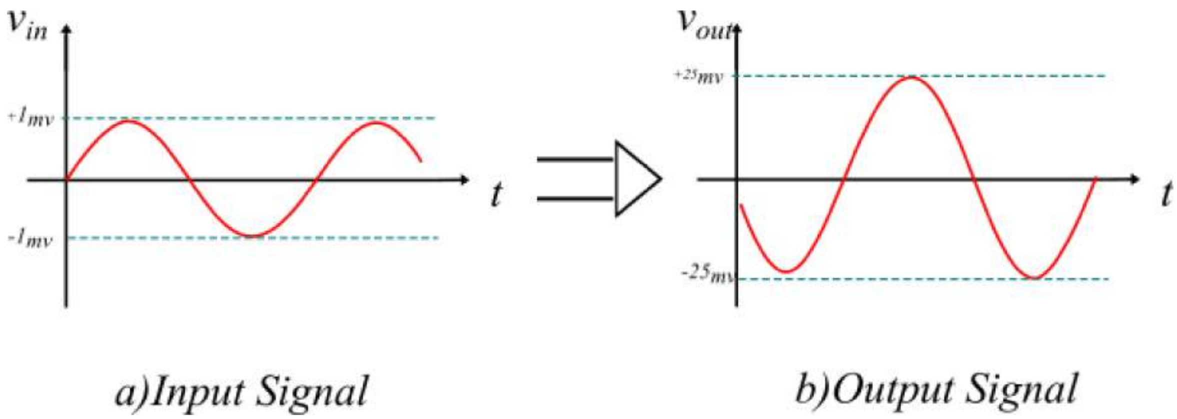

Abbildung 2.18: Results Sample for Class A amplifier

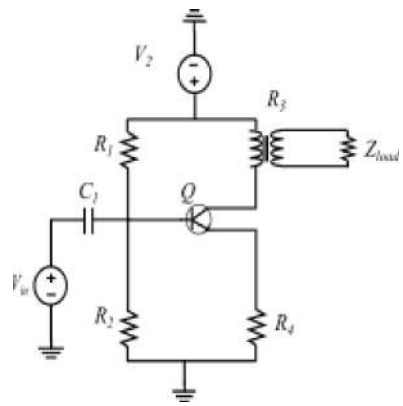

Abbildung 2.19: Transformer coupled amplifier

works as a class A amplifier. The output signal wave-form of the sample [3] for operation is roughly in class A can be seen in Figure2.18 and by checking the results it is seen that class A shifts the input signal and the output amplitude of signal is increased without almost any distortion.However as the class A amplifier is a purely linear amplifier, the efficiency of these types can be as low as 30% which is calculated based on the Equation **??**.

$$\eta = \frac{P_{out}}{P_{DC}} \cdot 100 \tag{2.9}$$

Different typologies are introduced and examined to modify class A amplifiers to attempt to increase the efficiency to about 50%. One of these combinations can be seen in Figure2.19 where the efficiency of class A amplifier is increased by adding a transformer directly to the collector of the transistor. This type is referred to as Transformer Coupled Amplifier in literature [39]. The transformer in the design acts as an inductive device that will produce back electric and magnetic field(EMF) based on the Lenz's law which might

[3] results from simulation is observed and the graph is based on simulation

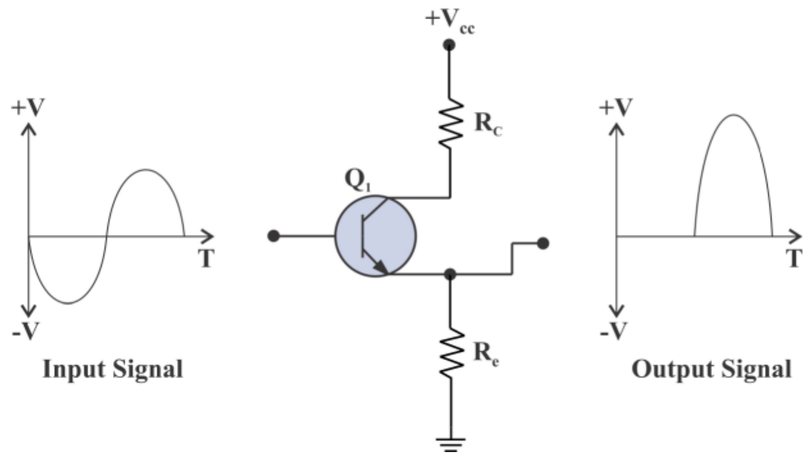

Abbildung 2.20: Single ended class B amplifier

damage the transistor and the system.

Class B Amplifiers

Ohter designs and amplifiers are introduced to overcome the problems in class A amplifiers. However, class A amplifiers are still used in some circuits based on their pure linearity. The second basic power amplifier class is referred to as class B amplifiers. Class B amplifiers' working principles is better understood by comparing the working region of the transistor with class A amplifiers. The same circuit diagram of class A amplifier as in in Figure 2.17 is considered.The basic class B amplifier could produced by setting R_1 value to 36k ohm which biases the base of the transistor when input signal is bigger than 0.6 mili volt. The transistor is turned off for input signal values lower than 0.6 mili volt (approximately zero). Therefore, the amplifier does not operate for the negative half-wave and the output wave-form is roughly as seen in Figure 2.20
As is observed, the output signal wave-form contains only the positive half-wave. This design however gives rise to a high level of distortion which has decreased the usage of this design in electrical systems.
Nowadays, class B amplifiers are mainly used for their performance in the push-pull design. The previous model is modified by adding and connecting the NPN and PNP transistors in series, which is referred to as the push-pull design,and each transistors functions for a half wave of the signal and the overall design the output signal will contain the positive and negative half wave-form.This model is depicted in Figure 2.21
By checking the output signal wave form of the above-mentioned model, it is observed during zero-crossing that the section amplifier will be off for a short period of time which gives rise to distortion in the signal wave-form. The

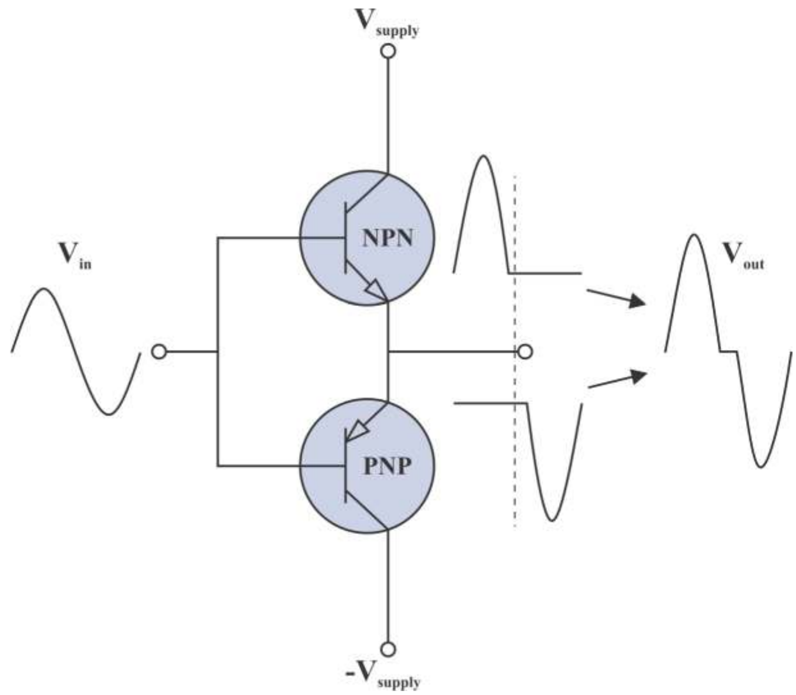

Abbildung 2.21: Class B Push-Pull Configuration

reason behind this is based on the transistor's working principle. The turn-on process of each transistor requires a threshold voltage value.Therefore, each transistor's turn-on process requires some time until the input signal value is as high as their threshold voltage to turn on the transistors. The required time is the reason for this particular cross-sectional area in the output signal wave-form. For a better understanding, the input signal value and the output signal are shown in Figure **??**

Class B amplifier are more efficient than class A amplifier as the transistors are not turned on for the entire period. The theoretical maximum efficiency of class B amplifiers is at around 78%.However, the cross-over distortion of class B amplifier has influenced the popularity of this class.

For Class C amplifiers, the biasing voltage to saturation region occurs but due to its complexity, this review focuses on Class AB amplifiers instead. Class C amplifiers are commonly used for RF signal and their operations are not suitable for Audio amplifiers as half the wave-form of the input signal is lost.The distortion in class B amplifiers is almost similar to the time taken to achieve 600 mili volt to turn on or off transistors which is referred to as crossover distortion.

Class AB

As the main disadvantage of the class B amplifier is the cross-over distortion inspite of their high efficiency, therefore a combination of the class A and B

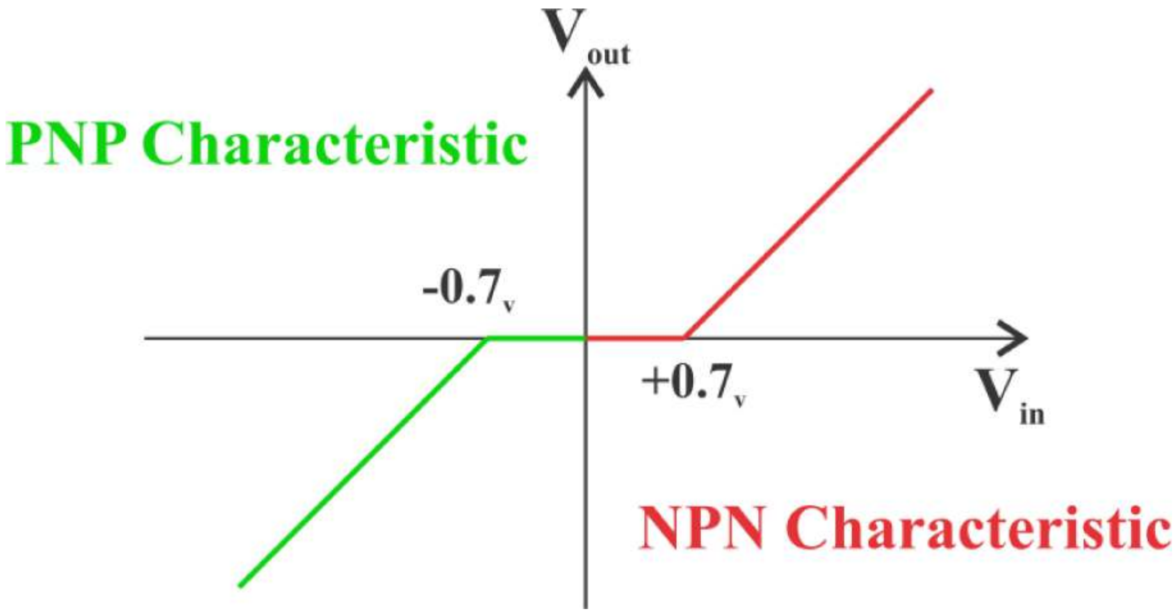

Abbildung 2.22: Class B cross-over distortion characteristics

is utilized and the efficiency and linearity of B and A respectively can be used in a combination of these amplifiers referred to as class AB amplifiers. The working principle of the class AB amplifiers can be elucidated with Figure 2.23

As shown in the wave-forms of the class AB amplifier, the two transistors and the circuit components are designed in such a way that the transistor turn On and Off separately but work in a small region together to overcome the cross-over distortion in class B amplifier. As both the transistors are not on for the entire working duration of the circuit, the dissipated power will be less than that of a class A amplifier and the maximum theoretical efficiency of this class is at around 78 %.

A generic class AB amplifier schematic is shown in Figure 2.24 As in seen the circuit diagram of the Class AB amplifier, class AB and Class B amplifiers are almost the same circuit and both classes use the push-pull design. The main difference of these is the biasing method. Class AB amplifier transistors as mentioned before is biased in a manner which provides a short time where both of the transistors are in the On region and for this purpose, different biasing methods have been introduced in literature and they can be listed as:

- Voltage biasing
- Resistor biasing
- Adjustable amplifier biasing

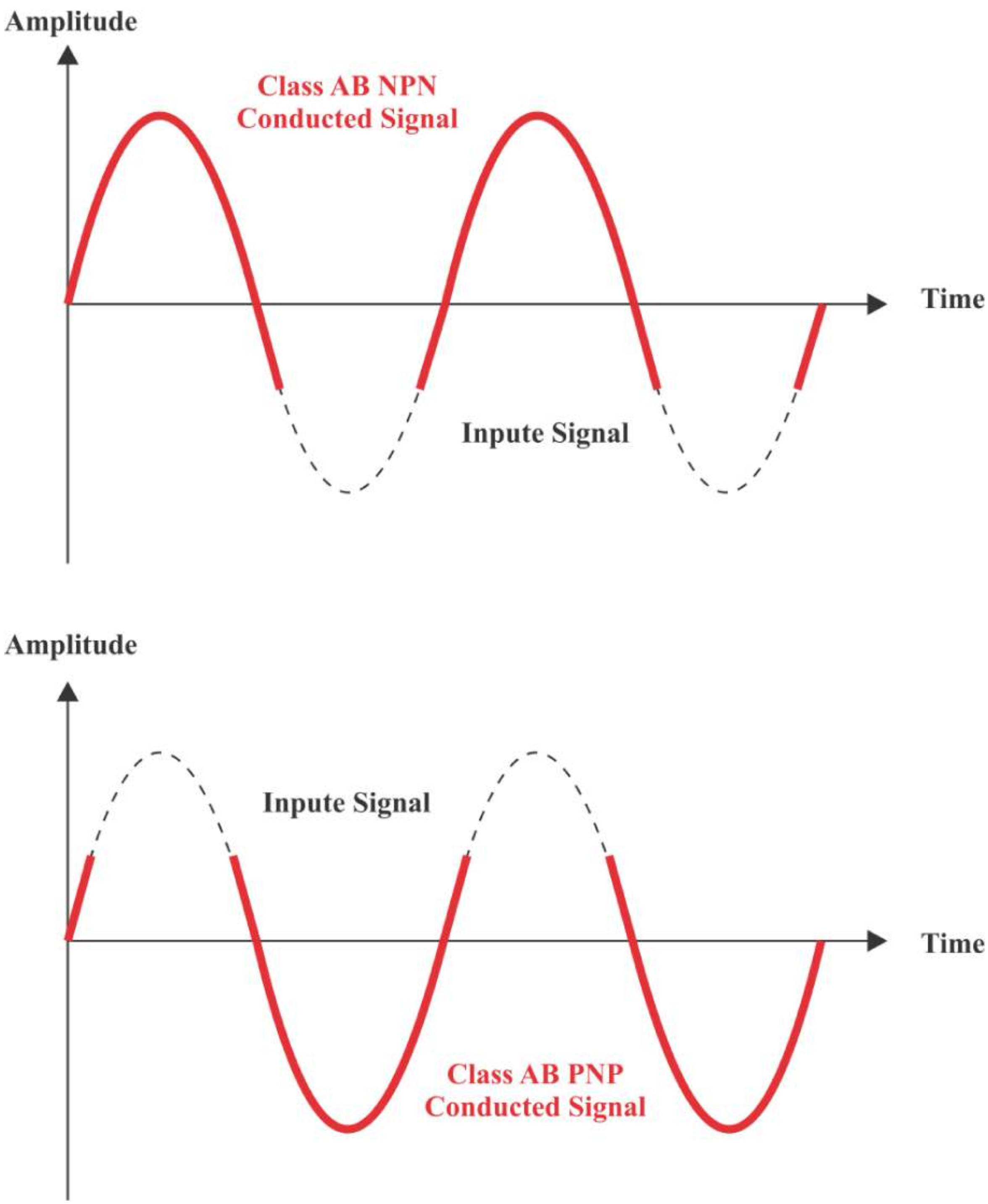

Abbildung 2.23: NPN and PNP-based class AB amplifier conduction angle

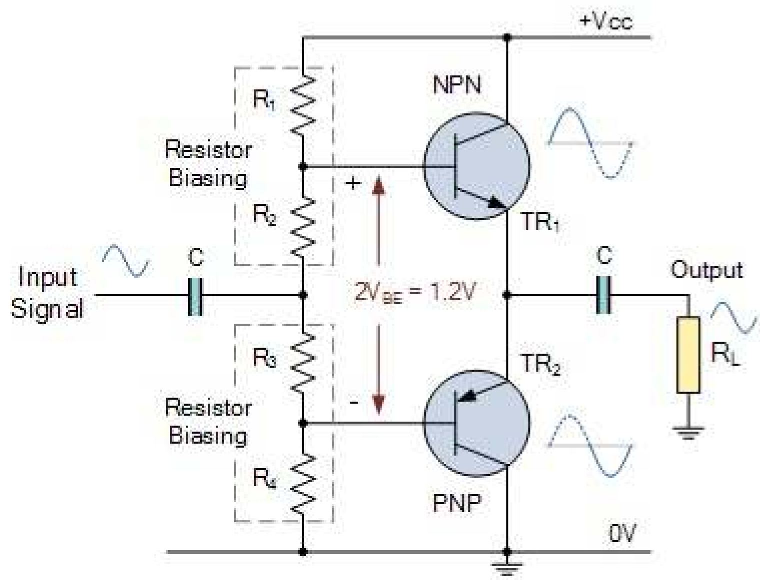

Abbildung 2.24: Class AB circuit diagram

- Amplifier driver stage

All the schematics of these biasing types are shown in Figure 2.25
Amplifier driver stage biasing has a better quality and reasonable efficiency compared to other methods, and therefore in this report, the focus is on the simplification of this biasing. In this method the circuit is very similar to class B by using two transistor for the amplification process(PNP NPN), and one NPN transistor is used similar to class A for biasing process, with the addition of two diodes to assist in reducing the distortion of class B amplifier. [40].
The main linear amplifiers are mentioned in this section. However new methods and designs have been introduced to enhance the linearity and the efficiency of the linear amplifiers such as the class H and class G amplifier.

2.3.2 Non-Linear Amplifiers

Until this section, all the introduced amplifiers are placed in linear amplifier group. Other groups of amplifiers work based on the switching methods. In non-linear amplifiers as fast switching is required , MOSFETs and IGBTs are used instead of basic transistor in older models. Thus, efficiency of these types are much better in comparison to the linear amplifiers. However, as the switching process is always combined with adding harmonics to the signals, the linearity of these types require some special filtering design.The comparison of the input signal and the output signal in Non-linear amplifiers is as shown in the graphs in Figure 2.26

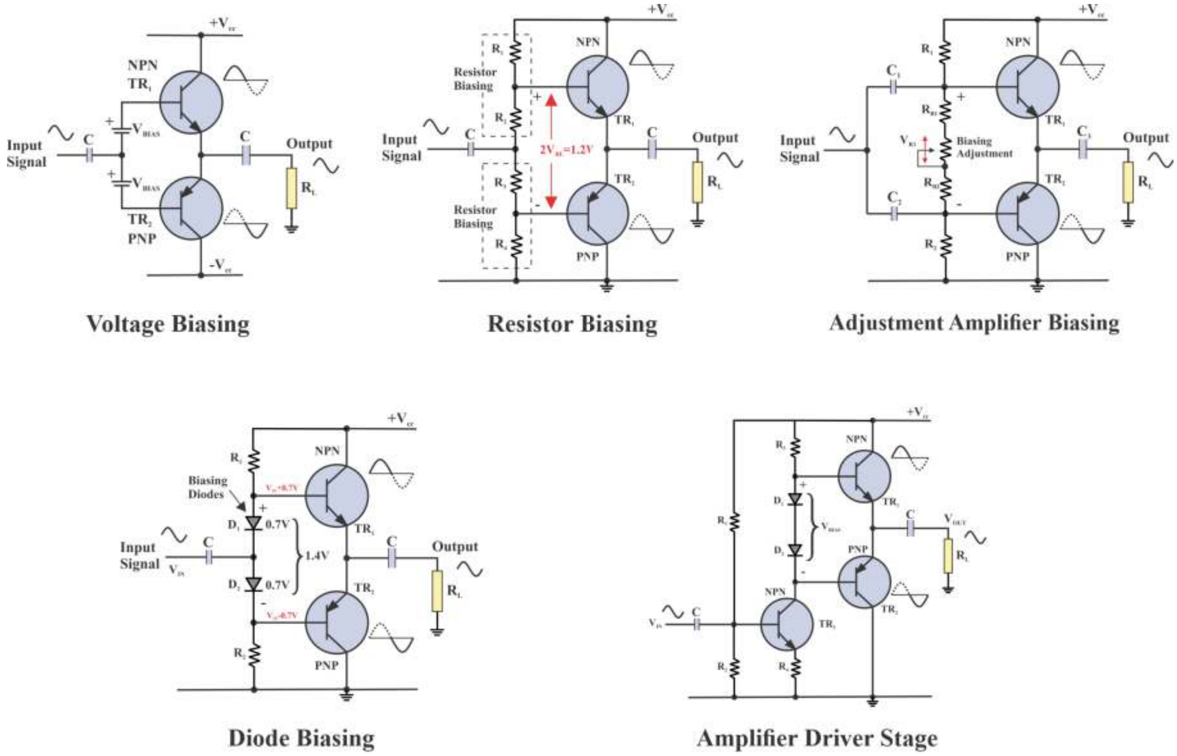

Abbildung 2.25: Different class AB biasing methods

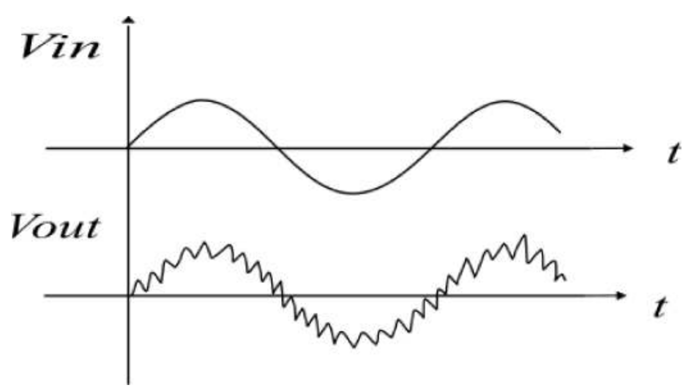

Abbildung 2.26: Non-linear signal comparison

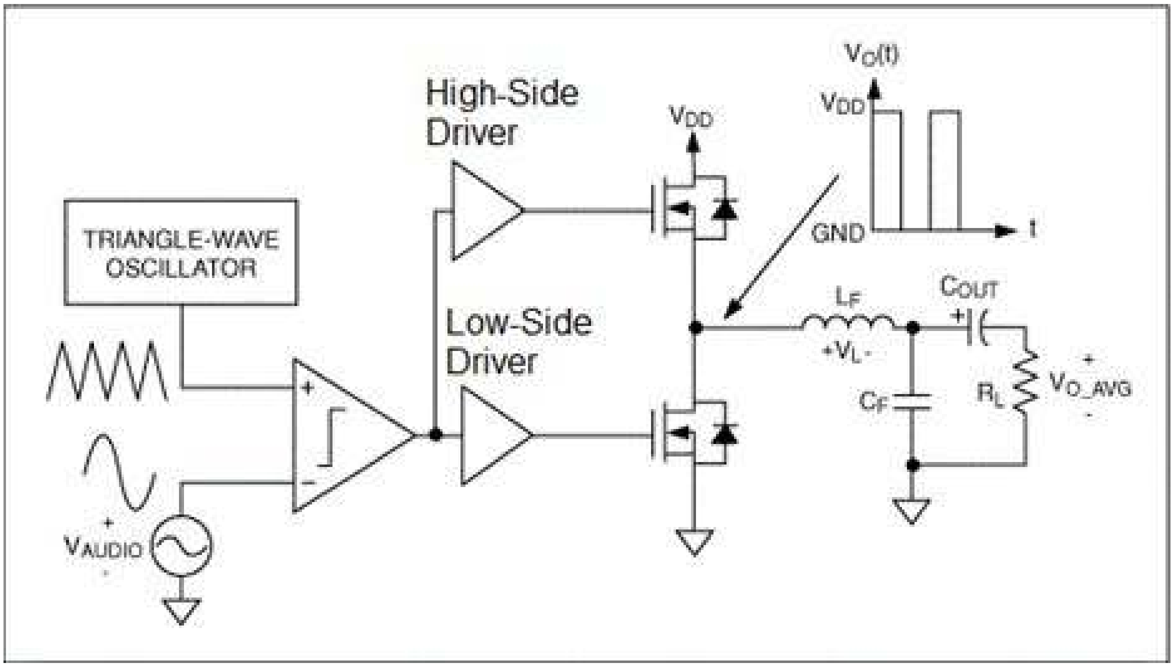

Abbildung 2.27: Class D amplifier schematic

Class D Amplifiers

In non-linear amplifiers, two different methods are introduced which are named as:
1. Delta sigma modulator
2. PWM
In this report ,as the functionality of the PWM method is more popular and understandable, PWM method and the circuit diagram functionality are highligted. Clas D amplifier is the one of the more popular designs in non-linear amplifiers. In thi review, class D amplifier is used for explaining the general working principle of the non-linear amplifiers. In class D amplifiers, MOSFETs or IGBTs are used instead of transistors based on the switching process requirement.The advantages of the class D amplifier and the switching process brings the opportunity to control input voltage and also reduce the heat sink size of the circuit while dissipating power as heat is enormously reduced by using switching functionality. On the other hand, switching process are not immediate and based on the dead time for which we need extra components in MOSFET Drivers such as IR2110s.As switching is not immediate, it provides a path for the low impedance between two MOSFETs which causes a failure in timing which in turn leads to significant distortion.
The general and basic circuit diagram of the class D amplifier can be seen in Figure2.27
In class D amplifiers, the input signal is compared with a reference signal(triangular signal). The frequency of the triangular signal should be at least 10

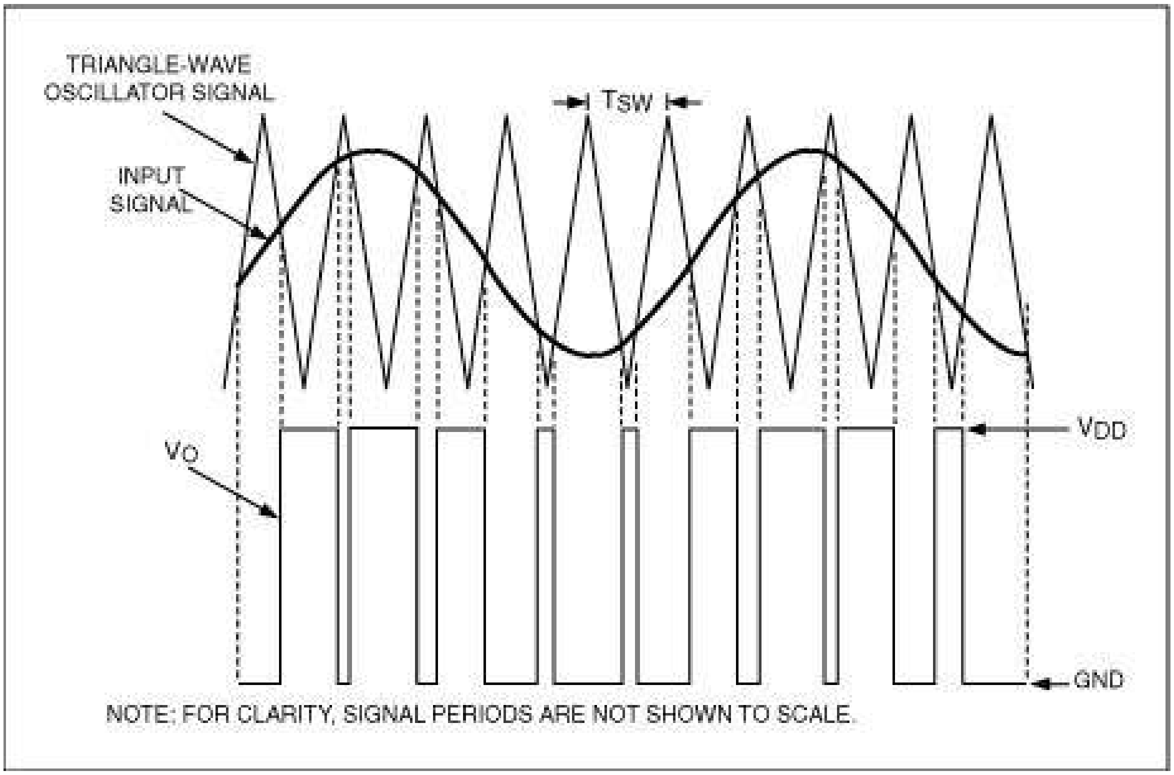

Abbildung 2.28: The Output-Signal Pulse Widths Vary Proportionally with the Input-Signal

times higher than the input signal to get better coverage of input signal. The output signal is formed and based on the output gain and duty cycle, a new signal form is prepared for amplification process by the two MOSFETs.As the switching always brings noise to signal the output signal is in the form of AC and input signal but possessing a triangular formation in the signal.The switching process and duty cycle can be seen in Figure2.28

This distortion for audio signals is not acceptable and that must be fully filtered before the input. It is also noteworthy that the filter design in class D in some cases can be a complicated process and differs from circuit to circuit. Based on these issues, class D amplifiers are rarely used and audio companies prefer to use linear class amplification. [41].

3 Description of the main idea

Because of their great efficiency, inverters based on conventional power electronics building blocks are utilized to generate sinusoidal or harmonic output voltages. However, in cases where high output frequencies are required such as telecommunication and audio amplifiers or for ultrasonic actuators, a high switching frequency is required to guarantee a sufficiently high pulse number for a high quality output voltage. This, in many situations, results in huge de-rating of available power or raises the requirements on filter design, inverter design, and/or total system cost. Filter elements are often employed to smooth the rectangular output voltage of switching elements. These filter components will have a significant impact on the total volume and cost of the system. As an alternative, resistive losses with a transistor in linear operating mode can be used to decrease the difference between the switching components' non-sinusoidal output voltage and the required smooth output voltage.(see Figure 3.1 and 3.2). While this may result in decreased efficiency, the total system bulk and complexity may be minimized.

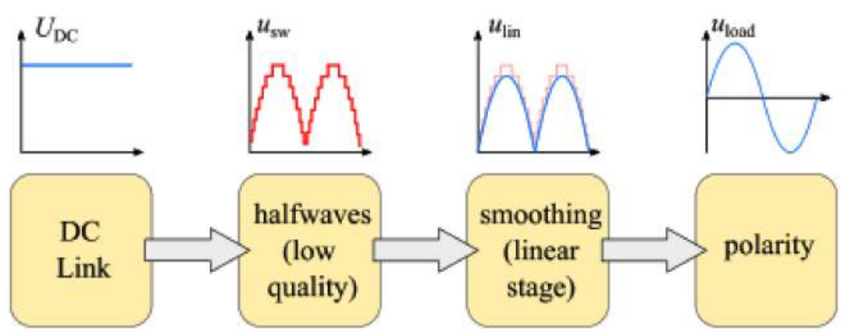

Abbildung 3.1: Conversion steps for generation a AC output voltage with a hybrid linear approach

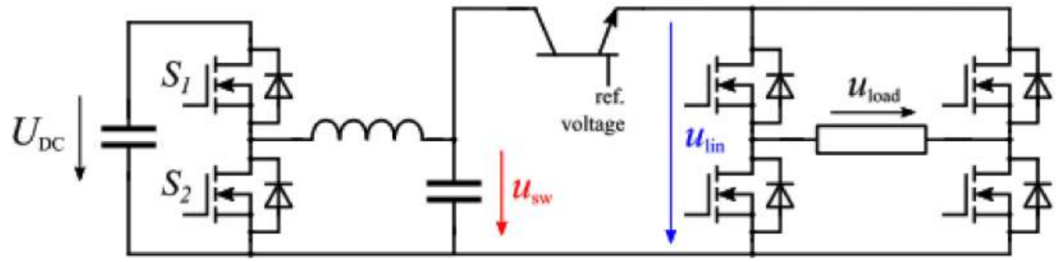

Abbildung 3.2: Exemplary circuit diagram for a hybrid linear inverter

In addition to the reduced horizontal resolution caused by a low pulse number, the vertical resolution might be constrained if a multilevel inverter with fixed output voltage levels is employed. An example is given in Figure 3.3. Here, a four-level voltage U_{sw} is reduced to sinusoidal half waves U_{in} by reducing the voltage difference Δu with a linear stage.

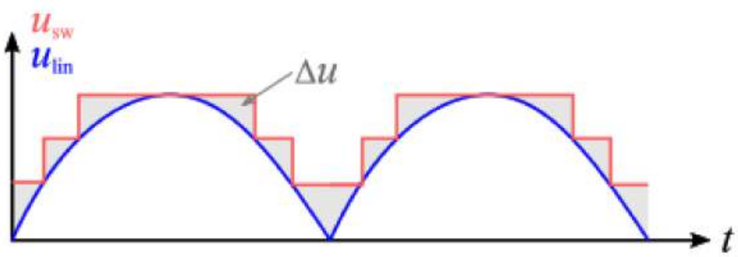

Abbildung 3.3: Exemplary AC voltage generation with hybrid linear approach by using a four-level voltage

In this thesis, three major techniques for output-voltage sine-wave distorting reduction is used as listed in following sections.

3.1 Envelope Tracking

Based on the supply techniques mentioned in section 2.1for the envelope tracking approach. In this thesis, the serial hybrid structure is explored in depth. As previously stated, a multi-level converter can be used for stepped wave form voltage generation and responsible for low frequency's range in this arrangement, with a linear hybrid amplifier linked in series for high frequency power. [42] [43]

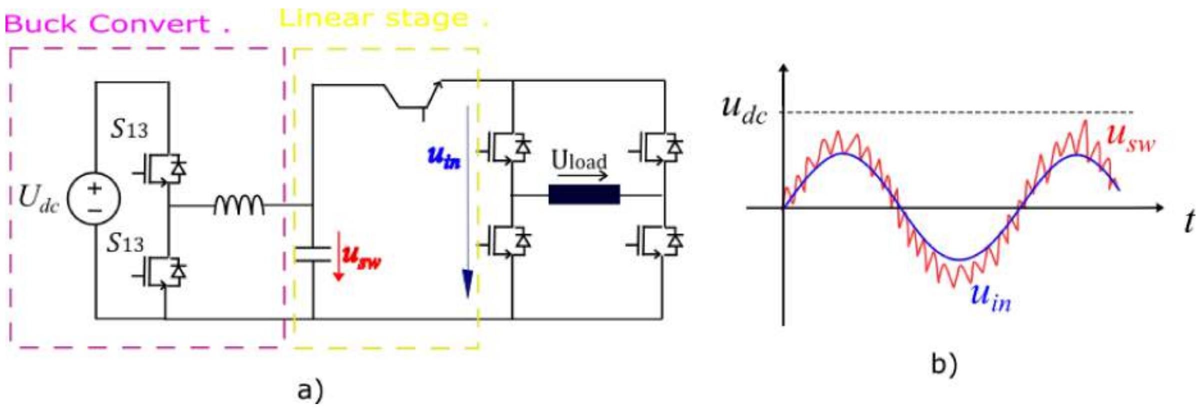

Abbildung 3.4: Exemplary circuit diagram for limited horizontal resolution,a) schematic of linear stage and a buck converter b)exemplary output voltages

3.2 Limited Horizontal resolution

Horizontal resolution refers to the quality of a signal in the horizontal direction. The horizontal resolution of a DC to AC converter is restricted by the inverter's switching frequency. As a general rule, the system's switching frequency should be at least 20 times greater than the intended AC output's fundamental frequency. As a result, in higher frequency applications, the horizontal resolution may be restricted. Even if high frequency switches could be added, the structure's output signal would have a lot of distortion due to the high frequency switching process. The signal can be purified by using a high frequency passive filters. However, as a result, the size of the filter will increase, which may provide an issue in terms of system size and cost.Figure 3.4(a) is shown the main idea of the limited horizontal resolution. In this design a Buck converter and a linear stage are connected in series to each other and the result of the system can be roughly considered and shown in Figure3.4 (b).

3.3 Limited Vertical resolution

Multi level converters can be used for AC voltage production from a DC source too. However, based on number of H-bridges and the voltage levels , the voltage form will be different at the output of the structure. Based on the information as mentioned for Cascaded H-bridge converters in section 4.2 , output voltage will become closer to sine wave if the number of cells , which are connected to each other , is increased. Basically that can be said the vertical resolution of the inverter is highly depend on the number of cells which are cascaded to each other. So, increasing the number of the cells in CHB converters are not always best solution in economical point of view.

3.4 Linear Hybrid inverters

The combination of the linear stage and the multi-level converter can be used to improve the output signal's vertical and horizontal resolution. In this thesis, we focused on the linear hybrid inverter and the connection of a class AB linear amplifier and a CHB as a multi level converter.

4 Simulation

In this chapter, the desired model was compiled and designed by MATLAB Simulink software. The results of the two operational modes of the model are compared to each other.
The designed model has been used to convert DC voltage to AC voltage with a higher peak value which can be used for envelope tracking technique for telecommunication system or even for photo voltaic system. For that purpose, different sections and components work together to reduce distortions and provide a fully sinusoidal wave-form similar to the reference signal at the output of the system. In the first phase of the model designing, a 3-cell Cascade H-bridge inverter is designed in PLECS software and the working principle and supply modulation is studied. The model is modified by using a 5-cell CHB converter to obtain the smoothest possible signal wave form. The Cascade H-bridge converters can function under two conditions as a symmetrical or asymmetrical [44] & [45].
The symmetrical CHB is preferable for mass manufacturing since all of the switching components have the same voltage rating and the structure is more accessible due to the simple and identical control stage instead of the asymmetrical CHB structure. In the proposed model, the symmetrical CHB converter is used based on their simplicity in the design point of view.
After the design of the CHB converter and the voltage modulation of this phase, different type of analoge amplifiers and their connections with the CHB converter (in series or parallel) are examined to overcome its output distortion and bulky filter design is replaced with linear amplifier structure combination to the multi-level converter.
The optimal option of analogue amplifiers based on the acceptable linearity performance and related high efficiency to that was the Class AB amplifier and its connection to the CHB and results are shown in 4.3.
Finally, the small high frequency filters are designed to overcome the switching distortion. As the main objective of the design of the system was reducing the size of the filter component and the overall circuit size ,the linear amplifier was designed with the size in focus. Thus, the filter design of the system was pretty small and used to filter the high frequency.The results are as shown in 4.4.In this model, an LC filter was sufficient and based on each

cell's functionality and in an effort to reduce the cost of the system, the output capacitor is divided to five capacitors, one for each cell, which provides the opportunity to use cheaper capacitors for lower voltage levels.The primary disadvantage is that greater capacitance values are required for each cell, while the voltage rating for each capacitor is decreasing dramatically (five times lower in this case).
At the end of this chapter, two operational mode for the designed system are compared to each other.

4.1 H-bridge

One of the main components of the Cascade H-bridge (CHB) converters are the H-bridge cells. The CHB converters are designed based on H-bridges and their working principles. A H-bridge can be seen in Figure 4.1 .As is observed from figure, the H-bridge consists of four switches and a DC voltage source. In the proposed design, IGBT switches are used. For each IGBT, a diode is connected in parallel to control and block flowing backward current in the IGBT, and to provide a path for backward current in H-bridge. The DC supply voltage of each cell was considered to be a 100 volt dc for a realistic simulation.
Base on the H-bridge explanation provided in the previous section, Figure4.1 can be modified to Figure 4.2 for the more realistic simulation.The current path and the working principle of H-bridge is shown in Figure 4.3 for a better understanding of the switching principle in H-bridge cells.
As is seen in Figure 4.3, the current has two paths based on the switching principle in the H-bridge. The switches are controlled by the gate voltage of the IGBTs. The switches will conduct when the gate of an IGBT is supplied with voltage and they will turn off in the opposite manner.Thus, each H-bridge has the ability to provide two voltage steps,one in a negative and another in a positive manner based on the current flow direction.

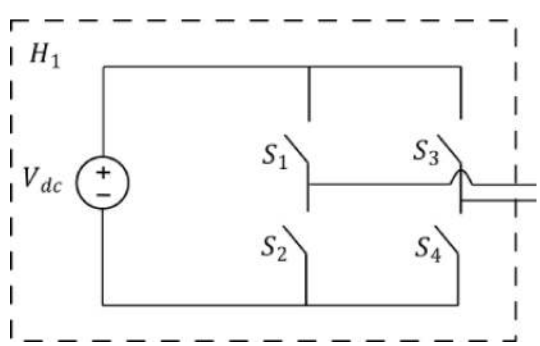

Abbildung 4.1: H-bridge

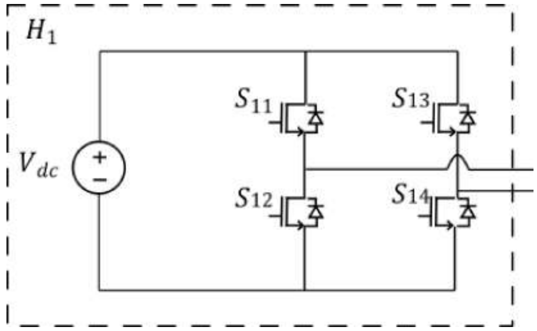

Abbildung 4.2: One H-bridge Cell with IGBT and Diode

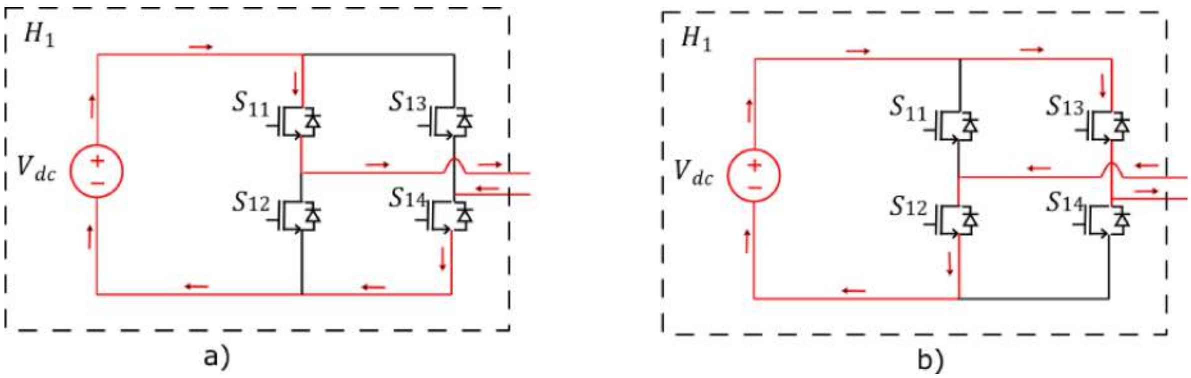

Abbildung 4.3: H-bridge switching principle

4.2 Cascade H-bridge Converter

Cascade H-bridge converters, shortly CHB, are built by cascading or connecting H-bridge cells or modules in series.The functionality of each H-bridge allows for providing voltage steps for each negative and positive peaks.Therefore, in CHBs, by connecting H-bridges in series, more voltage steps are provided at the output of the system.[1]
In the provided model, a 11 level symmetrical CHB was chosen. Based on Equation 2.6, a 5 H-bridge cells is required to be connected in series for a 11-voltage level production. The schematic and cells connections in MATLAB Simulink can be found in Figure 4.4.
The DC supply voltage of each cells are designed to be 100 volt, and thus the peak voltage value of the output wave form can be calculated as:

$$U_p = n \cdot U_z = 5 \cdot 100 = 500\,V \tag{4.1}$$

The whole process of control stage for switching for cascaded H-bridge converter follows a simple logic using the comparison of a totally sine wave reference signal(V_r)and the desired threshold value for each cell. The positive voltage step production occurs for each H-bridges with Switches S_1 &

[1]Deeply explained in 2.2

Cells constant	Value	Unit
U_1	96	Volt
U_2	192	Volt
U_3	288	Volt
U_4	384	Volt
U_5	480	Volt

Tabelle 4.1: Constant Value for comparison process of each cell

S_4, as seen in Figure 4.3 and the same procedure and concept occurs with S_2 & S_3 to provide the negative voltage step for each cell. The switching modulation logic was performed in MATLAB simulink for the desired CHB and this schematic for cell number 1 is as shown in Figure 4.5
The constant value for each cell which is used for switching modulation is examined for different values and the best option for providing the closest possible sine wave current at the output of the CHB is calculated. For the last cell, the constant voltage value is calculated based on the Equation 4.2 and the constant values for the other cells are calculated base on the last cell value by using Equations 4.3 & 4.4 and the results are summarised in Table **??**.

$$U_c = (n - \frac{1}{n}) \cdot U_z \tag{4.2}$$

$$S = (\frac{U_c}{n}) \tag{4.3}$$

$$U_{c,n-1} = U_{c,n} - S \tag{4.4}$$

The obtained results and the voltage wave form at the output of the 11 level CHB with the reference signal is shown in Figure 4.6.
As can be seen in the results shown in Figure 4.6, when zero-crossing occurs, an extra step occurs in the output waveform of the CHB due to the diode's working principle. In the model, the diodes were considered with respect to realistic parameters and the forward voltage of each diode is considered as 0.6 volt. When the voltage is crossing the zero value and changing direction, at-least two diodes conduct for each cell and a 6 volt peak is observed each time based on diode operation.

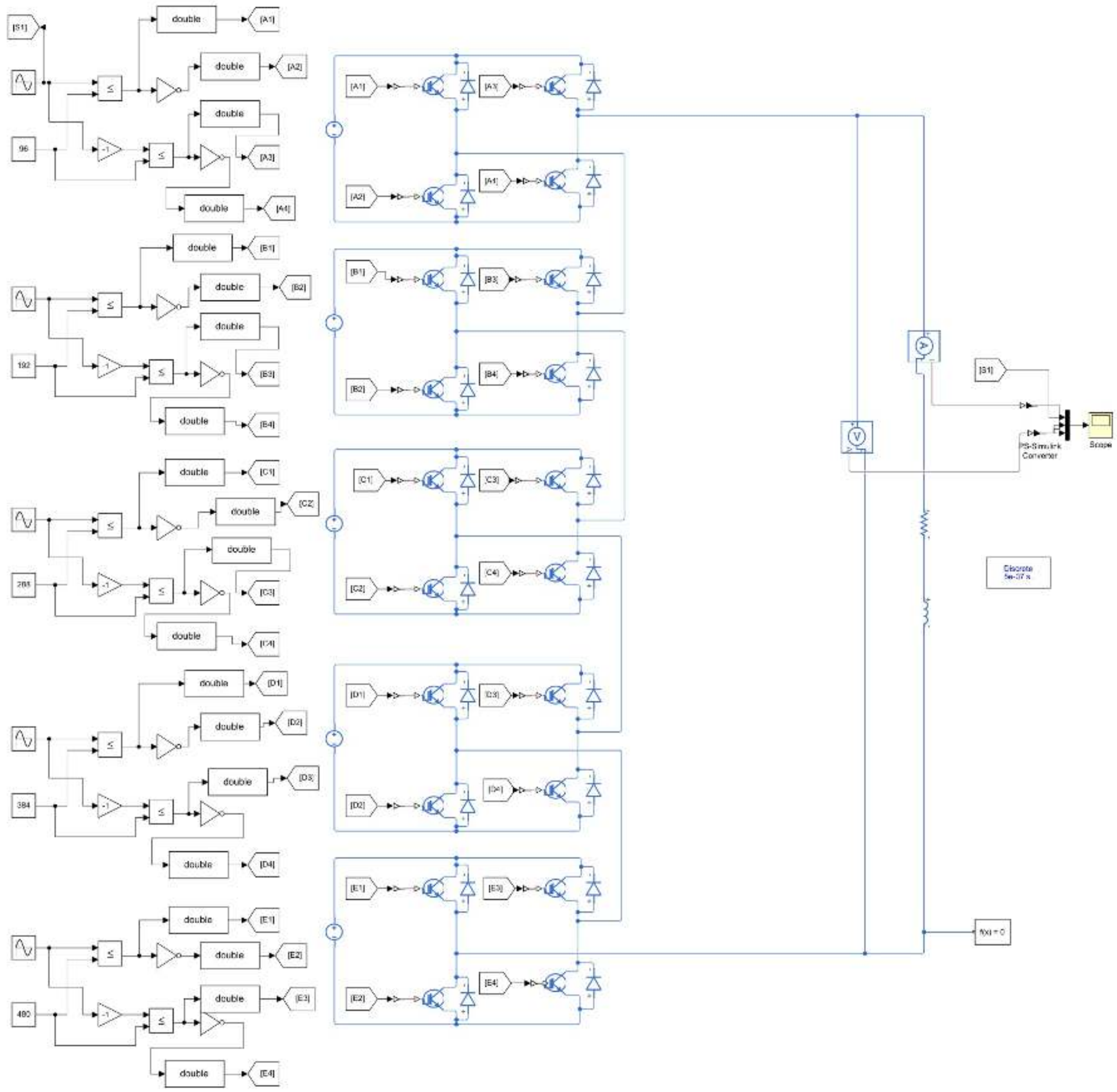

Abbildung 4.4: CHB model Schematic in MATLAB Simulink

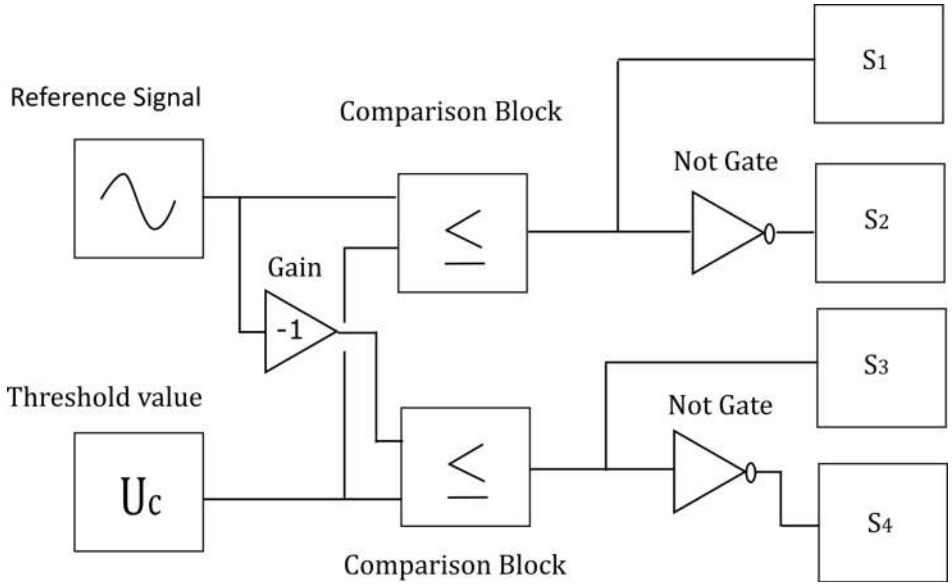

Abbildung 4.5: CHBs Switching modulation logical schematic

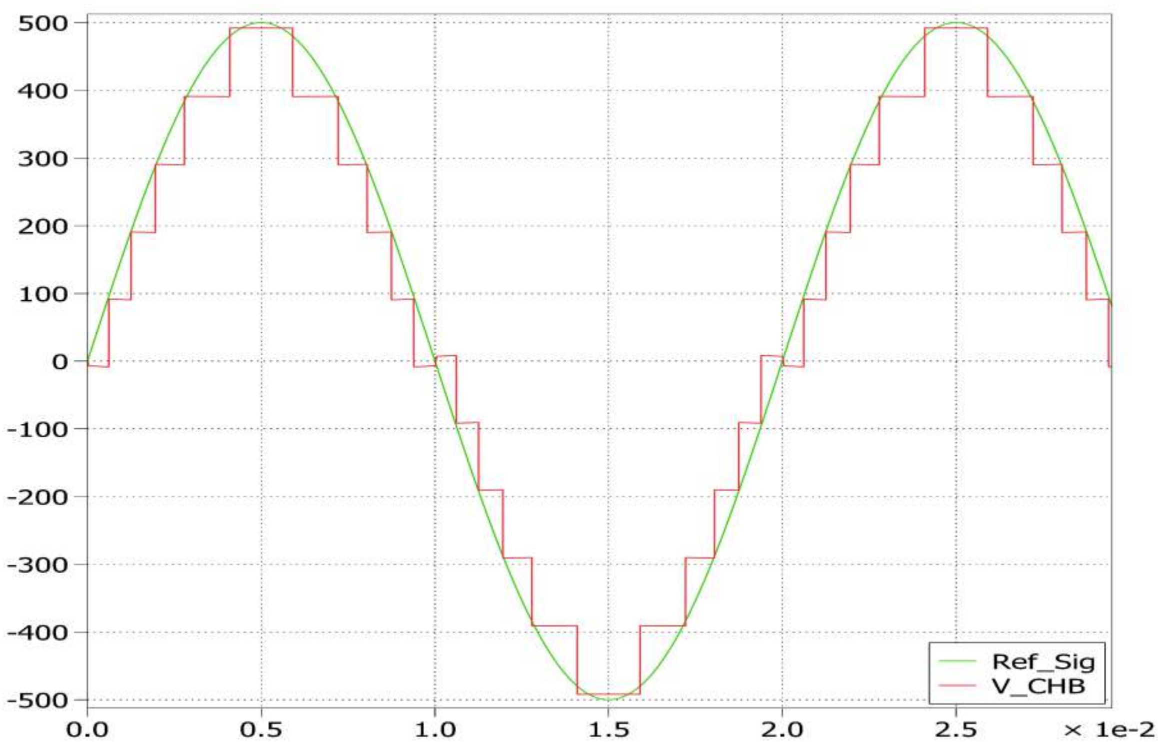

Abbildung 4.6: 11 level CHB Voltage output with reference signal

4.3 Linear amplifier

Choosing and using analogue amplifiers was a time consuming process. The designed CHB model was transferred from PLECS software to MATLAB Simulink for further studies and the different classes of linear amplifiers are examined in different connection formats to the CHB module.Class A and AB amplifier were observed to have a better linearity performance in the system. Class AB is selected to connect in series to the CHB and was used for smoothing the stepped voltage at the output of the cascade H-bridge converter. The schematic of class AB amplifier and its connection to the CHB is shown in Figure 4.7.

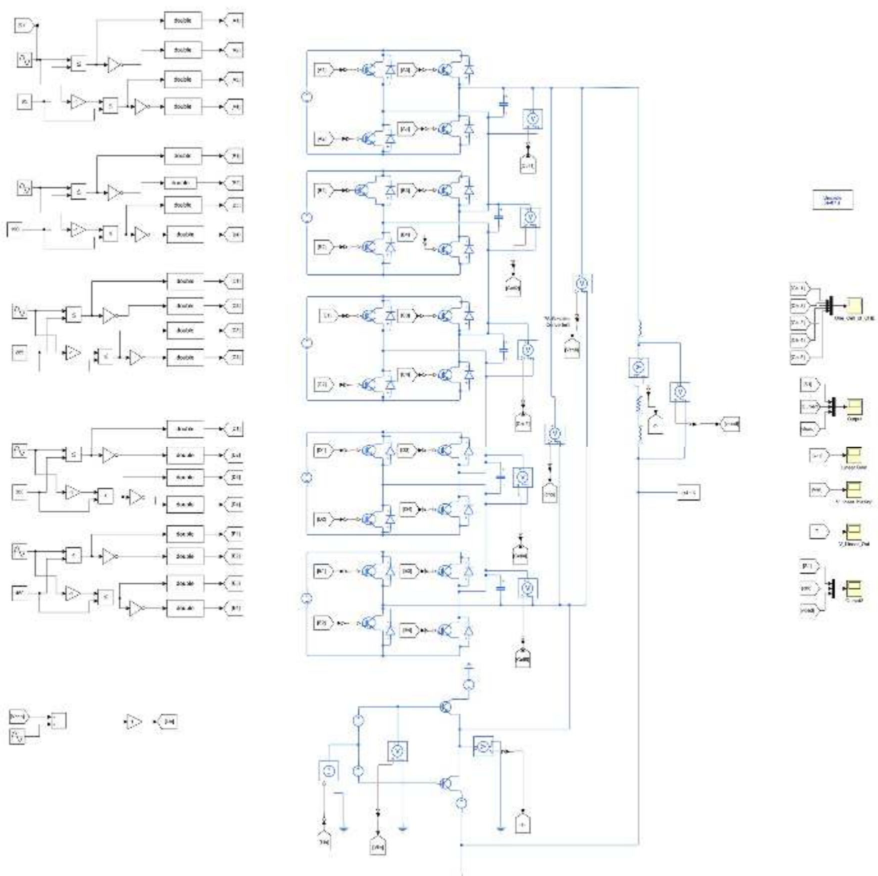

Abbildung 4.7: Schematic of the first operational mode

The DC supply of the class AB amplifier should be high enough to be able to filter and remove each voltage step from the CHB. In this design, as each cells in CHB is responsible for 100 volt DC and the each voltage step size is 100, the DC supply source of the amplifier should be at least 100 to be able to cover the difference. The voltage biasing method for class AB amplifier is selected based on the simplicity of its design can be modified to the driver biasing to remove 0.7 volt at the biasing scheme.

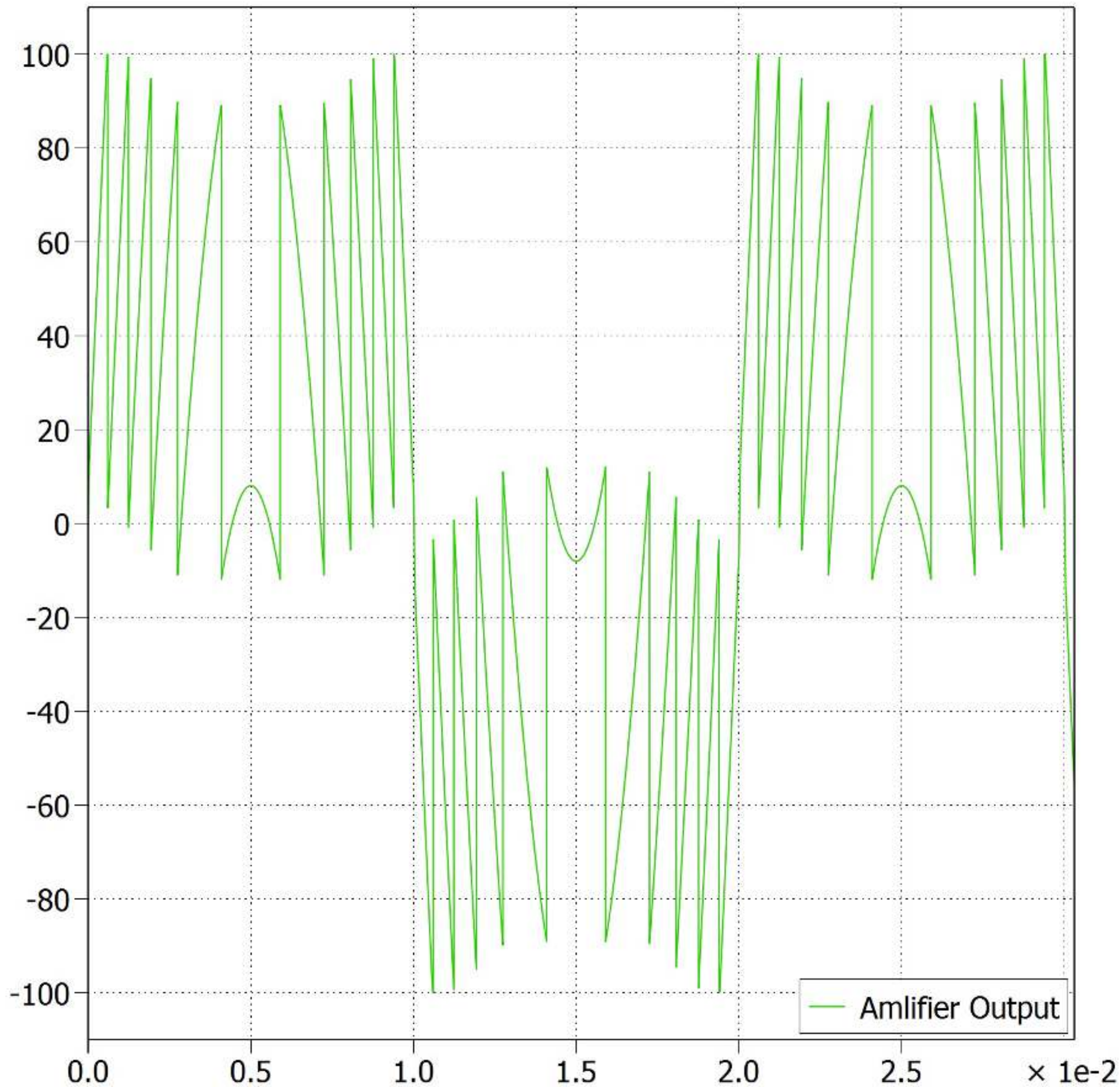

Abbildung 4.8: First operational mode linear amplifier output

The Control stage is used to subtract the stepped voltage wave-form from the desired signal wave-form and the difference of that at the output of the linear amplifier is as shown in the graph in Figure 4.8.

4.4 Filter Design

Based on the linear amplifier working principle and the explanation provided previously, the designed model will not require a large filter design. The filter component will be reduced in size and as a result, the electrical circuit can be built in a more compact manner. As the output load is detected and considered as an almost ohmic load, an LC filter is sufficient for the filtering

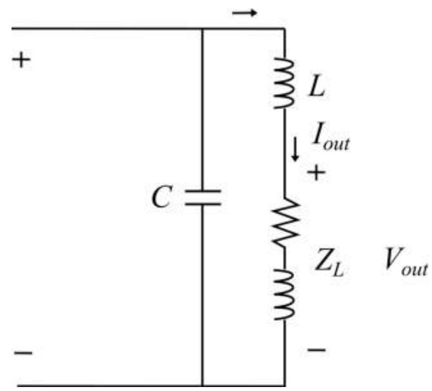

Abbildung 4.9: LC Filter connection to the load

Component	Value	Unit
Capacitor	100	nF
Inductor	25	H
C_s	500	nF

Tabelle 4.2: Calculated Filter values

process.
The LC filter is made connection to the load as in Figure 4.9, where the inductor is connected in series with the load and the capacitor is connected in parallel to the load.
The filtering process is initiated by checking the total remaining distortion in the output wave-form in the frequency domain and the results demonstrate that the chosen filter should be able to overcome the distortion by assuming the inductor value as $25 \cdot 10^{-6}$ Henris. The capacitor value can be calculated by using Equation 4.5.The desired values of the LC filter is listed in Table 4.2

$$F_r = \frac{1}{\sqrt{L * C}} \tag{4.5}$$

As the output voltage of the system will be around 500 volts at peak values, placing a capacitor for the filtering process to withstand that voltage rating will be costly. The calculated value for the capacitor in LC filter can be broken down into five smaller capacitors which can connected to each cell separately which is the equivalent of all capacitors getting connected in series together. The new capacitors will be cheaper and chosen for lower voltage rating values and this process reduces the cost of the system.
Thus, the final LC filter design considered is as shown in Figure 4.10, and the each capacitor values can be calculated as mentioned as C_s in Table 4.2.

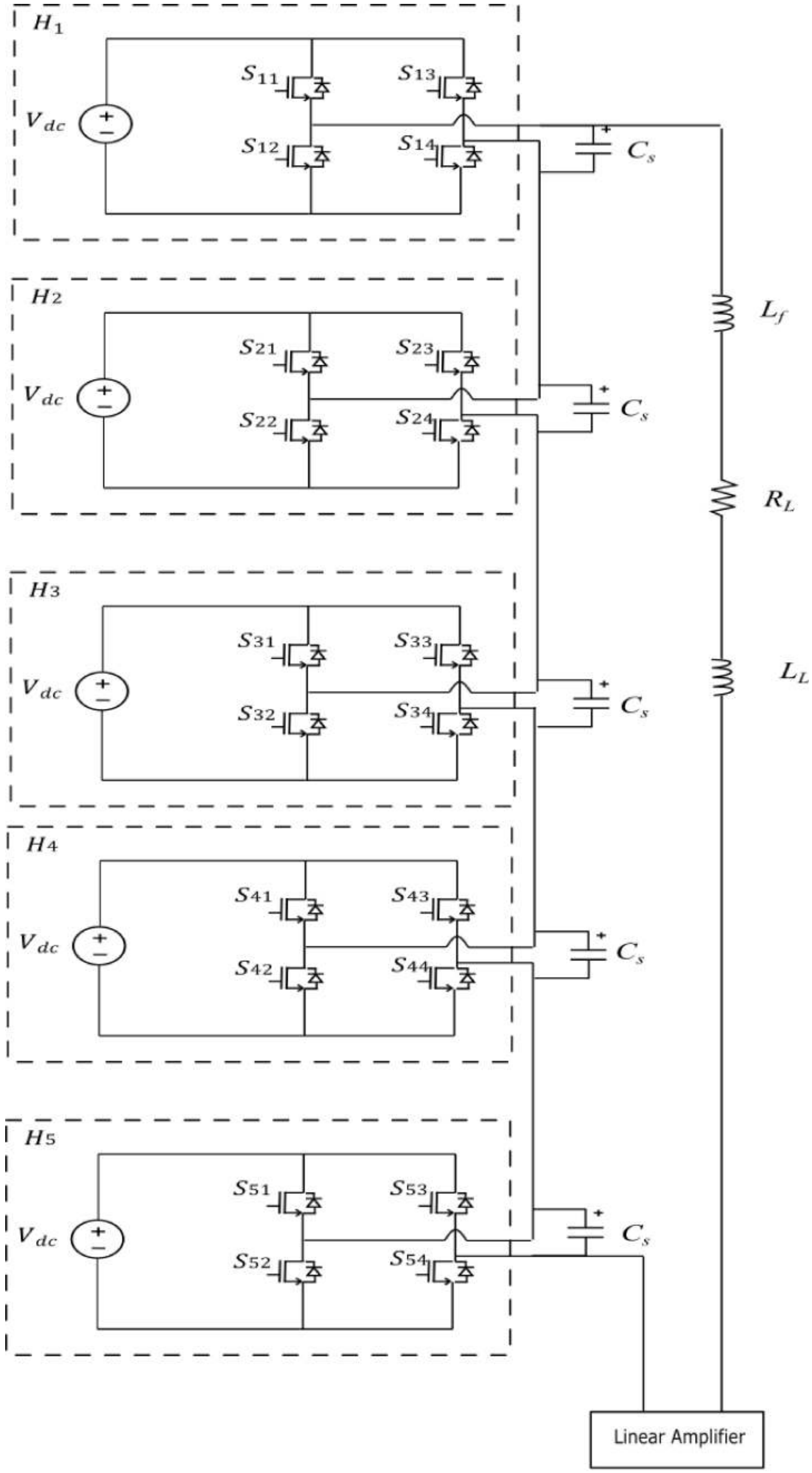

Abbildung 4.10: LC filter connection scheme with model

4.5 First Operational Mode

In the first operational mode, the voltage difference between reference signal and Cascaded H-bridge output waveform should be minimal and be as close as possible to the reference or the desired signal at the output of the system.
In the first operational mode, the desired CHB wave form is designed to be lower than the reference signal as is seen in Figure 4.6.The schematic, component connection , the linear amplifier, the CHB connection and supply modulations is the same as in series which can be seen in Figure 4.7.
The chosen linear amplifier, Class AB,should be able to cancel or in other words, add up the difference between the signals to the CHB wave form and make the CHB wave form similar to the reference signal. Thus, the difference voltage, shown in Figure 4.11, should first be amplified (increased) and then added, based on the Kirchhoff law and connection in series, to the CHB wave form.
For this operational mode, the output signals and all necessary results are shown in Figure 4.12.
As is observed from the schematic and results in Figures 4.12 & **??**, the main disadvantage of this operational mode is that the linear amplifier should be able to boost up the voltage difference between CHB and the reference signal. This boosting process requires two separate DC voltage supplies to be provided to the class AB amplifier. These voltage supplies should have atleast the same value as the DC voltage supply of each cell of the CHB (U_z) which can omit the voltage difference value.
The linear amplifier control stage and the circuit schematic can be seen in Figure 4.13
All initial values for this operational mode are mentioned in Table 4.3.

Components	*Load*	*Filter*	*unit*
Resistor	100	-	ohm
Inductor	0.01	25	H
Capacitor	-	50	F

Voltage source	*value*	*unit*	*Frequency*
U_z	100	V	DC
U_l	100	V	DC
Ur_{peak}	500	V	50 Hz

Cells constant	Value	Unit
U_1	96	Volt
U_2	192	Volt
U_3	288	Volt
U_4	384	Volt
U_5	480	Volt

Tabelle 4.3: First Operational mode initial values

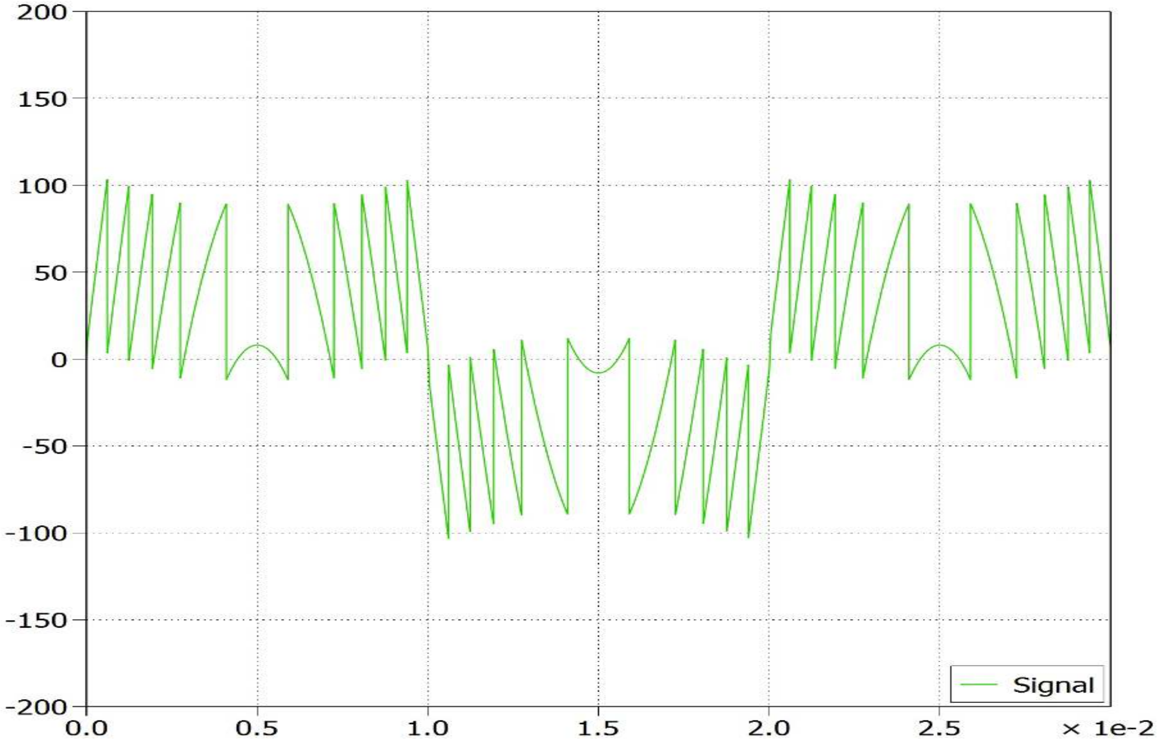

Abbildung 4.11: First Operational mode voltage difference

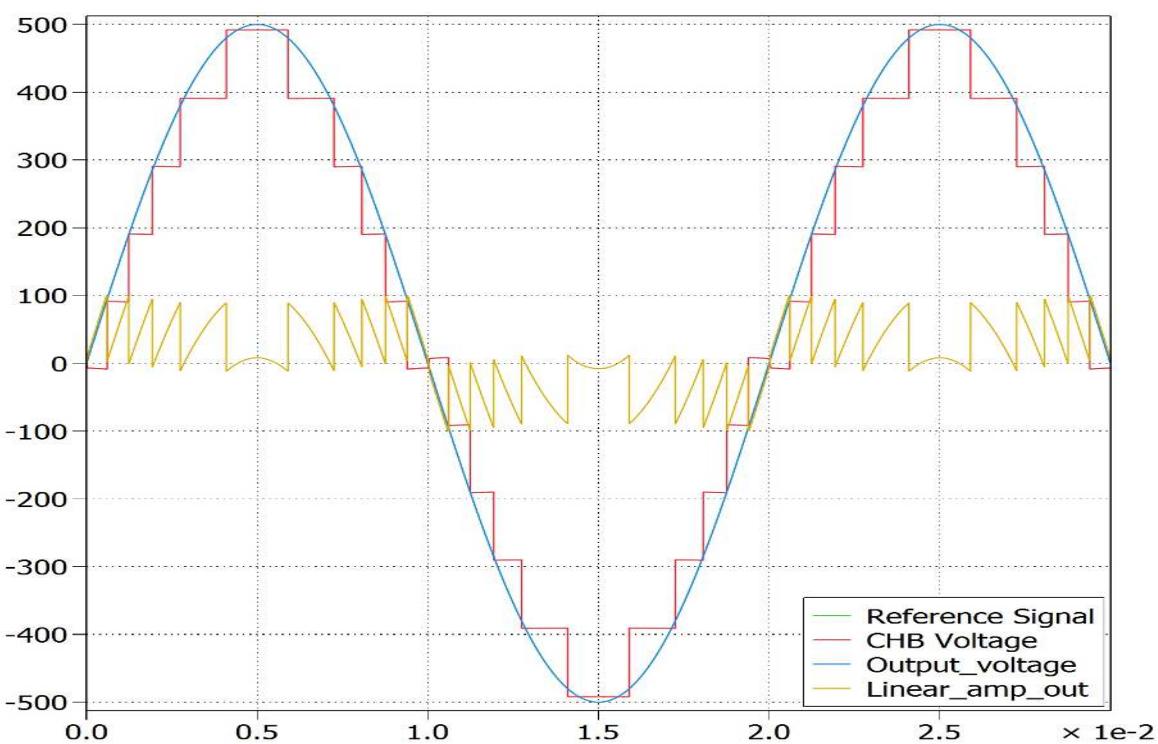

Abbildung 4.12: First operational mode results

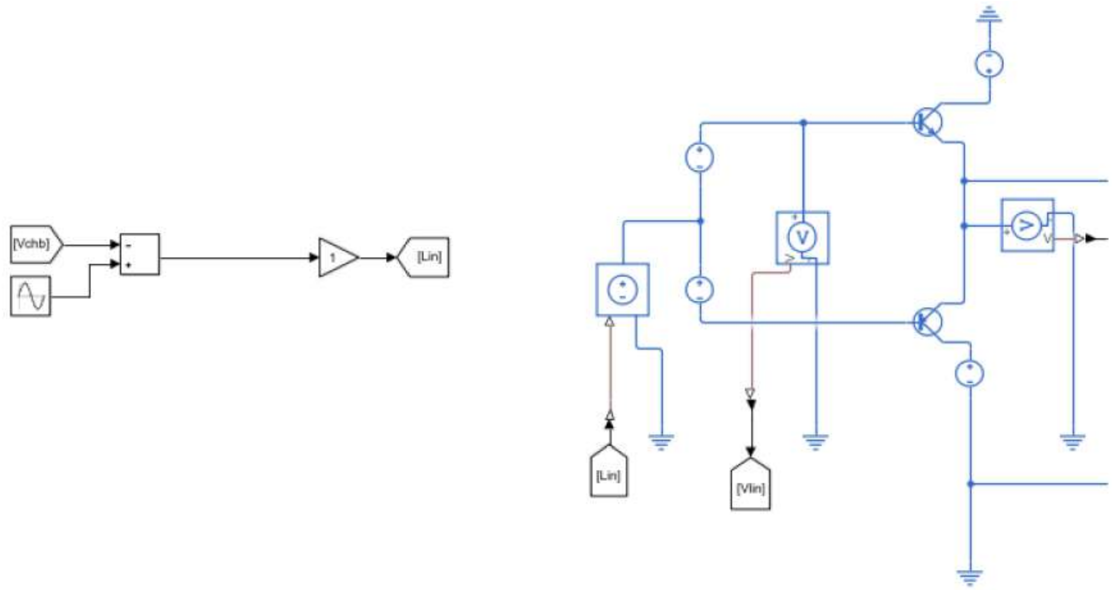

Abbildung 4.13: Linear amplifier control stage of first operational mode

4.6 Second Operational Mode

In the second operational mode, the Cascade H-bridge is designed such as to have a higher voltage value than the reference signal in each step as is seen in Figure 4.14 The stepped wave-form voltage from the CHB should be reduced in some way to come closer to the reference signal wave-form, as seen in the graph. Figure 4.15shows the desired differential form which should be subtracted form the stepped wave form voltage from the Cascaded H-bridge converter.
The operational mode's process algorithm seems straightforward at first glance, but because the major aim of this operational mode was to eliminate the DC source for the linear stage, we ran into several issues, which we will discuss in this part.
In the first stage, the linear amplifier's DC voltage source was removed, and the load voltage at the system's output was calculated by feeding the difference signal into the class AB amplifier, The control stage is shown in Figure 4.16.
The load voltage wave-form is fairly similar to the reference signal, as shown by the findings, however there is a distortion for each step. By inspecting the features and working areas of transistors, it is possible to determine if the transistors will operate in active or saturated mode. Simulation results are shown in Figure4.17.
As a future stage, a MOSFET will be used instead of a transistor so that voltage may be controlled more easily and for the starting one n-channel MOSFET is added for a positive half wave of the signal and after modifica-

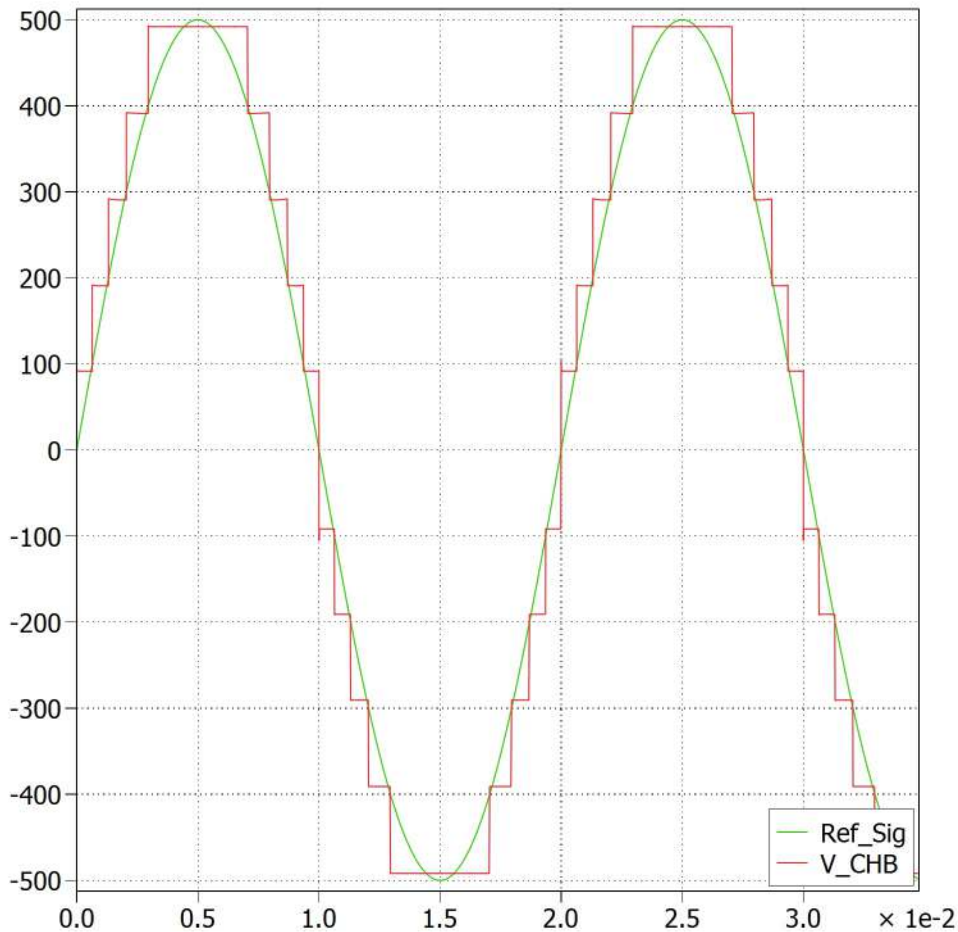

Abbildung 4.14: CHB reference signal in second operational mode

tion of the first one, The control stage can be employed for both positive and negative half wave.
We attempted to get MOSFETs into saturation mode in order to achieve a higher value at the MOSFET's output for the reduction procedure, based on the working principle of MOSFETS and the working areas. The output signal was insufficient to produce satisfactory results in the output waveform.
According to the operating principle of MOSFETs as illustrated in Figure 4.18, the outcomes in saturation mode are influenced by the drain to source current in the MOSFET, which should be taken into account during the control stage.
As shown in Figure 4.19 we next attempted to build a new control stage for regulating MOSFET current value and summing it with the prior voltage control stage .results of the new control stage is shown in Figure4.19
We adjusted the control stage for the MOSFET based on Schichmann-Hodges equation as listed in Table 4.4.
Schichmann-Hodges equations are reordered based on the gate to source voltage as shown in Equation 4.6 and the control stage schematic in MATLAB

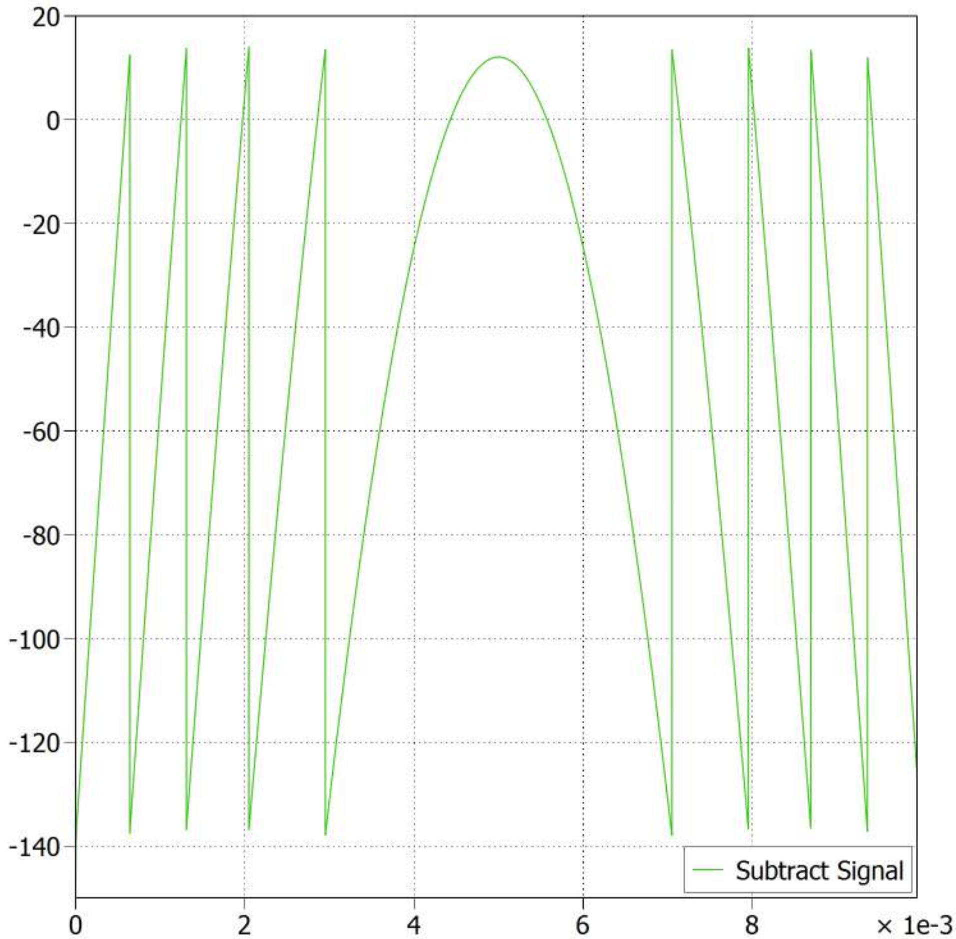

Abbildung 4.15: Difference from CHB and reference signal

Tabelle 4.4: Schichmann-Hodges equation

Cut off	$V_{gs} \leq V_t$	$I_{ds} = 0$
Linear	$V_{gs} > V_t, V_{ds} \leq V_{gs} - V_t$	$I_{ds} = \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot [(V_{gs} - V_t) \cdot V_{ds} - \frac{V_{ds}^2}{2}] \cdot (1 + \lambda \cdot V_{ds})$
Saturation	$V_{gs} > V_t, V_{ds} > V_{gs} - V_t$	$I_{ds} = \frac{1}{2} \cdot \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot (V_{gs} - V_t)^2 (1 +_{ds})$

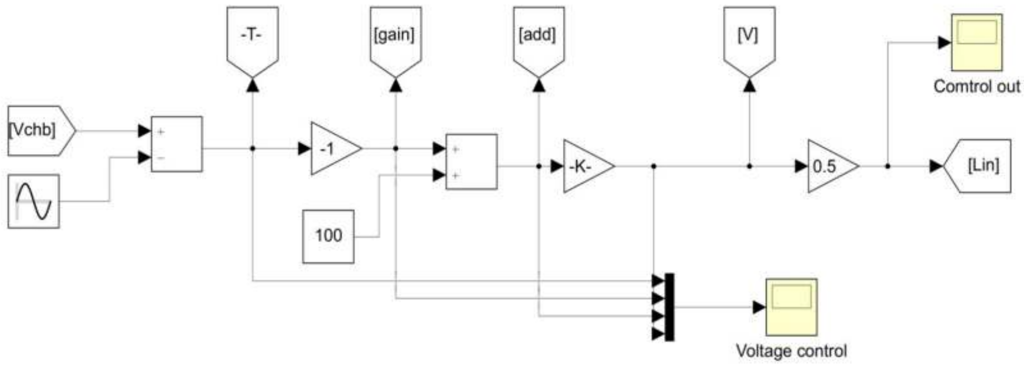

Abbildung 4.16: Voltage control stage for the second operational mode

Simulink is shown in Figure4.20

$$V_{gs} = \sqrt{\frac{2 \cdot L \cdot I_{ds}}{\mu \cdot C_{ox} \cdot W \cdot (1 + \lambda V_{ds})}} + V_t \tag{4.6}$$

In Figure 4.20 the delayed block is added to control stage to provide initial value for compiling. Results of the control stage and the out put of the MOSFET and the output voltage form for the load is shown in Figures 4.21 & 4.22.
As that can be seen from results the drain to source voltage of the MOSFET after a period drop down enormously and as a result of that the MOSFET is going to work in linear mode. Until now the control stage for V_{gs} was feed forward and for controlling the the stepped voltage a feed-back loop is added to control stage by PI block in MATLAB Simulink to ensure that the correct wave form is supplying the gate to source of the MOSFET. The results of the control stage is shown in Figure 4.23.
Because of the breadth and time constraints of the master thesis deadline, it is not possible to go any farther in finding a solution to the problem. This phase can be viewed as a precursor to future research into modifying the control stage for the second operating mode.

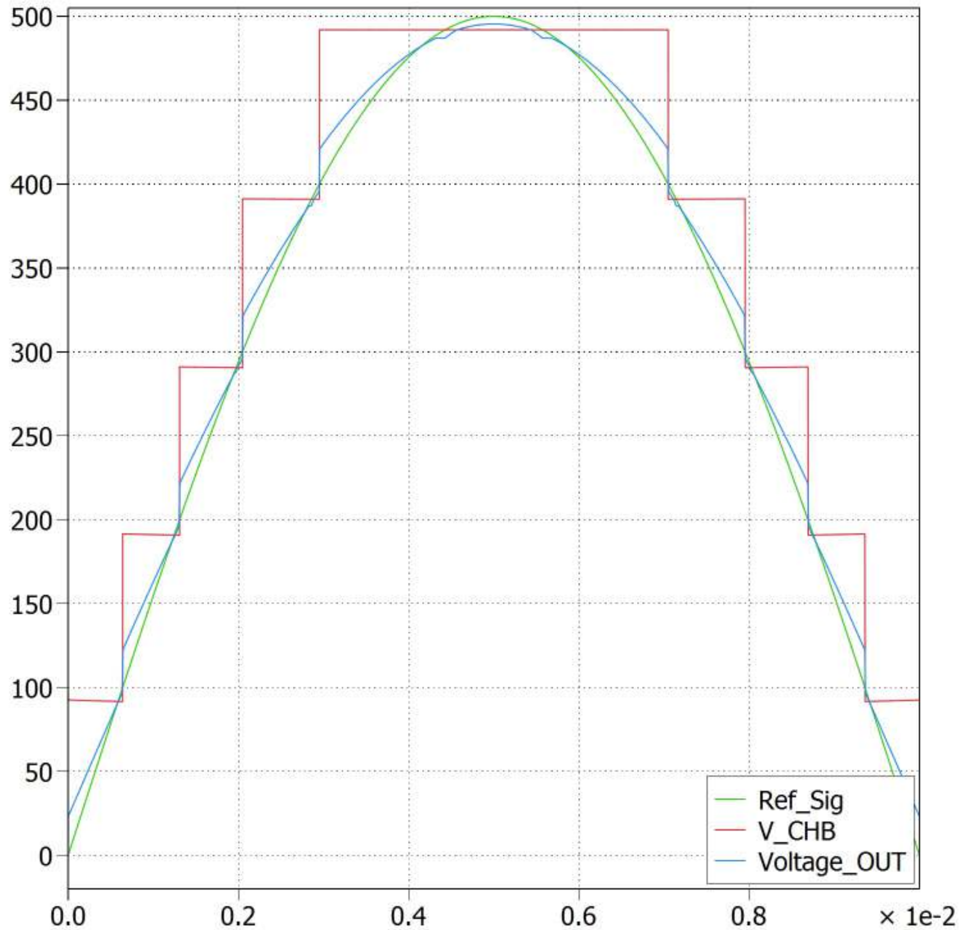

Abbildung 4.17: Second operational mode with class AB amplifier

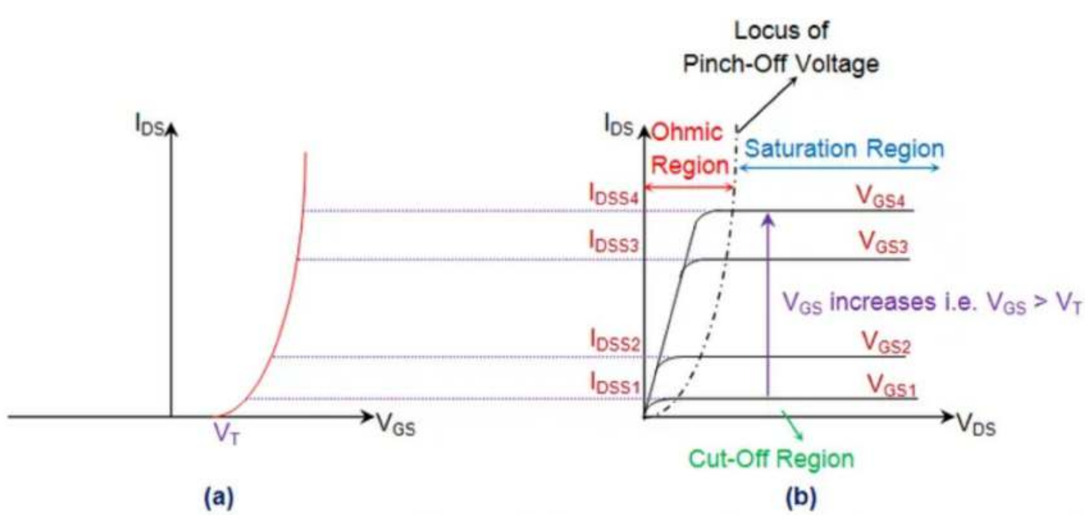

Abbildung 4.18: n-channel MOSFET working regions,[5]

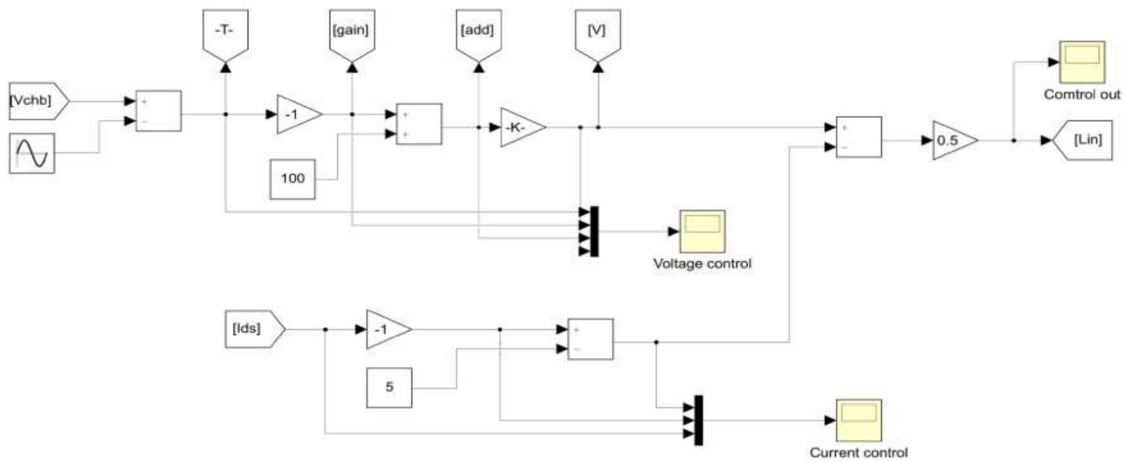

Abbildung 4.19: Current and voltage control stage

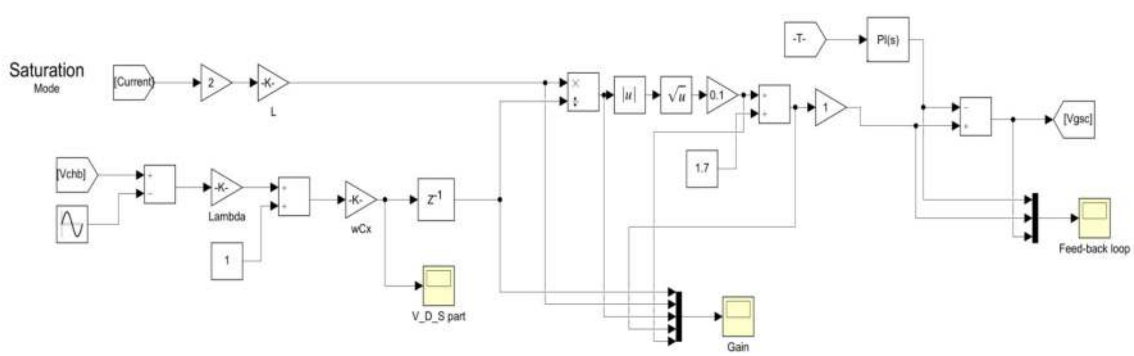

Abbildung 4.20: Control stage based on Schichmann-Hodges equation

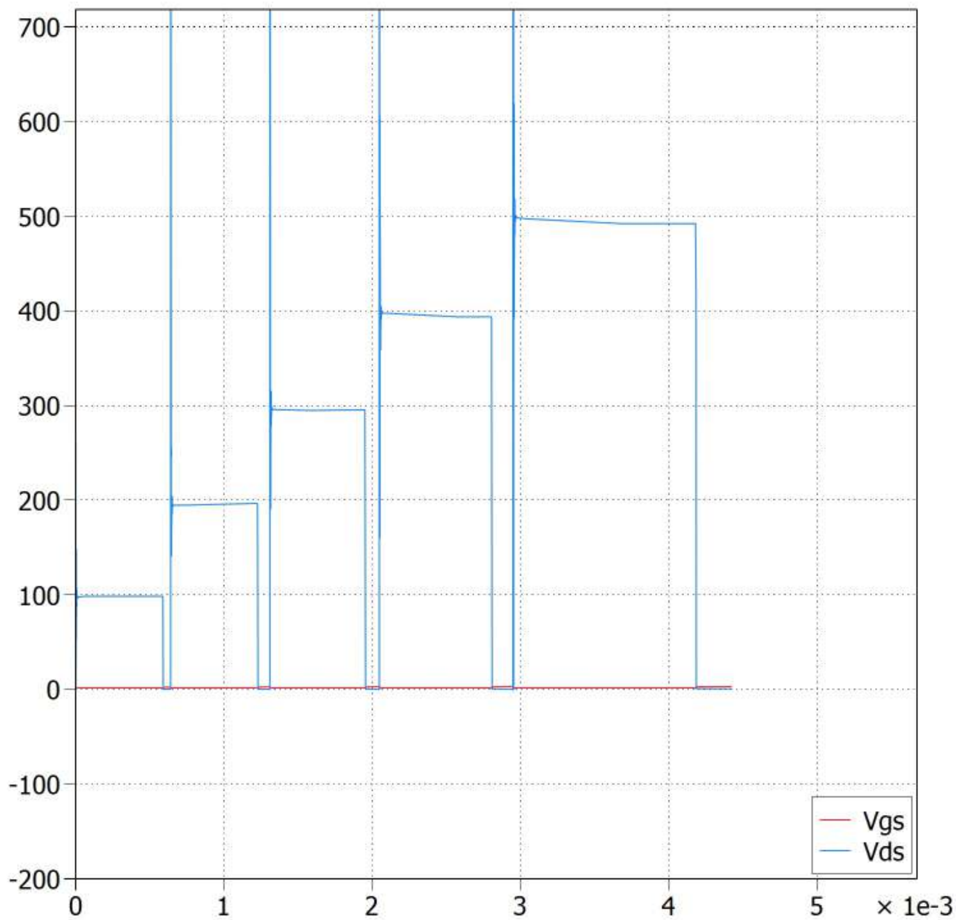

Abbildung 4.21: Gate to source voltage and drain to source voltage of the MOSFET

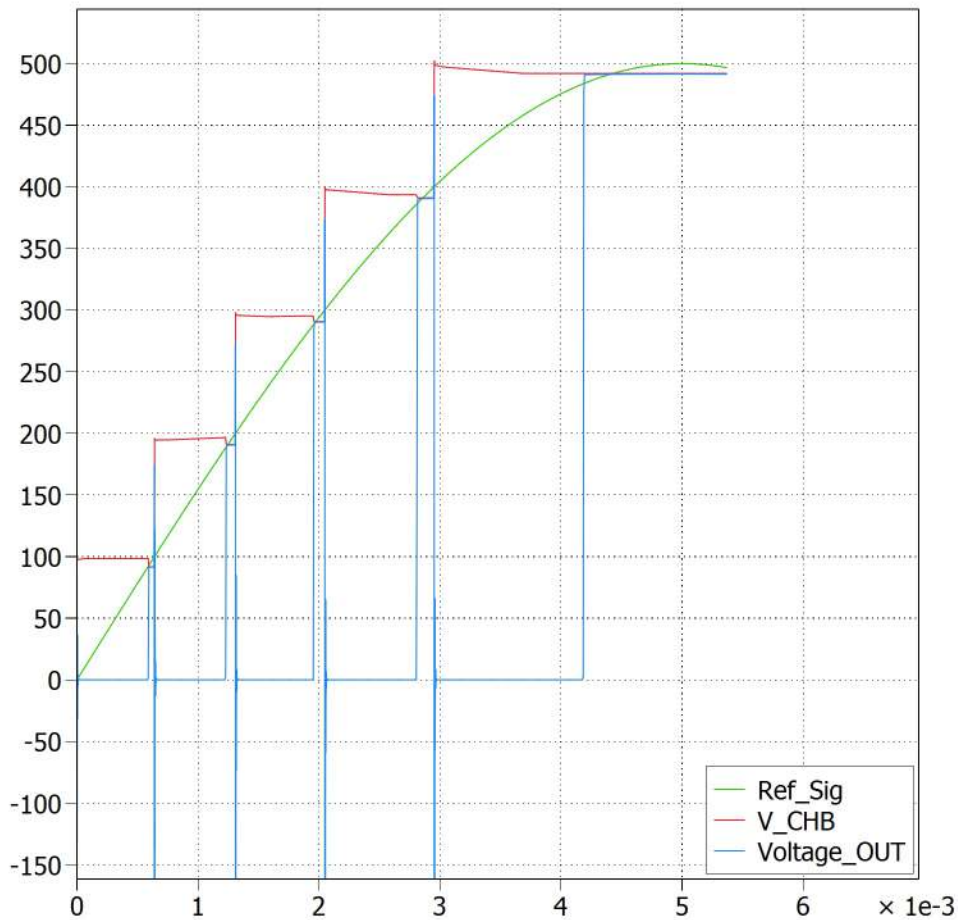

Abbildung 4.22: Output of the system with MOSFET

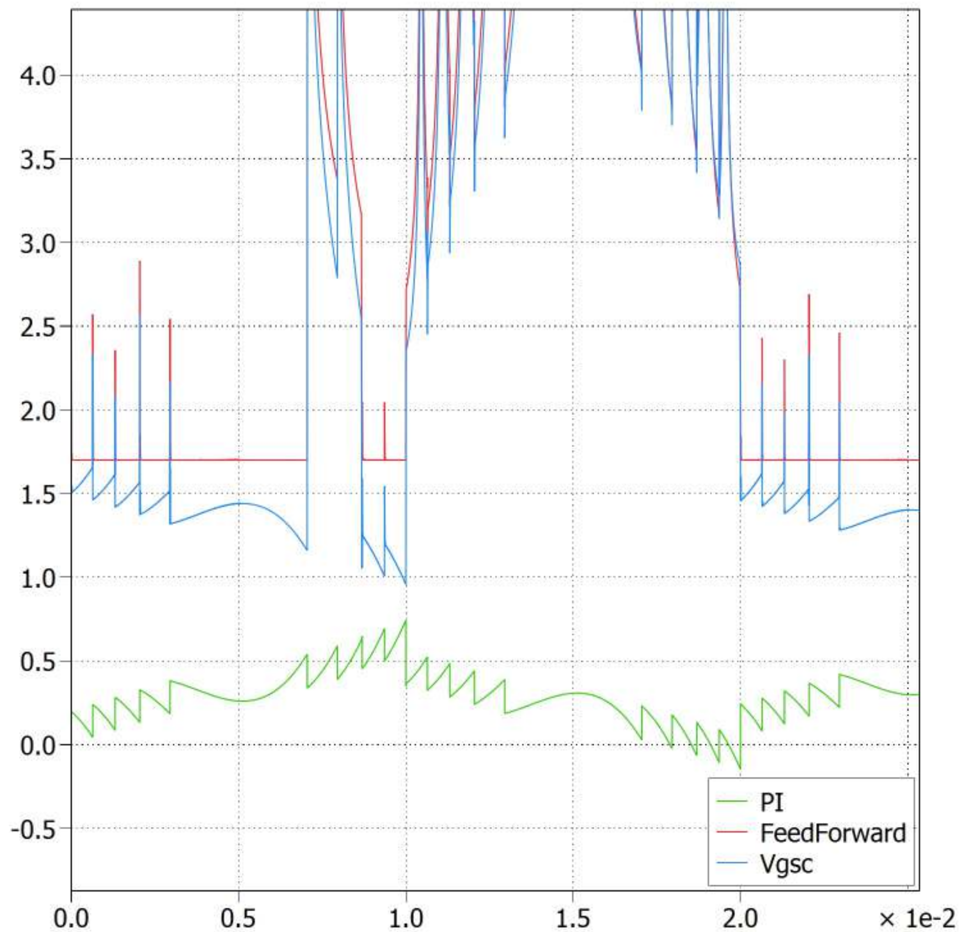

Abbildung 4.23: PI block results

5 Conclusion

This thesis is introduced a serial switch linear hybrid structure . Cascade H-bridge converter was chosen as a multi-level inverter for a stepped voltage generator due to its advantages. As a result, five H-bridges are cascaded in series and generate 11-level voltage steps at the cascade H-bridge inverters output. The output stepped voltage of the CHB is smoothed by adding a class AB power amplifier in series with the CHB design. The control stage is added to modify and fix the stepped voltage to a completely sinusoidal wave-form as the desired voltage at the output of the system. Simulation was performed and the designed circuits were compared in detail. The control stage of the inverter was modified to overcome the disadvantages of the models and possibilities for future studies were mentioned.
As a conclusion to this thesis, the designed system is theoretically functional and providing acceptable results for the first operational mode.However removing the DC source for the linear amplifier is become problematic in second operational mode. Modification of the second operational mode for serial linear hybrid inverters can be mention as future studies possibility.
Paralel linear Hybrid inverter and combination of the serial and parallel linear hybrid inverter can be mentioned also as future studies.

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