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Multilevel Z-source inverter intelligent control For Electrical Vehicles

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ملخص :

تلعب المحولات متعدد المستويات دورًا حاسمًا في تحويل الطاقة المستمرة من مصادر الطاقة المتجددة كالألواح الشمسية، خلايا الوقود، والبطاريات إلى طاقة تيار متناوب لمختلف لاستخدامات الصناعية اليوم. تستخدم بشكل كبير في السيارات الكهربائية لسهولة التحكم بها. يتطلب هذا التحويل الحفاظ على مؤشرات رئيسية مثل الجهد AC، قيمة التيار، الطور، التردد، وجودة شكل الموجة. تقوم هذه المحولات بدمج مصادر التيار المستمر منخفضة الجهد لتحقيق مخرجات جهد أعلى باستخدام مكونات إلكترونية للطاقة ذات تصنيف أقل. باستخدام وحدات المحولات المتتالية التي يتحكم فيها تقنيات تعديل عرض النبضة (PWM)، تقلل هذه المحولات من التشويه التوافقي الكلي (THD) وتنتج شكل موجة يشبه إلى حد كبير الموجة الجيبية.

تم تقديم طوبولوجيا جديدة إلى السوق تُعرف بمحولات مصدرZ-، والتي يمكن أن تعمل كمحول رفع أو خفض للجهد، تقوم هيكلتهاعلى شبكة LC لإدارة الجهد. نستكشف من خلال هذا العمل مختلف المحولات وبالخصوص محول مصدر Z-ذو خمسة مستويات باستخدام تقنيات التعديل بعرض النبض PWM مثل: SHEPWM ، SBCPWM، MBCPWMو THI. تجمع هذه الطوبولوجيا بين فوائد المحولات متعددة المستويات ومحولات مصدرZ-، وتدرس استراتيجيات التحكم لتنظيم الجهد تحت ظروف متغيرة. تم التحقق من فعالية هذا النهج من خلال محاكاة MATLAB Simulinkوالتجارب العملية.

الكلمات المفتاحية: محولات متعددة المستويات, تشوه الهارمونيك الكلي,محول Z سورس, تعديل عرض النبضة,السيارات الكهربائية.

Abstract

Multilevel inverters are crucial for converting DC power from renewable sources like solar panels, fuel cells and batteries into AC power for multiple uses in the industry today. And mainly in electric vehicles for its simple control.This conversion requires maintaining key metrics such as AC voltage, current output, phase, frequency, and waveform quality. These inverters integrate multiple low-voltage DC sources to achieve higher voltage outputs using lower-rated power electronic components. By using cascaded inverter modules controlled with PWM techniques, they reduce total harmonic distortion (THD) and produce a waveform that closely resembles a sine wave.

A new topology that has been introduced to the market the z-source inverter, which can function as a boost or buck inverter, uses an LC network to manage voltage. This study explores a five-level z-source inverter using multi-carrier sinusoidal pulse width modulation with techniques like SHEPWM, SBCPWM, MBCPWM and Third harmonic injection. It combines the benefits of multilevel and z-source inverters and examines control strategies for voltage regulation under varying conditions. The approach's effectiveness has been validated through MATLAB Simulink simulations.

Keywords: Multilevel Cascaded inverters, Total harmonic distortion, Z-source inverter, Pulse width modulation, SHEPWM, SBC, MBC, Third harmonic injection , electrical vehicles.

Résumé :

Les onduleurs multiniveaux sont essentiels pour convertir l'énergie continue provenant de sources renouvelables comme les panneaux solaires, les piles à combustible et les batteries en énergie alternative utilisée dans de multiples applications industrielles aujourd'hui. Ils sont principalement utilisés dans les véhicules électriques en raison de leur contrôle simple. Cette conversion nécessite le maintien de paramètres clés tels que la tension alternative, le courant de sortie, la phase, la fréquence et la qualité de la forme d'onde. Ces onduleurs intègrent plusieurs sources de courant continu à basse tension pour obtenir des sorties de tension plus élevées en utilisant des composants électroniques de puissance de moindre capacité. En utilisant des modules d'onduleur en cascade contrôlés par des techniques de modulation de largeur d'impulsion (PWM), ils réduisent la distorsion harmonique totale (THD) et produisent une forme d'onde qui ressemble de près à une onde sinusoïdale.

Une nouvelle topologie introduite sur le marché est l'onduleur de source-Z, qui peut fonctionner comme un onduleur élévateur ou abaisseur, utilisant un réseau LC pour gérer la tension. Cette étude explore un onduleur de source-Z à cinq niveaux utilisant la modulation de largeur d'impulsion sinusoïdale à porteuse multiple avec des techniques telles que SHEPWM, SBCPWM, MBCPWM et l'injection de troisième harmonique. Elle combine les avantages des onduleurs multiniveaux et de source-Z, et examine les stratégies de régulation de tension sous des conditions variables. L'efficacité de cette approche a été validée par des simulations MATLAB Simulink.

Mots-clés : Onduleurs multiniveaux en cascade, Distorsion harmonique totale, Onduleur de source-Z, Modulation de largeur d'impulsion, SHEPWM, SBC, MBC, Injection de troisième harmonique, véhicules électriques.

Table of Contents

Acknowledgements 2
I. General introduction : 1
Chapter I: Insights of the inner workings of Electric vehicles 2
I.1 Electric Vehicle 3
I.2 Challenges for Electric Vehicle 3
I.3 EV Design Challenges 4
I.4 HISTORY OF MODERN TRANSPORTATION 5
I.5 The Advantages and Disadvantages of Electric Vehicles 6
I.5.1 Advantages: 6
I.5.2 Disadvantages: 7
I.6 Components of electric vehicle 8
I.6.1 Batteries 8
I.6.2 Inverter 9
I.6.3 DC-DC Converter 10
I.6.4 Mechanical reducer 11
I.6.5 Gearbox 11
I.6.5.1 Solution with a fixed-ratio mechanical reducer 12
I.6.5.2 Multi-motor solutions 13
I.7 HYBRID ELECTRIC VEHICLE 14
II. Chapter II: Overview on different power converters and simulation results. 16
II.1 INTRODUCTION 17
II.2 DC to AC converters 18
II.2.1 Half And Full bridge inverter: 19
II.2.2 Multilevel Inverters: 20
II.2.2.1 Diode-Clamped Multilevel Inverters 21
II.2.2.2 Capacitor-Clamped Multilevel Inverters (Flying Capacitor Inverters) 22
II.2.2.3 Multilevel Inverters Using H-Bridges (HBs) Converters 24
II.2.2.4 Cascaded Equal Voltage Multilevel Inverters (CEMI) 24
II.2.2.5 Binary Hybrid Multilevel Inverter (BHMI) 25
II.3 DC to DC converters 25
II.3.1 step-down (buck) converter 26
II.3.2 step-up (boost) converter: 27
II.3.3 buck-boost converter 28
II.4 Z-source topology 28

II.4.1 Operating Principle of the Z-Source Inverter 29
II.4.2 Determination of Amplification Coefficients 30
II.4.3 Overvoltage Factor *B* 33
II.5 Review of PWM control methods for ZSI 34
II.5.1 Simple ST Boost Control (SBC) 34
II.5.2 Maximum ST Boost Control (MBC) 35
II.5.3 Third Harmonic injection: 35
II.6 Simulations and Results: 36
II.6.1 Z source : 36
II.6.1.1 Open loop results: 36
II.6.1.2 Closed Loop Results: Using PID controler: 38
II.6.2 Simple ST Boost Control (SBC) 39
II.6.3 Third Harmonic injection: 41
III. Chapter III: Theorical and simulation results 43
III.1 BLOCK DIAGRAM OF THE PROPOSED TOPOLOGY 44
III.2 Selective Harmonic elimination SHE 45
III.3 Fuzzy Logic Controller 46
III.3.1 Fuzzification Components 47
III.3.2 Fuzzification of the Crisp 47
III.3.3 Decision making and Rule evaluation Mechanism of FLC 48
III.3.4 Outcome of Fuzzy Controller 49
III.4 SUMMARY AND DISCUSSION: 50
III.4.1 Simulink Model of the PI Controller 50
III.4.2 Simulink of Fuzzy Logic Controller 51
III.5 Comparisons of output performance 52
IV. General Conclusion 43

LIST OF FIGURES

FigI.1: Basic EV design parameters

FigI.2: Basic Block Diagram of an EV

FigI.3: The different types of batteries used in EVs

FigI.4: three phase inverter moter

FigI.5: DC-DC Converter

FigI.6: Single-engine solution with a gearbox

FigI.7: Solution with a fixed-ratio mechanical reducer

FigI.8: Multi-motor solutions

Fig I.9: Parallel HEV block diagram

Fig I.10: Parallel HEV block diagram

Fig II.1: The block diagram of a power electronics system.

Fig II.2: (a) Half bridge inverter (b) Full bridge inverter

Fig II.3: One phase leg of an inverter: (a) two levels, (b) three levels, and (c) m levels.

Fig II.4 : Family tree of multilevel inverters

Fig II.5: Diode-clamped multilevel inverter circuit topologies: (a) three-level, (b) five-level

Fig II.6: Capacitor-clamped multilevel inverter circuit topologies: (a) three-level, (b) five-level.

Fig II.7: Multilevel inverter based on the connection of HBs

Fig II.8: Waveforms of cascaded multilevel inverters

Fig II.9: A dc-dc converter system.

Fig II.10: Step-down dc-dc converter.

Fig II.11: Step-up dc-de converter.

Fig II.12: Buck-boost converter

Fig II.13: ZSI basic structure

Fig II.14: mode 1 schematic

Fig II.15: mode 2 schematic

Fig II.16: mode 3 schematic

Fig II.17: Z-source Duty ratio effect on voltage

Fig II.18: SBC method waveforms

Fig II.19: MBC method waveforms

Fig II.20: Matlab Simulink block diagram of Z-source converting topology open loop
Fig II.21: voltage response of Z-source 1
Fig II.22: voltage response of Z-source 2
Fig II.23: voltage response of Z-source 3
Fig II.24: voltage response of Z-source 4
Fig II.25: Matlab Simulink block diagram of Z-source converting topology closed loop
Fig II.26: voltage response of Z-source 5
Fig II.27: voltage response of Z-source 6
Fig II.28: Simulink model of SBC with z source
Fig II.29: Output for SBC Voltage Without filter
Fig II.30: Output for SBC Voltage With filter
Fig II.31: Simulink model of MBC with z source
Fig II.32: Output for MBC Voltage Without filter
Fig II.33: Output for MBC Voltage With filter
Fig III.1: Block diagram of the proposed model
Fig III.2: Three-Phase System Generator
Fig III.3: Proposed Signal
Fig III.4: Matlab structure of the proposed Fuzzy logic controller
Fig III.5: Fuzzy membership functions for Input
Fig III.6: Output Membership functions for change in modulating signal
Fig III.7: Matlab model for PI controller
Fig III.8: Load voltage and FFT analyser with PI controller
Fig III.9: Load current and FFT analyzer of inverter with fuzzy logic controller

LIST OF SYMBOLS AND ABBREVIATIONS

AC - Alternating Current

DC – Direct Current

SPWM - Sinusoidal Pulse Width Modulation

SHE PWM Selective Harmonic Elimination

THD - Total Harmonic Distortion

FLC - Fuzzy Logic Controller

MBCPWM – Max Boost Control

SBCPWM – Simple Boost Control

THIPWM - Third Harmonic Injection

ZSI – Z Source Inverter

EV - Electrical Vehicle

CSI - Current Source Inverter

PEV - Pure Electric Vehicle

HEV - Hybrid Electric Vehicle

FCEV - Fuel-Cell Electric Vehicle

PHEV - Plug-in Hybrid Electric Vehicle

BEV- Battery Electric Vehicle

AEV - All Electric Vehicle

EVCU - Electric Vehicle Control Unit

SOC - State Of Charge

ICE - Internal Combustion Engine

HB - H-Bridges

CEVMI - Cascaded Equal Voltage Multilevel Inverter

BHMI - Binary Hybrid Multilevel Inverter

PID – Proportional Integral Derivative

General introduction:

Electric vehicles (EVs) represent a significant advancement in sustainable transportation, driven by the need for efficient power conversion systems to optimize performance and meet environmental goals [1]. Central to this technological evolution is the Z-Source inverter, an innovative type of inverter that addresses the limitations of traditional voltage-source inverters (VSI) and current-source inverters (CSI). Unlike these conventional inverters, the Z-Source inverter employs a unique impedance network, consisting of inductors and capacitors, to couple the inverter main circuit to the power source. This design allows the Z-Source inverter to perform both buck (voltage reduction) and boost (voltage increase) operations [2], providing greater flexibility and efficiency in managing power conversion. This capability is particularly crucial in EV applications, where the power source voltage can fluctuate significantly due to varying battery conditions.

The Z-Source inverter utilizes Pulse Width Modulation (PWM) to control the output voltage and frequency, ensuring that the electric motor operates at optimal performance levels. PWM is a widely used technique that adjusts the duty cycle of the inverter's switching signals to regulate the power delivered to the motor. By precisely controlling these signals, the inverter can efficiently manage the conversion process, reducing power losses and improving overall system efficiency. [2]

In summary, integrating a PWM-controlled Z-Source inverter into electric vehicles marks a significant advancement in power conversion technology. The dual capability of the Z-Source inverter for DC-DC and DC-AC conversion, combined with PWM control, efficiently manages EV power needs, enhancing performance and reliability. This technology not only boosts EV efficiency but also supports sustainable transportation solutions, addressing challenges in power conversion and control and contributing to the ongoing evolution of electric vehicle technology.

Problematic:

As the rising demand on EV new control and topologies are needed in the industry to improve the performance and efficiency of the power system of these vehicles, we saw a new inverter topology that might be promising in the field,

Objectives:

Using Intelligent control (Fuzzy Logic Controller) to create a control method that both optimize the inverter and the Z-source while getting good results at the output to use later to supply a motor.

Reduce the THD as low a possible using SHEPWM and Filtering the output signal.

In the realm of electric vehicles (EVs), our research focuses on optimizing their inner workings, from the motor that propels them to the battery that stores their energy. As you know, EVs rely heavily on a complex interplay of components.

Chapter 1 dives into these core components – the electric motor, battery pack, transmission (if used), and the control system. We'll see how they orchestrate the movement of the vehicle efficiently.

Chapter 2 delves into the fascinating world of power electronics, the unsung heroes managing the flow of power within an EV. Here, we'll explore DC-DC and DC-AC converters, Z-source inverters, and a technique called Pulse Width Modulation (PWM).

Finally, Chapter 3 unveils the heart of our research – the proposed power electronics topology. This novel design aims to... (insert details about your proposed solution here). We'll analyze the results obtained through simulations and compare its performance to existing solutions.

Chapter I:

Insights of the inner workings of Electric vehicles

I.1 Electric Vehicle

Electric vehicles have number of advantages like good dynamic behaviour, higher efficiency, reduced emission, and sustainable alternative. There are several categories of electric vehicles like pure electric vehicle (PEV), hybrid electric vehicle (HEV), gridable hybrid electric vehicle, and fuel-cell electric vehicle (FCEV) as reported in [1.2]. The architectures and energy-management models for the electric vehicle are reported in [3] Hybrid electric vehicle has superior fuel economy and performance [4]. While the advancement in the control theory of hybrid electric vehicle is necessary for its progress, further research is required to reduce the system complexity and high cost of hybrid electric vehicle [5]. The gridable hybrid electric vehicle is also known as plug-in hybrid electric vehicle (PHEV). The pure electric vehicle is also known as battery electric vehicle (BEV) and all electric vehicle (AEV). The battery electric vehicle is the most suitable category of the electric vehicle to meet the objective of zero emission vehicle. A comparative performance of plug-in hybrid electric vehicle and battery electric vehicle shows that the plug-in hybrid electric vehicle is being preferred over battery electric vehicle but the reduction in the battery cost will increase the usage of battery electric vehicle [6]. A detailed design of the low-cost autonomous battery electric vehicle is reported for maximum traffic flow [7]. The electric vehicles face many challenges which must be overcome to make it popular.

I.2 Challenges for Electric Vehicle

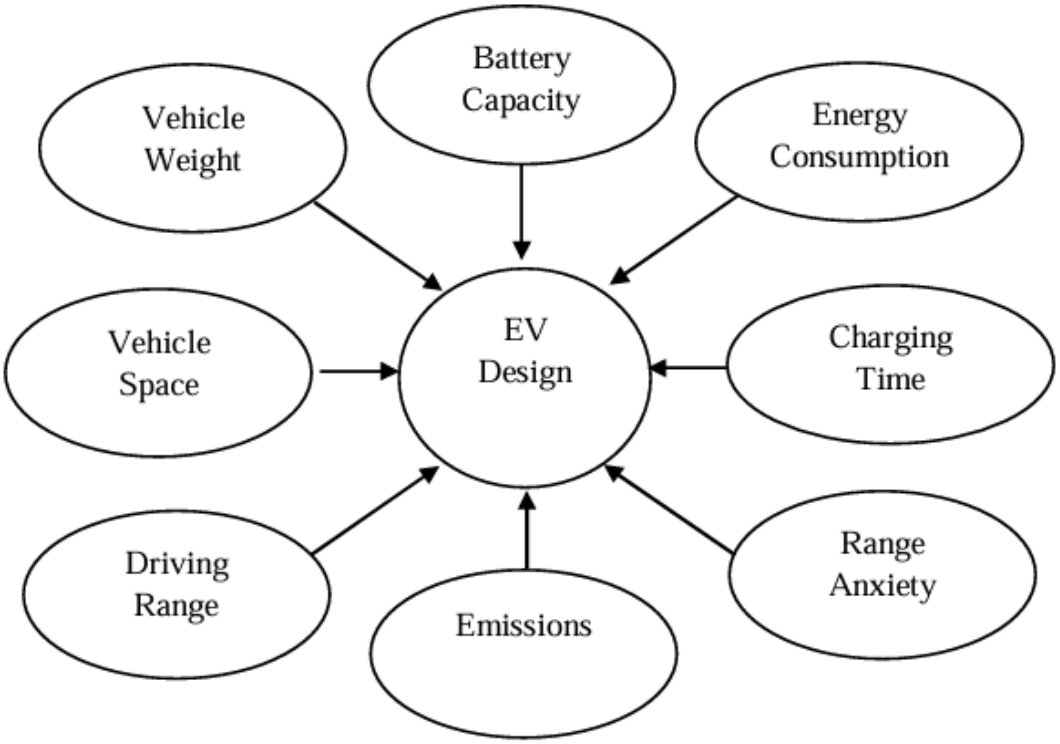
As an only source of power in battery electric vehicle, the battery pack is the series and parallle! combination of the number of battery cells. The management of equal voltage across each battery cell during charging is a challenging task. This function is performed by the battery management system (BMS) through various cell balancing schemes. A passive cell balancing scheme with variable balancing resistor is reported for fast charging [8]. The longer charging time of the battery pack used in the electric vehicle is another challenge. To meet this challenge, some manufactures of the electric vehicle are using high voltage batteries. Several multi-level inverter topologies are reported to handle the high voltage from batteries [9]. The multi-level inverter uses higher number of components which reduces its reliability and increases the probability of fault. Several schemes for fault-tolerant operation of the multi-level inverters are reported [10]. Further research is required for

the quantitative analysis of transition from faulty state to healthy state and design of fault-tolerant topologies to handle multiple faults either individually or cumulatively. The use of speed sensor in electric vehicle also reduces its reliability [11]. Hence, a speed sensor-less drive system is reported for electric vehicle in [12]. Further research is required for the effective speed sensor-less operation of the electric vehicle at low and zero speed. The control unit is the mind of the electric vehicle and smooth functioning of the electric vehicle control unit (EVCU) is responsible for the safety of passenger and vehicle. Safety standards and control unit for various sections of the electric vehicle is reported in [13]. The market

penetration of the battery electric vehicle depends upon the charging infrastructure. Hence, various aspects and key challenges of the charging infrastructure is reported in [14]. Many of the electric vehicles available in the market are very costly, and researchers are working to develop cost effective technology for electric vehicle [15].

I.3 EV Design Challenges

The optimum section of electric drive, battery, conversion system and control methods will impact in cost reduction, effective charging time and drive range in the Electric vehicle. The major challenges to modeling an efficient battery system are life cycle, weight, energy density, cell voltage, power density, cost, recycling, and emissions. But due to the limited availability of resources and involvement of advanced technologies in battery cell manufacturing, EV manufacturers are not able to meet their goals [20].



FigI.1: Basic EV design parameters

The choice of battery technology remains the principal concern to attain the right balance in EV development as shown in Figure 1.1 [20]. At present, many researchers have developed a new battery system and its charging facility has enabled EVs to become more popular and be regarded as the start of a new phase in automotive transportation. Nevertheless, the size, packaging, and mode of charging, remain a major concern and need attention in the advancement of EVs. The following are the basic design parameters of an EV.

a. Battery Capacity: It is the amount of charge stored in the battery and is predetermined by the battery type, design, and cell chemistry.
b. Charging time: Compared to fossil fuel-based vehicles, EVs consume more time for refuelling or recharging.
c. Driving Range: The driving range of an EV depends on the battery capacity and driving scenario.
d. Range Anxiety: Limited drive range, non-availability of charging infrastructure and longer charging time contribute to range anxiety.
e. Emission: EV has zero emissions at the tailpipe. However, they indirectly are responsible for emissions at generating stations.
f. Energy Consumption: As the efficiency of a traction motor is about 95%, the overall energy efficiency of an EV meets 85%, whereas fossil fuel-based vehicles have a maximum efficiency of 25%.
g. Vehicle Space: In EVs, the housing of the battery pack or series of batteries is more important in terms of safety and cooling.
h. Vehicle Weight: The weight of the vehicle increases with the increase in battery capacity.
i. State of charge (SOC): is the level of charge of an electric battery relative to its capacity. The units of SoC are percentage points (0% = empty; 100% = full).

Achieving emission limitations in EVs is a crucial step toward emission-free vehicles. However, it necessitates a better interpretation of emission-free EVs and the subsequent energy sources [21].

I.4 HISTORY OF MODERN TRANSPORTATION

The first EV was invented in 1837, with a speed of 6 kmph and a driving range of 2.5 km. Contrary to common belief, the initiation of EVs was held at the beginning of the 19th century. Before World War I, EVs are estimated to be at 33% of the overall vehicles on the streets. Then again, after due to the huge production of the ICE based vehicles EV sales got quashed. In the 1990s, the huge production of EVs began again. At present EVs have become more popular as an alternative to FVs. Table 1.1 briefly describes the evolution of EVs from the beginning [22].

Late 1800's & The early 1900s	In the late 1800s, EVs like Baker Motor Vehicles and Detroit Electric stood at the top, sourced by lead-acid batteries and most of the charging was done at households. Thereafter for several decades, EVs were unpopular as the FVs became more dominant.
The late 1900s	Far ahead in the 19th century, the shortage of fossil fuels set the demand for EVs.

	In the 1990s, GM announced the famous EV1 vehicle on a rent basis. The first EV1 vehicle utilized a 137-horsepower induction motor (IM) and an 18.7 kilo-Watthour (kWh) lead-acid (Le-Ad) battery pack offering about 80 miles of range according to the Environmental Protection Agency (EPA). Subsequent models were manufactured with a 26.4kWh Nickel Metal Hydride (NiMH) pack and offered 140 miles of range. A few more models, the Ford Ranger EV, Toyota RAV4 EV, and the Nissan Altra EV were the first EVs to make use of a lithium-ion (Li-ion) battery pack.
2000s & 2010s	In 2008, Tesla brought out the first 200+ mile EV known as the "Roadster" which could accelerate to 60 miles per hour (mph) in 4 seconds. In 2010, Nissan commenced supplying the Nissan Leaf, one more innovatory EV, that could cover 73 miles on a single charge.
2020 & Beyond	With the advancements in EV technology, 2020 and 2021 have been recognized as crucial years for the implementation of EVs. Chevrolet Bolt EUV covers 247 miles of range and 200 horsepower. Tesla Model Y, Ford the Mach-e, and Volkswagen the ID.4, cover 200 miles of range.

Table I.1: History of electric vehicles

OEMs like Tata, Nissan, Ford, Toyota and Hyundai are coming up most enhanced versions of sport utility vehicles (SUVs) with a driving range of more than 500 km per single charge.

I.5 The Advantages and Disadvantages of Electric Vehicles

I.5.1 Advantages:

1. **Environmental Benefits:**

- **Lower Emissions:** Electric vehicles (EVs) produce zero tailpipe emissions, reducing greenhouse gases and air pollutants.
- **Sustainability:** EVs can be powered by renewable energy sources like solar and wind, reducing dependency on fossil fuels.

2. **Cost Savings:**

- **Lower Operating Costs:** Electricity is generally cheaper than gasoline, and EVs have fewer moving parts, leading to lower maintenance costs.
- **Incentives:** Many governments offer tax credits, rebates, and other incentives to encourage EV adoption.

3. **Performance:**

- **Instant Torque:** EVs provide quick acceleration and smooth performance due to the instant torque from electric motors.
- **Quiet Operation:** Electric motors are quieter than internal combustion engines, resulting in a more pleasant driving experience.

4. **Energy Efficiency:**

- **Higher Efficiency:** Electric motors are more efficient than combustion engines, converting more energy from the battery to power the vehicle.

I.5.2 Disadvantages:

1. **Limited Range:**

- **Range Anxiety:** EVs typically have a shorter driving range compared to gasoline vehicles, which can be a concern for long-distance travel.
- **Charging Infrastructure:** Although improving, the availability of charging stations is still not as widespread as gasoline stations.

2. **Charging Time:**

- **Longer Refueling Time:** Charging an EV takes longer than refueling a gasoline vehicle, even with fast chargers.

3. **Higher Initial Cost:**

- **Upfront Price:** EVs generally have a higher purchase price compared to traditional vehicles, though this is offset by lower operating costs over time.

4. **Battery Life and Disposal:**

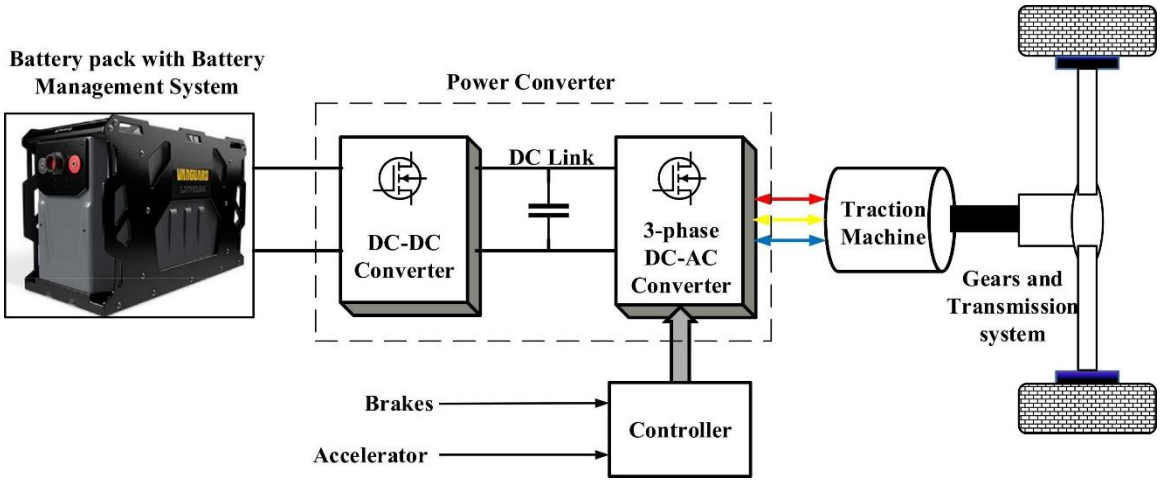
- **Battery Degradation:** Over time, EV batteries lose capacity, which can reduce the vehicle's range.
- **Environmental Impact:** The production and disposal of batteries can have significant environmental impacts if not managed properly.

5. **Limited Model Availability:**

- **Fewer Options:** While the variety of EV models is increasing, there are still fewer choices compared to gasoline-powered vehicles.

I.6 Components of electric vehicle

The basic block diagram representation of an EV is depicted in , with the necessary sub-systems such as the traction battery, inverter, electrical machine, and mechanical transmission. The two control phases of an EV's power system are battery management and electric drive control. The functionality of each block of an EV is discussed in the following subsections:



FigI.2: Basic Block Diagram of an EV

I.6.1 Batteries

The electric vehicle's heart is its battery, acting as a clean energy reservoir. Just like a gas tank in a traditional car, the battery stores the electricity that powers the electric motor. This electric current flows from the battery to the motor, propelling the vehicle forward smoothly and silently. The range, or how far an EV can travel on a single charge, is directly tied to the battery's capacity. The bigger the battery, the farther you can drive! Thankfully, technology is on our side. Most modern EVs utilize Lithium-ion batteries, boasting a higher energy density compared to older technologies. Think of energy density as the amount of energy packed into a specific space. A higher density battery stores more energy, allowing for extended ranges on those electric road trips. While Figure 2 showcases various battery types, Lithium-ion currently reigns supreme in the EV world.



Nickel Metal Hydride



Nickel-Zinc



Lead acid



lithium ion

FigI.3: The different types of batteries used in EVs

The table below shows the characteristics of each battery

Battery Type	Energy/Weight Watt-hours/Kg	Energy/Volume Watt-hours/L	Power/Weight Watt/Kg	Energy/US$ Watt-hr/$
Lead-acid	30-40	60-75	180	4-10
Nickel-Zinc	60-70	170	900	2-3
Lithium-Ion	160	270	1800	3-5

Table I.2: Properties of batteries used in EVs.

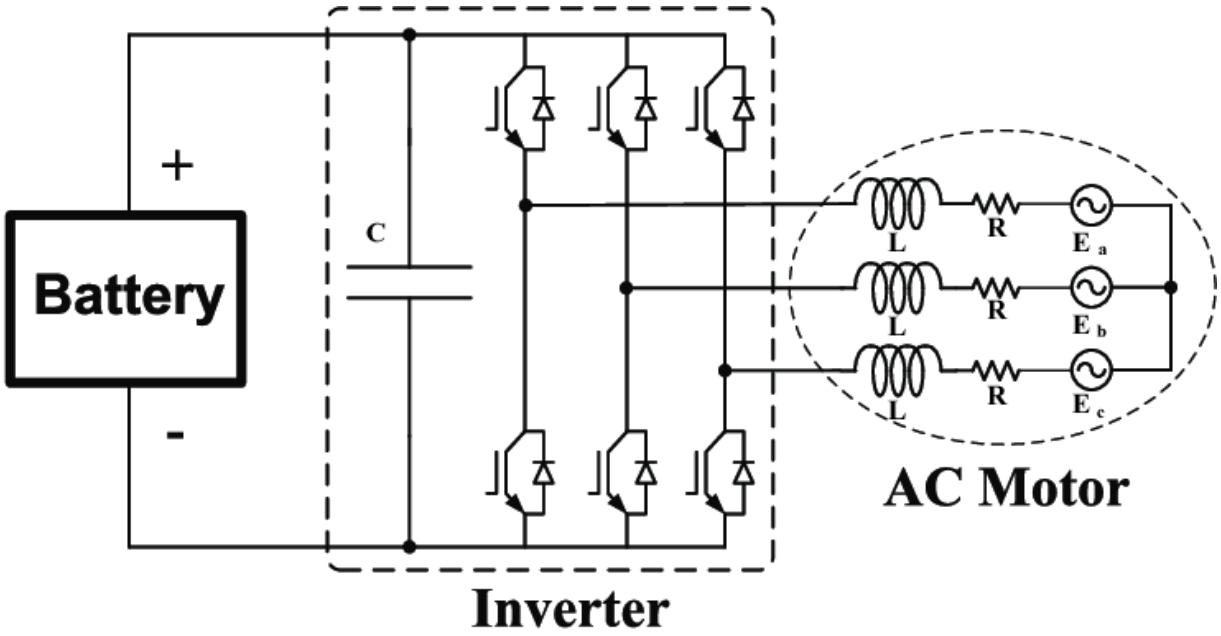
I.6.2 Inverter

The actuator can be powered by a current inverter or a voltage inverter, but for battery power in this power range, a three-phase voltage inverter is a good solution.

The inverter allows the machine to be supplied with variable frequency current, enabling the adjustment of its torque and speed. The electronic control unit generates control signals for the inverter based on the rotor position and the current measurements within the machine. In

practical applications, motors are often powered by current-controlled voltage inverters using pulse width modulation (PWM) techniques to achieve precise control over motor operation [16].

Current control is achieved using regulators that track a reference with variable frequency and amplitude



FigI.4: three phase inverter moter

I.6.3 DC-DC Converter

The different configurations of EV power supply show that at least one DC/DC converter is necessary to interface the FC, the Battery or the Supercapacitors module to the DC-link.

In electric engineering, a DC to DC converter is a category of power converters and it is an electric circuit which converts a source of direct current (DC) from one voltage level to another, by storing the input energy temporarily and then releasing that energy to the output at a different voltage. The storage may be in either magnetic field storage components (inductors, transformers) or electric field storage components (capacitors).

DC/DC converters can be designed to transfer power in only one direction, from the input to the output. However, almost all DC/DC converter topologies can be made bi-directional. A bi-directional converter can move power in either direction, which is useful in applications requiring regenerative braking.

The amount of power flow between the input and the output can be controlled by adjusting the duty cycle (ratio of on/off time of the switch). Usually, this is done to control the output voltage, the input current, the output current, or to maintain a constant power. Transformer-

based converters may provide isolation between the input and the output. The main drawbacks of switching converters include complexity, electronic noise and high cost for some topologies. Many different types of DC/DC power converters are proposed in literature[16][17]



FigI.5: DC-DC Converter

I.6.4 Mechanical reducer

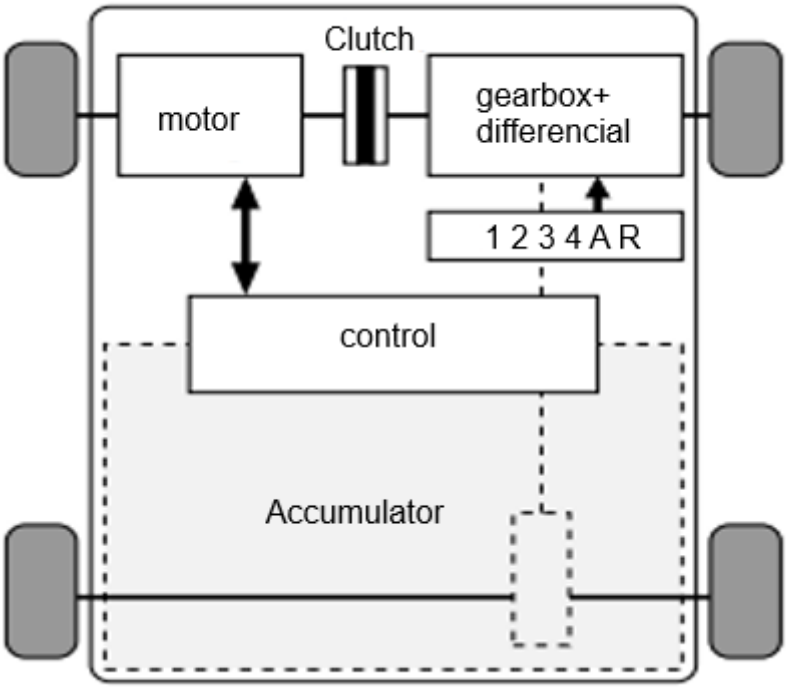
The mechanical transmission of an electric vehicle (EV) is the connection between the motor and the wheels. We can consider several possible solutions for the association of elements necessary for power transmission, which include the mechanical reducer (with a fixed ratio), the gearbox, and potentially the differential.

The choice of reducer is closely linked to the type of vehicle and the choice of motor, which has a volume and mass primarily determined by its torque. To reduce the onboard mass and the cost of the motorization, the motor is generally associated with a mechanical reducer. This allows the reduction of the torque that the motor needs to provide by increasing its rotational speed. It must be perfectly adapted to the functional requirements of the vehicle.

I.6.5 Gearbox

A significant advantage of employing a single-motor gearbox transmission lies in its ability to utilize a **lower-torque motor**. This, in turn, allows for a **lighter motor** to achieve a given

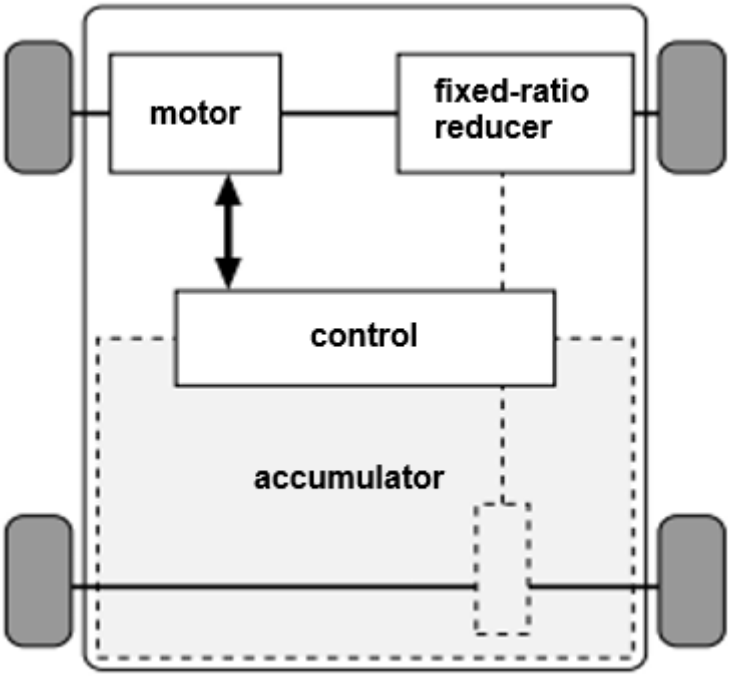
maximum speed. It's worth noting that between gear shifts (within a small range), if the motor possesses the capability to operate at **constant maximum power**, this can also eliminate power fluctuations. The figure above illustrates this concept [17] [18]



FigI.6: Single-engine solution with a gearbox.

I.6.5.1 Solution with a fixed-ratio mechanical reducer

The maximum torque that such a motor with a fixed-ratio reducer must deliver is higher than that which a motor associated with a gearbox would need to produce.



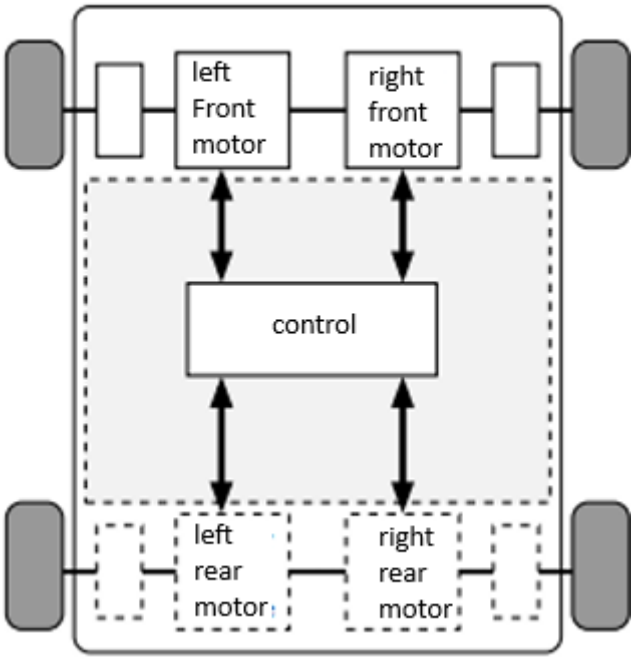
FigI.7: Solution with a fixed-ratio mechanical reducer.

Indeed, the short ratios at low speeds allow for an increase in torque at the wheels.

I.6.5.2 Multi-motor solutions

At first glance, it may seem advantageous to independently motorize the wheels to eliminate mechanical transmission components such as the differential and the double universal joints required in the two previous solutions.

After eliminating the gearbox and the clutch, the mechanical transmission chain is simplified. This allows for the implementation of two-wheel drive solutions, either at the front or the rear, as well as four-wheel drive solutions. [18] [19]



FigI.8: Multi-motor solutions

I.7 HYBRID ELECTRIC VEHICLE

Hybrid Electric Vehicle (HEV) performance in terms of reduced emissions and improved fuel efficiency seems to be promising as an alternative technology. These type of vehicles generally have both energy storage system and energy conversion possibilities, that helps for its propulsion. The hybridization factor of a HEVs can be defined by the ratio of power provided by the electric motor to the total power available by both the Internal Combustion Engine(ICE) and the motor. HEVs are partly battery-electric and partly conventional cars. The battery in the vehicle acts as an additional energy source to supplement the main engine so that the vehicle operates at its maximum possible efficiency and also a range of the vehicle operation is extended. Basically, there are two types of HEVs, which are termed as series and parallel hybrid electric vehicles and they are named in the way it is connected in the vehicle to supplement engine operation. The series hybrid vehicles have the engine connected in series with the electric motor, which in turn drives the vehicle. In this case, the engine powers up the electric motor and the electric motor drives the vehicle They are also known as range-extended vehicles[23]. The block diagram for the series HEV is shown in Figure 1.9.

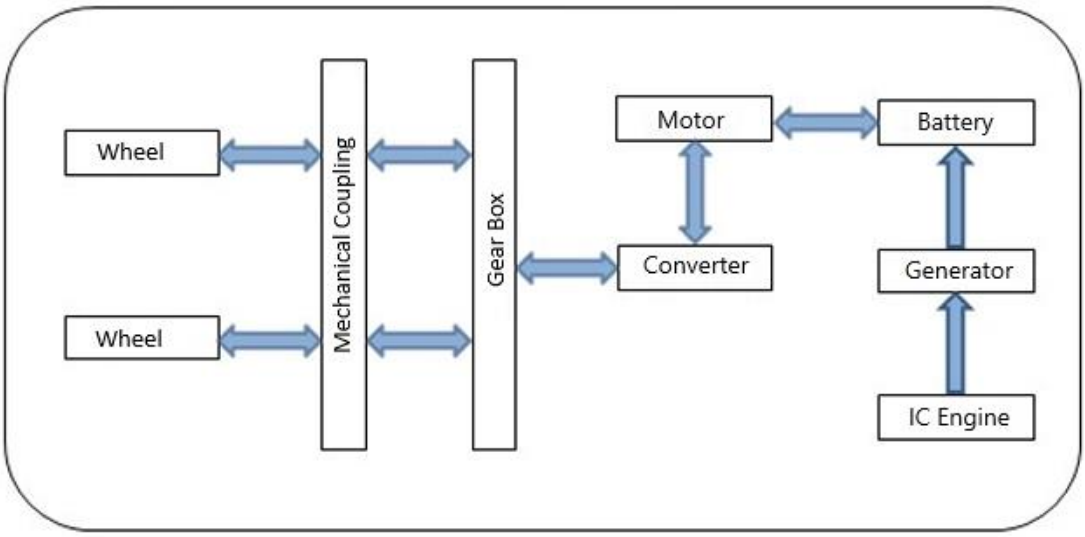


Fig I.9: Parallel HEV block diagram

In contrast to this, in the parallel hybrid vehicle, the wheels can be driven directly either electrically or by the engine. In some driving modes, even both of them could be used simultaneously. This is one of the most common types of the hybrid electric vehicle used, due to its unique advantages like higher efficiency for long driving, higher flexibility in switching between the electric motor and IC engine and cheaper due to simple clutch or belt driven torque conversion. The block diagram for parallel HEV is shown in Figure 1.10.

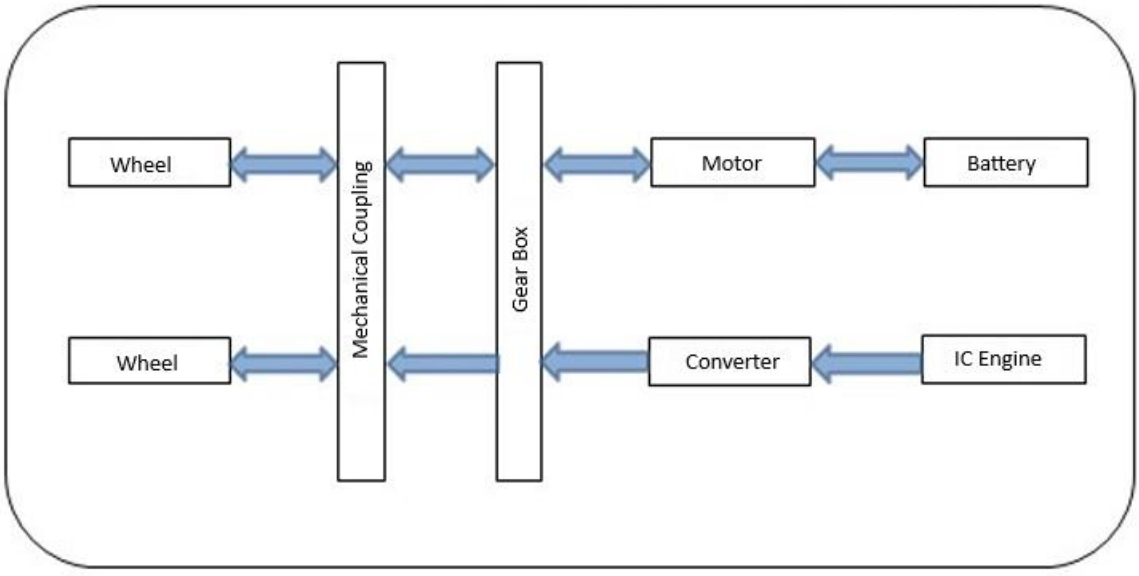


Fig I.10: Parallel HEV block diagram

In both of these types, when the engine is not fully loaded, then this additional energy would be stored in the battery, for using it, during heavy loading conditions later. In this way, hybrids provide improved fuel economy and emissions are reduced considerably, compared to

conventional gasoline engine operation. Also, the regenerative braking concepts provide additional power recovered and stores into battery[24]. Typically, at low speeds, the vehicles are driven electrically and at high loads and speed, they are driven by the engine, which results in improved efficiency and reduced emissions. There are several studies existing in the literature, which analyses the alternative fuels and power train technologies for the vehicles in terms of both technical and economic perspective. One of the key defining characteristics in each of those studies is the methodology that estimates the vehicle efficiency in terms of either relative or absolute vehicle energy for the respective technologies.

Chapter II:

Overview on different power converters and simulation results.

II.1 INTRODUCTION

Electric vehicles (EVs) represent a pivotal shift in the transportation industry, focusing on sustainability, efficiency, and reduced emissions. Central to the functionality of these vehicles are power electronic converters, which manage and transform electrical energy to meet the diverse needs of the vehicle's systems. Two critical types of converters in EVs are DC-to-DC converters and DC-to-AC converters, with the Z-source inverter emerging as an innovative solution for enhancing performance and reliability.

DC-to-DC converters play a crucial role in EVs by adjusting the voltage levels between different components. These converters ensure that the battery's direct current (DC) power is efficiently stepped up or down to match the requirements of various subsystems, such as the drivetrain, lighting, and auxiliary electronics. High efficiency and precise voltage regulation are key attributes of DC-to-DC converters, contributing to the overall energy efficiency and performance of electric vehicles. They help in maintaining optimal power flow and extending the battery life, thus improving the vehicle's range and reliability.

DC-to-AC converters, also known as inverters, are essential for converting the DC power stored in the vehicle's battery into alternating current (AC) power required by the electric motor. The motor, which drives the vehicle's wheels, typically operates on AC power due to its superior performance characteristics, such as smoother torque generation and greater efficiency at various speeds. Inverters must handle high power levels while providing robust control over motor speed and torque, ensuring smooth acceleration, deceleration, and regenerative braking. [26]

The Z-source inverter is a novel topology that has gained attention for its potential advantages in EV applications. Unlike traditional inverters, the Z-source inverter can both buck (step down) and boost (step up) the voltage, providing greater flexibility in power management. This capability is particularly beneficial in dealing with the wide voltage variations that can occur in an EV battery during different states of charge and discharge.

A distinctive feature of the Z-source inverter is its impedance network, typically composed of inductors and capacitors, which allows for a single-stage power conversion process. This results in higher efficiency, reduced component count, and improved reliability compared to conventional inverter designs. The Z-source inverter also enhances the vehicle's ability to handle fault conditions and transient responses, further contributing to the robustness and safety of the powertrain system. [28]

In summary, DC-to-DC and DC-to-AC converters are fundamental components in the architecture of electric vehicles, enabling efficient and reliable power management. The Z-source inverter, with its innovative design and operational advantages, represents a significant advancement in inverter technology, promising to enhance the performance and efficiency of future electric vehicles. As the demand for EVs continues to grow, ongoing developments in power electronic converters will play a crucial role in advancing the capabilities and adoption of these environmentally friendly vehicles.

II.2 DC to AC converters

In modern electrical and electronic systems, the need to convert electrical power from one form to another is fundamental. This necessity has led to the development of various conversion technologies, each designed to handle specific types of electrical conversion. The devices that perform these conversions are known as converters, and they play a crucial role in a wide range of applications, from household electronics to industrial machinery and renewable energy systems.

There are four main types of converters:

1. AC/DC Converters (Rectifiers): They transform AC into DC and are used when DC power is needed but only AC power is available.

2. DC/DC Converters: They convert one level of DC voltage to another, commonly used for voltage regulation in electronic systems.

3. DC/AC Converters (Inverters): They convert DC power back into AC power, crucial for applications that use DC sources but require AC power.

4. AC/AC Converters: They adjust AC power characteristics, such as voltage level or frequency, for specific equipment requirements or power transmission.

Various types of converters utilize unique technologies and approaches to efficiently and effectively achieve the desired conversion. Ongoing research and innovation in the development and enhancement of these technologies are crucial, as they are fueled by the increasing need for power conversion solutions that are more efficient, reliable, and adaptable.

To begin with, let us analyze inverters, also known as DC to AC converters, that transform direct current from sources such as batteries or solar panels into alternating current for regular electrical devices. Following that, we will delve into DC to DC converters, which regulate voltage levels to guarantee the optimal operation of electronic components. [26]

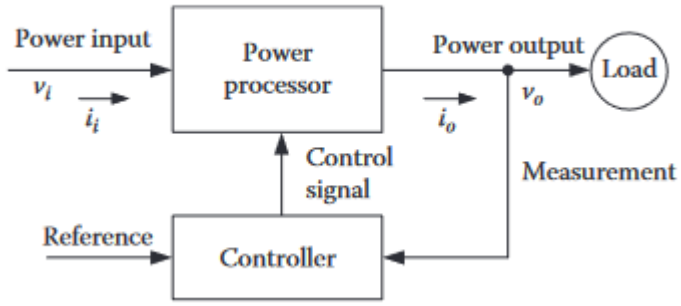


Fig II.1: The block diagram of a power electronics system.

II.2.1 Half And Full bridge inverter:

In a half-bridge inverter configuration, two capacitors of equal value are connected in series across the DC input. This arrangement creates a midpotential at the junction of the capacitors, with a voltage Vd across each capacitor. To ensure a constant potential at point 0 relative to the negative DC bus, large capacitances are utilized. This setup is similar to the basic one-leg inverter and produces an output voltage waveform.

By employing PWM switching, the current between the two capacitors, C+ and C-, is evenly divided. When switch T+ is on, either T+ or diode D+ conducts based on the direction of the output current, resulting in an equal split of current, io, between the two capacitors. Similarly, when T- is on, either T- or diode D- conducts, and io is again evenly divided. Consequently, C+ and C- effectively create a parallel path for io, maintaining the midpotential at junction 0.

In a steady state, io cannot have a DC component since it flows through the parallel combination of C+ and C-. These capacitors serve as DC-blocking capacitors, preventing transformer saturation if a transformer is utilized for electrical isolation. The energy from the transformer's leakage inductance does not affect the switches, as the current in the primary winding is not forced to zero with each switching operation.

For a half-bridge inverter, the peak voltage and current ratings of the switches are:

$$V_d = V_t (II.1)$$

$$I_T = i_{0.peak} \text{ (II. } \mathbf{2})$$

A full-bridge inverter consists of two one-leg inverters and is preferred for higher power ratings. With the same DC input voltage, the maximum output voltage of a full-bridge inverter is twice that of a half-bridge inverter. This means that for the same power, the output current and switch currents are half those of a half-bridge inverter. At high power levels, this is advantageous as it reduces the need for paralleling devices. [27]

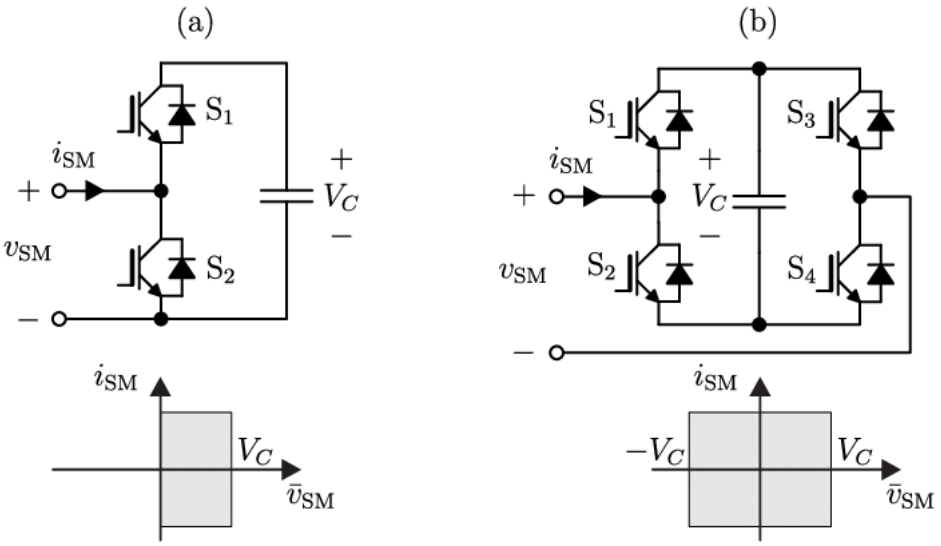


Fig II.2: (a)Half bridge inverter (b) Full bridge inverter

II.2.2 Multilevel Inverters:

Multilevel inverters use a different technique from the PWM method, which vertically chops a reference waveform to produce the desired output (e.g., a sine wave). Instead, the multilevel inverting technique accumulates levels horizontally to achieve the same waveform.

As they contain several power switches and capacitors. Output voltages of multilevel inverters are the sum of the voltages due to the commutation of the switches. A two-level inverter generates an output voltage with two levels with respect to the negative terminal of the capacitor. Similarly, a three-level inverter generates a three-level voltage, and an m-level inverter generates an m-level voltage. Thus, the output voltages of multilevel inverters have several levels. [26]

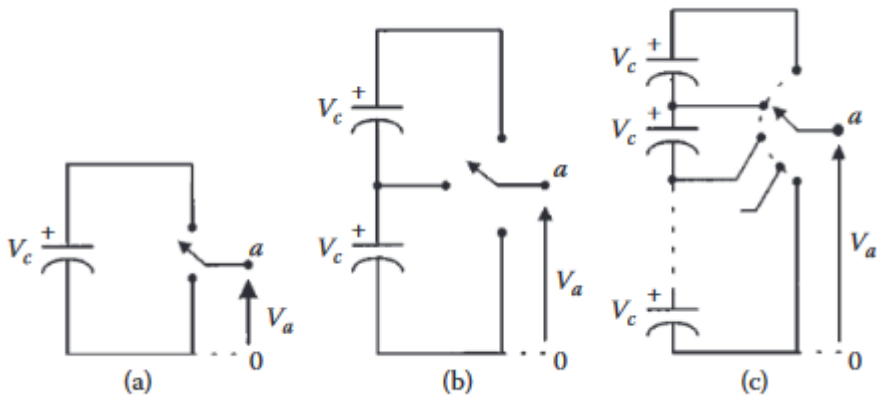


Fig II.3: One phase leg of an inverter: (a) two levels, (b) three levels, and (c) m levels.

Indeed, multilevel inverters have garnered significant interest in recent decades due to their numerous advantages. Different types of multilevel inverters have been proposed, tested, and implemented. [26]

we can name :

- Diode-clamped (neutral-clamped) multilevel inverters
- Capacitor-clamped (flying capacitors) multilevel inverters
- Cascaded multilevel inverters with separate DC sources
- H-bridge multilevel inverters

These variations offer solutions to various challenges and cater to different application requirements, making multilevel inverters versatile and adaptable in diverse scenarios.

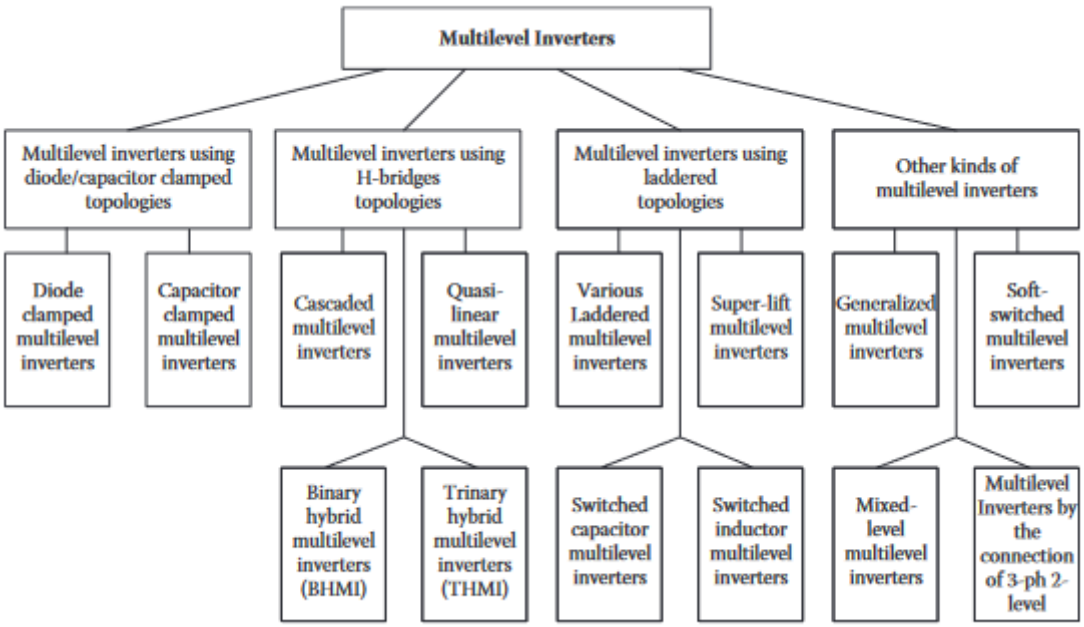


Fig II.4 : Family tree of multilevel inverters.

II.2.2.1 Diode-Clamped Multilevel Inverters

In Diode-Clamped Multilevel Inverters, the switching devices are arranged in series to achieve the desired voltage rating and output levels. Inner voltage points are clamped using either two extra diodes or one high-frequency capacitor. For an m-level inverter, the switching devices are required to block a voltage level of $\frac{V_{dc}}{(m-1)}$. Each clamping diode requires different voltage ratings for different inner voltage levels. [26]

In summary, an m-level diode-clamped inverter has:

- Number of power electronic switches = $2(m-1)$
- Number of DC-link capacitors = $(m-1)$
- Number of clamped diodes = $2(m-2)$
- Voltage across each DC-link capacitor = $-\frac{V_{dc}}{m-1}$ (II.3)

In a three-level diode-clamped inverter with $V_{dc} = 2E$, the DC-bus voltage is split into three levels by two series-connected bulk capacitors, $C1$ and $C2$. The midpoint of these capacitors, n, serves as the neutral point. The output voltage v_{an} has three states: E, 0, and $-E$. To achieve voltage level E, switches $S1$ and $S2$ are turned on; for $-E$, switches $S1'$ and $S2'$ are turned on; and for the 0 level, switches $S2$ and $S2'$ are turned on. [26]

Key components distinguishing this circuit from a conventional two-level inverter are $D1$ and $D1'$. These diodes clamp the switch voltage.

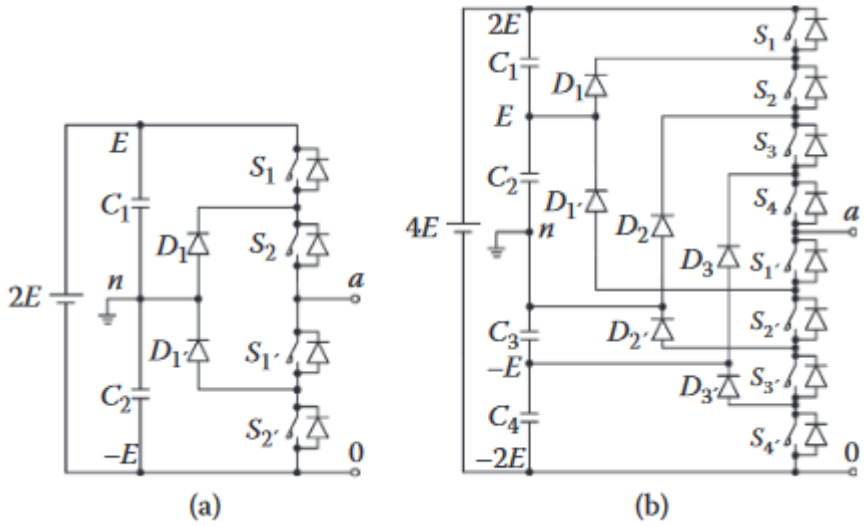


Fig II.5: Diode-clamped multilevel inverter circuit topologies: (a) three-level, (b) five-level.

II.2.2.2 Capacitor-Clamped Multilevel Inverters (Flying Capacitor Inverters)

Capacitor-clamped inverters, also known as flying capacitor inverters, use dependent capacitors to clamp the device voltage to one capacitor voltage level. This configuration allows for multiple output levels. [26]

A basic three-level inverter can produce an output of $v_{an} = E$, 0, or $-E$. For the voltage level E, switches S_1 and S_2 are turned on. For $-E$, switches S_1' and S_2' are turned on. For the 0 level, either pair (S_1, S_1') or (S_2, S_2') can be turned on. The clamping capacitor C_1 is charged when S_1 and S_1' are turned on and discharged when S_2 and S_2' are turned on. Proper selection of the 0-level switch combination can balance the charge of C_1.

A five-level capacitor-clamped inverter offers more flexibility. The voltage v_{an} can be synthesized with the following switching combinations:

- **For** $v_{an} = 2E$: Turn on all upper switches S_1–S_4.
- **For** $v_{an} = E$:
  - S_1, S_2, S_3, S_1': $v_{an} = 2E$ (upper C_4) $-E$ (C_1)
  - S_2, S_3, S_4, S_4': $v_{an} = 3E$ (C_3) $-2E$ (lower C_4)
  - S_1, S_3, S_4, S_3': $v_{an} = 2E$ (upper C_4) $-3E$ (C_3) $+2E$ (C_2)
- **For** $v_{an} = 0$:
  - S_1, S_2, S_1', S_4': $v_{an} = 2E$ (upper C_4) $-2E$ (C_2)
  - S_3, S_4, S_3', S_4': $v_{an} = 2E$ (C_2) $-2E$ (lower C_4)
  - S_1, S_3, S_1', S_3': $v_{an} = 2E$ (upper C_4) $-3E$ (C_3) $+2E$ (C_2) $-E$ (C_1)
  - S_1, S_4, S_2', S_3': $v_{an} = 2E$ (upper C_4) $-3E$ (C_3) $+E$ (C_1)
  - S_2, S_4, S_2', S_4': $v_{an} = 3E$ (C_3) $-2E$ (C_2) $+E$ (C_1) $-2E$ (lower C_4)
  - S_2, S_3, S_1', S_4': $v_{an} = 3E$ (C_3) $-E$ (C_1) $-2E$ (lower C_4)
- **For** $v_{an} = -E$:
  - S_1, S_1', S_2', S_3': $v_{an} = 2E$ (upper C_4) $-3E$ (C_3)
  - S_4, S_2', S_3', S_4': $v_{an} = E$ (C_1) $-2E$ (lower C_4)
  - S_3, S_1', S_3', S_4': $v_{an} = 2E$ (C_2) $-E$ (C_1) $-2E$ (lower C_4)
- **For** $v_{an} = -2E$: Turn on all lower switches S_1'–S_4'.

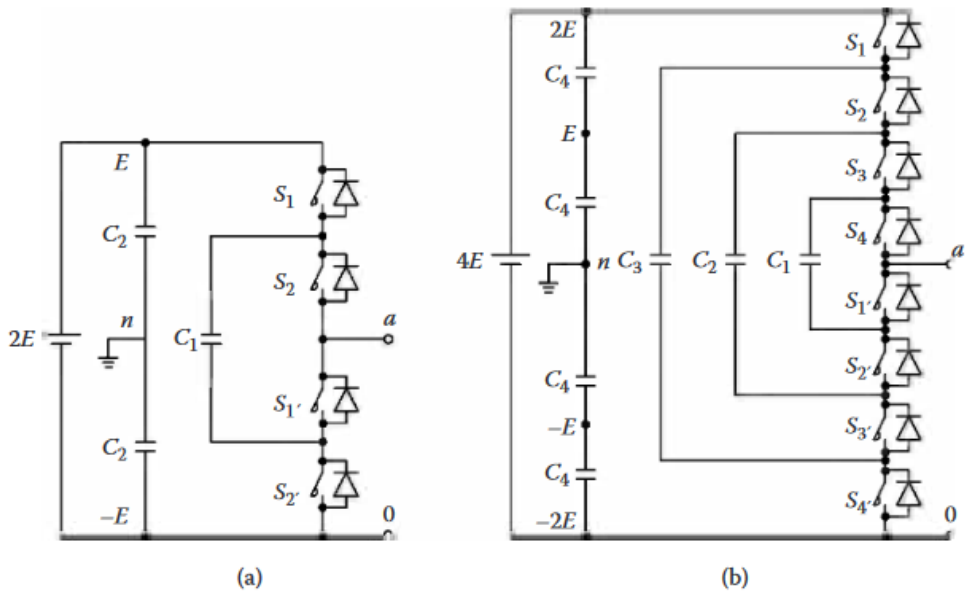


Fig II.6: Capacitor-clamped multilevel inverter circuit topologies: (a) three-level, (b) five-level.

Usually, the positive top level and negative top level each have only one combination to achieve their output values. Other levels have multiple combinations to implement their output values. In the descriptions provided, capacitors with positive signs are in discharging mode, while those with negative signs are in charging mode. By selecting the appropriate capacitor combinations, it is possible to balance the capacitor charge. [26]

II.2.2.3 Multilevel Inverters Using H-Bridges (HBs) Converters

The basic structure of multilevel inverters using H-bridges (HBs) is based on the connection of multiple H-bridges. Each phase leg of the inverter consists of several HBs; for example, three HBs (HB1, HB2, and HB3) can be connected in each phase. Each HB is supplied by a separate DC source. The resulting phase voltage is synthesized by adding the voltages generated by the different HBs. If the DC link voltages of the HBs are identical, the multilevel inverter is called a cascaded multilevel inverter. However, it is also possible to have different values among the DC link voltages of HBs, in which case the circuit is referred to as a hybrid multilevel inverter. [26]

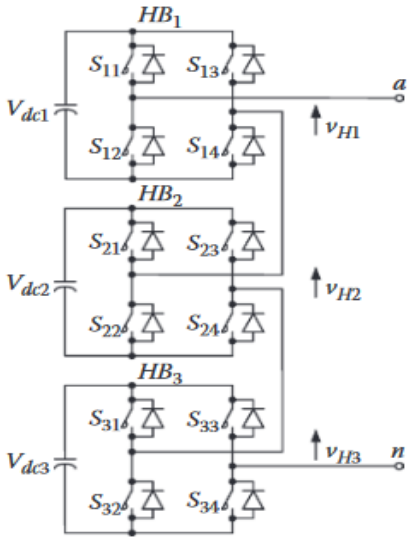


Fig II.7: Multilevel inverter based on. the connection of HBs

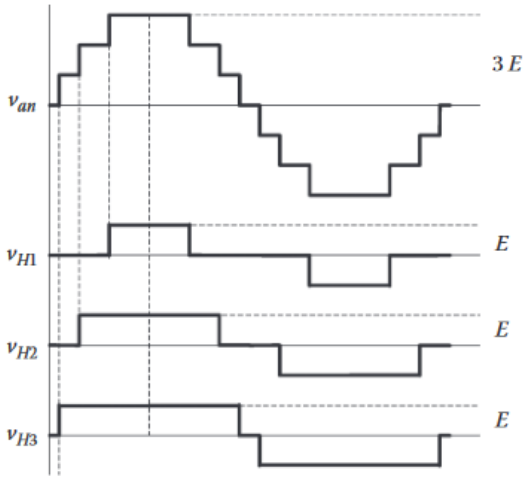


Fig II.8: Waveforms of cascaded multilevel inverters

II.2.2.4 Cascaded Equal Voltage Multilevel Inverters (CEMI)

In a cascaded equal voltage multilevel inverter (CEMI), all H-bridges (HBs) have identical DC link voltages, denoted as $V_{dc1} = V_{dc2} = V_{dc3} = E$, where E is the unit voltage. Each HB can produce three output voltages: $+E$, 0, and $-E$. By sequentially connecting the capacitors to the AC side through three power switches, the inverter can generate an AC output voltage ranging from $-3E$ to $+3E$, resulting in seven distinct voltage levels. [26]

II.2.2.5 Binary Hybrid Multilevel Inverter (BHMI)

In a binary hybrid multilevel inverter (BHMI), the DC link voltages of each H-bridge (HB) are set in a binary progression: $V_{dc_i} = 2^{i-1}E$. For a 3-HB one phase leg, the DC link voltages are:

$$V_{dc1} = E,\ V_{dc2} = 2E,\ V_{dc3} = 4E$$

the output waveform v_{an} has 15 levels. One key advantage of the BHMI is that the HB with the higher DC link voltage undergoes fewer commutations, thereby reducing switching losses. The BHMI demonstrates a seven-level (in half-cycle) inverter using this hybrid topology. The HB with the highest DC link voltage operates at a lower switching frequency, while higher switching frequency components, such as IGBTs, are used in the HBs with lower DC link voltages. [26]

II.3 DC to DC converters

DC-DC converters are vital in regulated switch-mode power supplies and motor drive applications. These devices typically start with an unregulated DC voltage, which is derived from rectifying the line voltage and can fluctuate with line voltage variations. Switch-mode DC-DC converters are designed to transform this unstable input into a steady DC output at the desired voltage level.

In many applications, these converters are paired with electrical isolation transformers in switch-mode power supplies. However, in motor drives, they are usually employed without isolation transformers. To keep the discussion straightforward, this chapter will focus on non-isolated converters, as isolation introduces additional complexity.

The types of DC-DC converters discussed in this chapter include:

1. Step-down (buck) converter
2. Step-up (boost) converter
3. Step-down/step-up (buck-boost) converter

4.zsource inverter

The step-down and step-up converters form the fundamental categories. The buck-boost and is acombination or variation of these basic types.

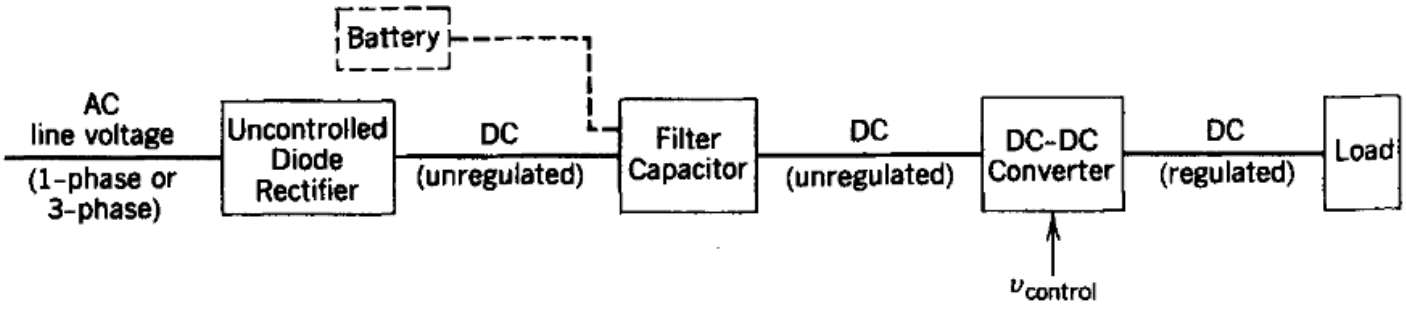


Fig II.9: A dc-dc converter system.

II.3.1 step-down (buck) converter

The step-down (buck) converter, as its name suggests, generates a lower average output voltage compared to the DC input voltage V_d. Its primary use lies in regulated DC power supplies and DC motor speed control.

In essence, the basic circuit functions as a step-down converter for a resistive load. Assuming an ideal switch, constant instantaneous input voltage V_d, and a purely resistive load, the output voltage waveform varies based on the switch position. The average output voltage can be computed in terms of the switch duty ratio:

$$V_o = D \cdot V_d = k \cdot V_{\text{control}} \quad (\text{II.}\mathbf{4})$$

where k is a constant, and V_{control} represents the control voltage.

By adjusting the duty ratio $\frac{t_{\text{on}}}{T_s}$ of the switch, V_o can be regulated. Notably, the average output voltage V_o changes linearly with the control voltage, akin to linear amplifiers.

However, practical applications of this circuit encounter two main challenges:

In real scenarios, the load typically possesses inductive characteristics. Even with a resistive load, some stray inductance is inevitable. Consequently, the switch might need to dissipate the inductive energy, risking damage.

The output voltage oscillates between zero and V_d, which is unsuitable for many applications.

To address these issues, a diode can be incorporated to manage the stored inductive energy.

Additionally, employing a low-pass filter comprising an inductor and a capacitor significantly reduces output voltage fluctuations. The corner frequency of this filter is deliberately set much lower than the switching frequency, effectively minimizing switching frequency ripple in the output voltage.

During the switch-on period, the diode becomes reverse biased, allowing energy to flow to both the load and the inductor. Conversely, when the switch is off, the inductor current passes through the diode, transferring some stored energy to the load.

In this analysis, the output filter capacitor is assumed to be sufficiently large, a common practice in applications requiring nearly constant instantaneous output voltage $v_o(t) = V_o$. The ripple in capacitor voltage (output voltage) is addressed in subsequent calculations.

It's evident that in a step-down converter, the average inductor current equals the average output current I_o, given that the average capacitor current in steady state is zero.

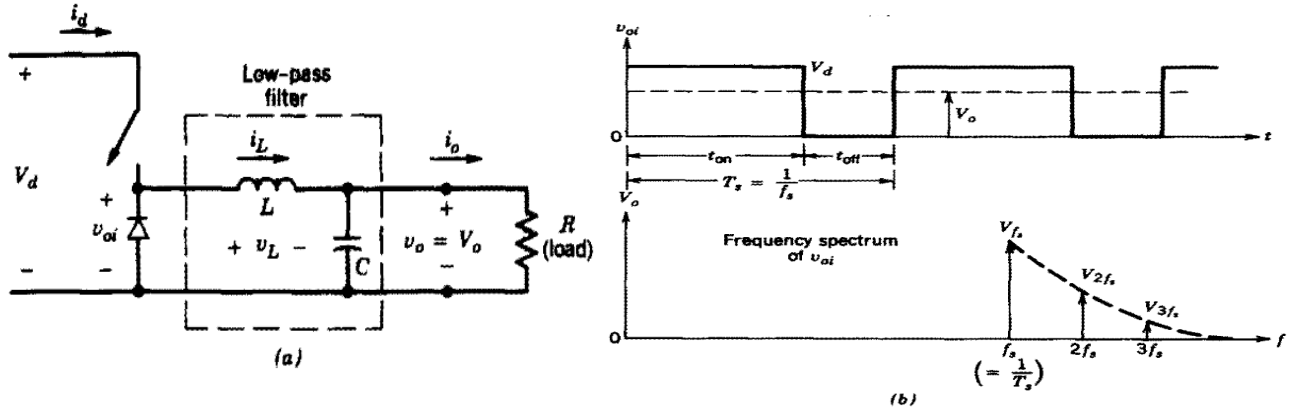


Fig II.10: Step-down dc-dc converter.

II.3.2 step-up (boost) converter:

In various applications such as regulated DC power supplies and the regenerative braking of DC motors, the step-up converter plays a pivotal role. Unlike its counterpart, the step-down converter, this device is engineered to elevate the output voltage above the input voltage. During its operational cycle, when the switch is activated, the diode within the circuit is reverse biased, thereby effectively segregating the output stage. This phase facilitates the transfer of energy from the input to the inductor. Conversely, when the switch is in the off state, the output stage not only receives energy from the inductor but also draws power from the input source. This dynamic interplay of energy transfer mechanisms characterizes the efficient functioning of the step-up converter, allowing it to cater to a diverse array of voltage enhancement requirements in practical engineering scenarios.

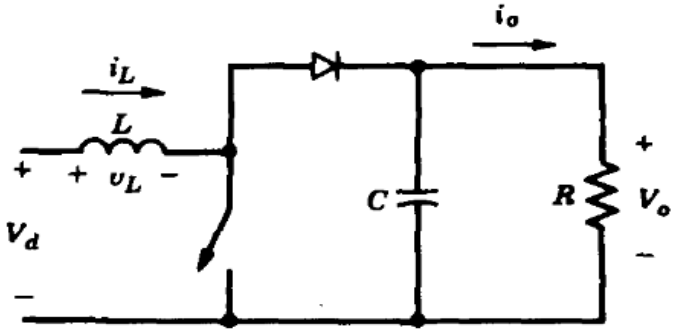


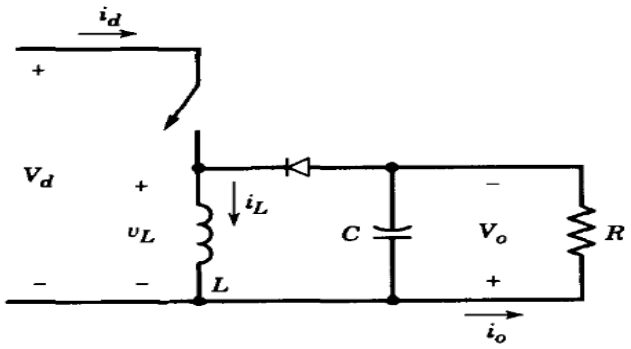
Fig II.11: Step-up dc-de converter.

II.3.3 buck-boost converter

The primary application of a buck-boost converter, derived from the cascade connection of step-down and step-up converters, lies in regulated DC power supplies. In scenarios where a negative-polarity output is desired concerning the input voltage's common terminal, and where the output voltage can either exceed or fall short of the input voltage, this converter proves highly advantageous.

This converter operates through a series of dynamic stages: during the closure of the switch, energy from the input is directed towards the inductor, while the diode becomes reverse biased. Conversely, when the switch opens, the energy previously stored in the inductor is efficiently transferred to the output, with no additional input energy being supplied during this interval.

In steady-state analysis, where the output capacitor is assumed to be significantly large, maintaining a constant output voltage $v_o(t)$ at V_o becomes the norm. The conversion ratio between the output and input voltages, denoted as V_o/V_d, hinges on the combined conversion ratios of the two cascaded converters. This relationship, contingent on the duty ratio D, allows for the output voltage to be either higher or lower than the input voltage. Such versatile voltage regulation capabilities make the buck-boost converter a vital component in various



power supply applications requiring precise voltage control.

Fig II.12: Buck-boost converter

II.4 Z-source topology

Z-source inverters use an impedance network to couple the inverter to the DC voltage source. This impedance network consists of a cross-coupled LC hybrid structure, allowing the inverter to boost the output voltage through specific control techniques. This design effectively combines the functions of a boost converter and a conventional inverter into a single system. [25]

In this section, we will delve into the details of the Z-source inverter, covering its structure, operation, and control mechanisms.

Structure and theorical theses

The Z-source inverter was recently introduced, with the term "Z-source" (Impedance Source) referring to the replacement of the traditional DC bus in the inverter with a cross-coupled hybrid LC stage. This innovation allows the inverter to achieve a higher AC output voltage than a conventional inverter, providing a natural boost effect. This enhancement is due to the capability of introducing shoot-through states in the inverter's arms, in conjunction with the traditional PWM control. The input DC source does not need to be reversible, and the inverter's control is slightly modified.[25]

The input voltage of the inverter is denoted as v_i. $\hat{V}_M$ represents the peak value of the fundamental output phase voltage of the inverter, and $\hat{v}_i$ represents the peak input voltage of the inverter. The modulation index m is defined as:

$$m = \frac{\hat{v}_i}{2\hat{V}_M} \quad \text{(II. 5)}$$

The boost factor b of the DC stage is defined as:

$$b = \frac{\hat{v}_i}{V_{\text{DC}}} \quad \text{(II. 6)}$$

The overall system gain B is defined as:

$$B = mb = \frac{\hat{V}_M}{V_{\text{DC}}} \quad \text{(II. 7)}$$

The DC stage of the Z-source inverter is a symmetrical structure with two capacitors, C_1 and C_2, both with a capacitance C, and two inductors, L_1 and L_2, both with an inductance L. This configuration results in identical voltages across the capacitors (V_C) and identical currents through the inductors (i_L). [25]

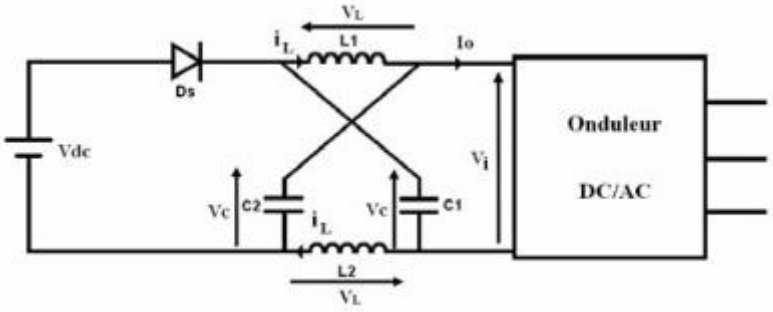


Fig II.13: ZSI basic structure

II.4.1 Operating Principle of the Z-Source Inverter

The Z-source inverter is capable of regulating output voltages not only through its modulation index m (as in a conventional inverter) but also by adjusting the input voltage v_i through controlling the durations of shoot-through states of the inverter's arms.

These shoot-through states occur during the freewheeling phases on the inverter's three-phase load (zero vectors of vector PWM). The states of the inverter as seen by the load remain unchanged, making the load insensitive to the shoot-through states of the Z-source stage. Maximum boost b is achieved by extending the shoot-through duration as much as possible, which depends on the duration of the zero vectors and thus the modulation index m. [25]

The operation of the Z-source inverter relies on the behaviors of the nonlinear elements surrounding the Z-source stage:

- The state of the diode D_s: conducting or blocked
- The state of the inverter: freewheeling, active state (power exchange between the DC stage and the load), shoot-through state of the inverter's arms

The table below shows the different configurations possible with the classic control of the Z-source inverter.

State of Diode D_s	Inverter Freewheeling	Inverter Active	Z-source Shoot-through
Conducting	YES	YES	NO
Blocked	NO	NO	YES

In normal operation, six combinations are not present in the Z-source stage:

- If the inverter arms are in a shoot-through state, the diode must be blocked due to the boost mode of the circuit.
- If the inverter is in an active state (power exchange between the DC stage and the load), the diode D_s is conducting.
- If the inverter is in a freewheeling state, D_s is typically conducting, related to the inverter's switching frequency and the usual values of L and C.

II.4.2 Determination of Amplification Coefficients

To calculate these coefficients, a succinct analysis of the three useful states of the Z-source inverter must be performed over a modulation period to determine the equations governing this system. [25]

Mode 1 - Ds Conducting and Active Inverter:
During this state, the inverter can be represented as a current source from the perspective of the Z-source continuous stage. The voltage values can be determined by the following equations:

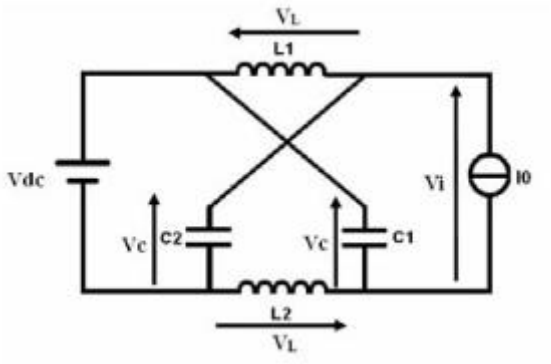


Fig II.14: mode 1 schematic

$$v_L = V_{dc} - v_C \quad \text{(II.8)}$$

$$v_i = v_C - 2V_{dc} = v_C \quad \text{(II.9)}$$

Mode 2 - Ds Conducting and Freewheeling Inverter (without short-circuit):
In this state, the inverter can be represented as an open circuit, and the voltages v_C and v_i remain the same as in Mode 1. This is a special case where i_0 is zero. [25]

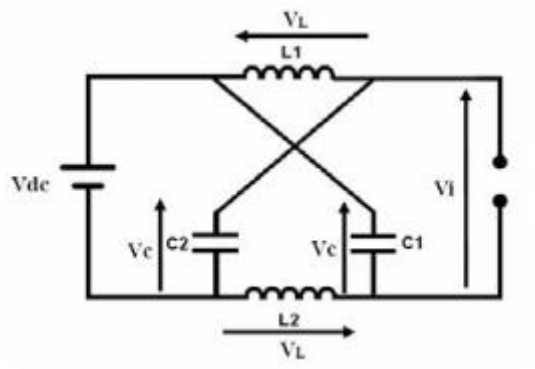


Fig II.15: mode 2 schematic

Mode 3 - Ds Blocked and Z-source Short-circuited:
During this state, at least one leg of the inverter is short-circuited, resulting in zero voltage output from the Z-source continuous stage. The voltage equations are:

$$v_L = v_C$$

$$v_i = 0$$

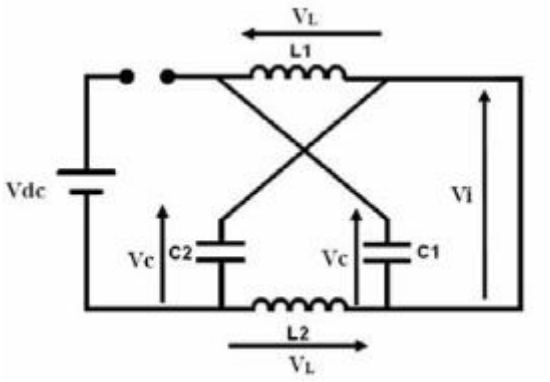


Fig II.16: mode 3 schematic

From these electrical equations, it is possible to deduce the voltage values during a modulation period and determine the amplification values. T [25] .Denotes the half-period of the Z-source structure command, which is based on triangular carriers:

$$T = T_0 + T_1 \qquad (\text{II.}\mathbf{10})$$

where T_0 is the duration of the Z-source inverter short-circuits ($V_i = 0$) and T_1 is the duration of the active states of the inverter during T. The short-circuit duty cycle D_0 is noted as $D_0 = \frac{T_0}{T}$.

The voltage across the capacitors can be calculated from the following equation:

$$v_L = \frac{T_0 v_C + T_1(V_{dc} - v_C)}{T} \quad (\text{II.}\mathbf{11})$$

Thus, the voltage across the capacitors becomes:

$$v_C = V_{dc}\frac{T_1}{T_0 + T_1} = V_{dc}\frac{T_1}{T} \quad (\text{II.}\mathbf{12})$$

Substituting into equation (5), we get:

$$v_i = V_{dc}\frac{T_1}{T} - 2V_{dc} = V_{dc}\left(2 - \frac{T_0}{T}\right) \quad (\text{II.}\mathbf{13})$$

The maximum input voltage of the inverter v_i can be calculated using equations (4) and (9), giving us the amplification coefficients:

$$v_i = V_{dc}\left(2 - \frac{T_0}{T}\right) \quad (\text{II.}\mathbf{14})$$

Therefore, the continuous stage amplification ratio b is:

$$b = \frac{v_i}{V_{dc}} = 2 - \frac{T_0}{T} = \frac{1}{1 - D_0} \quad (\text{II.}\mathbf{15})$$

To maintain a positive voltage v_i across the inverter, the short-circuit duty cycle D_0 must be less than 0.5.

The complete device amplification or reduction coefficient B is given by the equation:

$$B = m \cdot b \cdot V_{dc} = m \cdot \left(2 - \frac{T_0}{T}\right) \cdot V_{dc} \quad (\text{II.}\mathbf{16})$$

II.4.3 Overvoltage Factor *B*

In steady state, the average value of the voltage during the commutation of the inductance is known to be zero, therefore:

$$\langle V_L \rangle = \frac{T_{Cc} \times V_c + T_1 \times (V_{dc} - V_c)}{T} = 0 \quad (\text{II.}\mathbf{17})$$

The voltage across the capacitors can be calculated from equation (III.12). From this, we can deduce the average value of the inductance L, the voltage across the capacitors, and the average value of V_i:

$$V_{c1} = V_{c2} = V_c = \frac{T_1}{T_1 - T_{Cc}} V_{dc} \quad (\text{II.}\mathbf{18})$$

$$\frac{T_1 \times (2V_c - V_{dc})}{T} = \frac{T_1}{T_1 - T_{Cc}} V_{dc} = V_c = \frac{1 - D}{1 - 2D} V_{dc} \quad (\text{II.}\mathbf{19})$$

$$\langle V_i \rangle = \frac{T_1 \times (2V_c - V_{dc})}{T} = \frac{T_1}{T_1 - T_{Cc}} V_{dc} = V_c \quad (\text{II.}\mathbf{20})$$

To calculate the maximum inverter voltage $V_{i\,\max}$, we use the amplification coefficients of the structure:

$$V_{i\,\max} = \frac{T_1}{T_1 - T_{Cc}} V_{dc} = 2V_c - V_{dc} = \frac{1}{1 - 2\frac{T_{Cc}}{T}} V_{dc} \quad (\text{II.}\mathbf{21})$$

By substituting equation (III.15) into the continuous stage amplification ratio b:

$$b = \frac{V_{i\,\max}}{V_{dc}} = \frac{1}{1 - 2\frac{T_{Cc}}{T}} = \frac{1}{1 - 2D} \geq 1 \quad (\text{II.}\mathbf{22})$$

The relation between the input voltage and the maximum continuous bus voltage is:

$$V_{i\,\max} = \frac{1}{1 - 2D} V_{dc} \quad (\text{II.}\mathbf{23})$$

By multiplying equations (III.1) and (III.2), we find:

$$m \times b = \frac{2V_{m\,\max}}{V_{i\,\max}} \times \frac{V_{i\,\max}}{V_{dc}} \quad (\text{II.}\mathbf{24})$$

($V_{m\,\max}$: The peak value of the fundamental output voltage of the inverter)

The amplification factor of the complete device B is defined by the following equation:

$$m \times b = \frac{2V_{m\,\max}}{V_{dc}} = B \quad (\text{II.}\mathbf{25})$$

Where:

- D: the short-circuit duty cycle ratio.

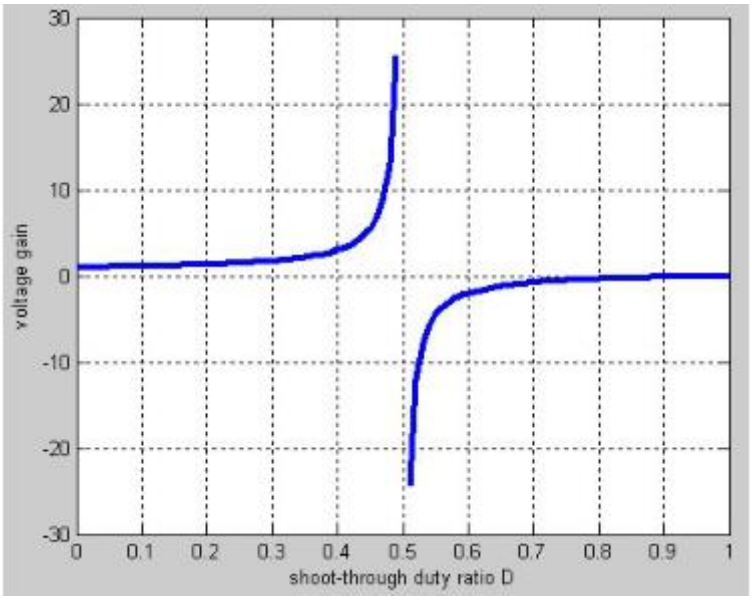


Fig II.17: Z-source Duty ratio effect on voltage

To maintain a positive voltage Vi across the inverter, the short-circuit duty cycle ratio D must be less than 0.5. [25]

II.5 Review of PWM control methods for ZSI

II.5.1 Simple ST Boost Control (SBC)

The SBC method [2], uses two straight lines equal to or greater than the peak value of the three phase references to control the ST duty ratio in a traditional sinusoidal PWM, as shown in Figure 4. When the triangular waveform is greater than the upper line, Vp , or lower than the bottom line, Vn , the circuit turns into ST state. Otherwise it operates just as traditional carrier based PWM. This method is very straightforward; however, the resulting voltage stress across the switches is relatively high because some traditional zero states are not utilized.

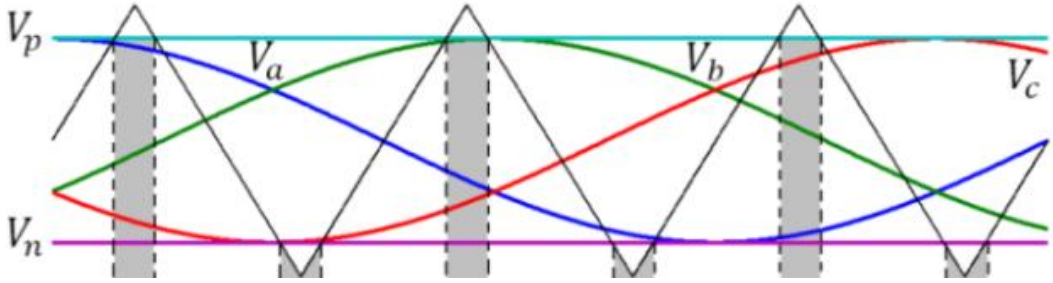


Fig II.18: SBC method waveforms

II.5.2 Maximum ST Boost Control (MBC)

Reducing the voltage stress under a desired voltage gain becomes more important to control the ZSI; this can be achieved by making the ST duty ratio as large as possible. The MBC control, [4], turns all the traditional zero states into ST state. As shown in Figure 5, the circuit is in ST state when the triangular carrier wave is either greater than the maximum curve of the references (V a , V b and V c) or smaller than the minimum of the references. The ST duty ratio varies at six times of the output frequency. The ripples in the ST duty ratio will result in ripple in the inductor current and the capacitor voltage. This will cause a higher requirement of the passive components when the output frequency becomes very low. Therefore, the MBC method is suitable for applications that have a fixed or relatively high output frequency.

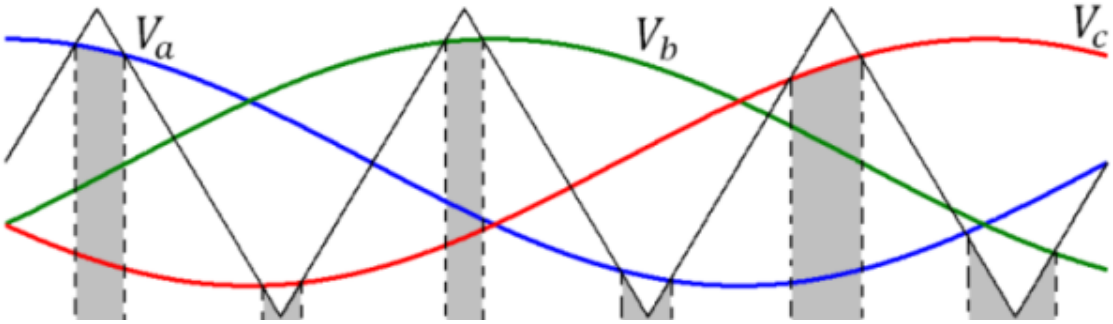


Fig II.19: MBC method waveforms

II.5.3 Third Harmonic injection:

The third harmonic injection method is a technique used in pulse-width modulation (PWM) to enhance the performance of inverters by improving their voltage output and reducing harmonic distortion. In a standard PWM inverter, the reference waveform is a pure sine wave. However, by injecting a third harmonic component into this reference waveform, the method allows the inverter to better utilize the DC bus voltage, thereby increasing the output voltage by approximately 15%. This is achieved without exceeding the maximum voltage ratings of the power devices. The third harmonic component, being a zero-sequence harmonic, does not affect the phase voltages directly but modifies the reference waveform in a way that the peak of the combined waveform is flattened. Consequently, this technique is particularly beneficial in applications such as motor drives and power supplies, where

improved voltage utilization and lower harmonic distortion are critical for efficient and reliable operation . [29]

II.6 Simulations and Results:

II.6.1 Z source :

II.6.1.1 Open loop results:

Figures:

For each figure we change the duty cycle of the switch to see how it works.

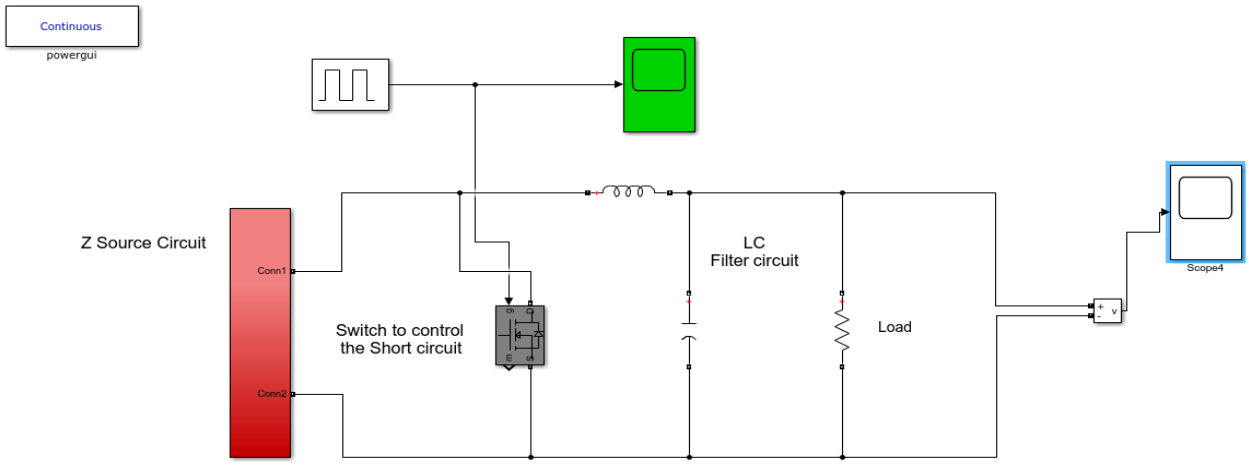


Fig II.20: Matlab Simulink block diagram of Z-source converting topology open loop

Starting With D=10%.

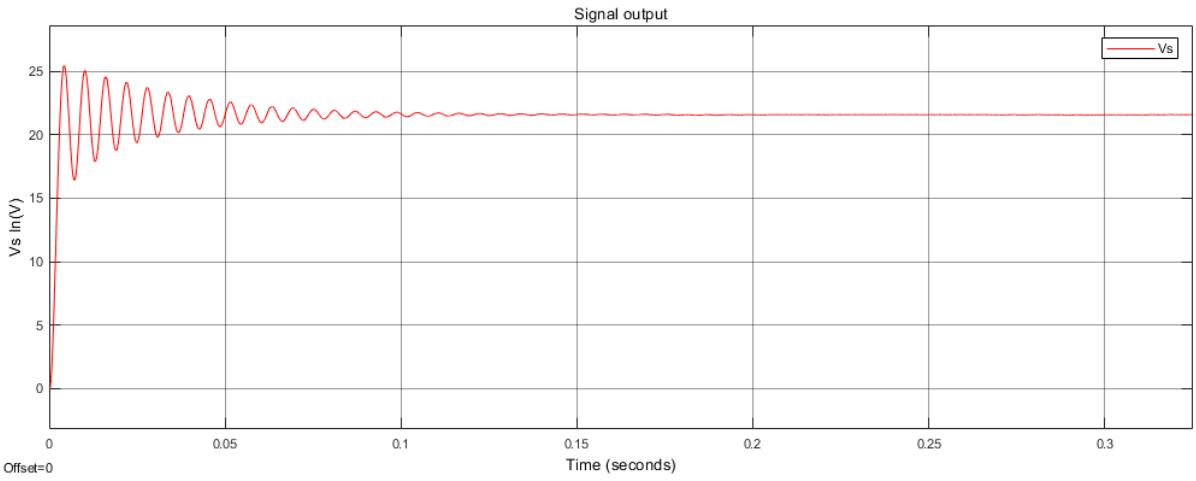


Fig II.21: voltage response of Z-source 1

Then we tried D=20%

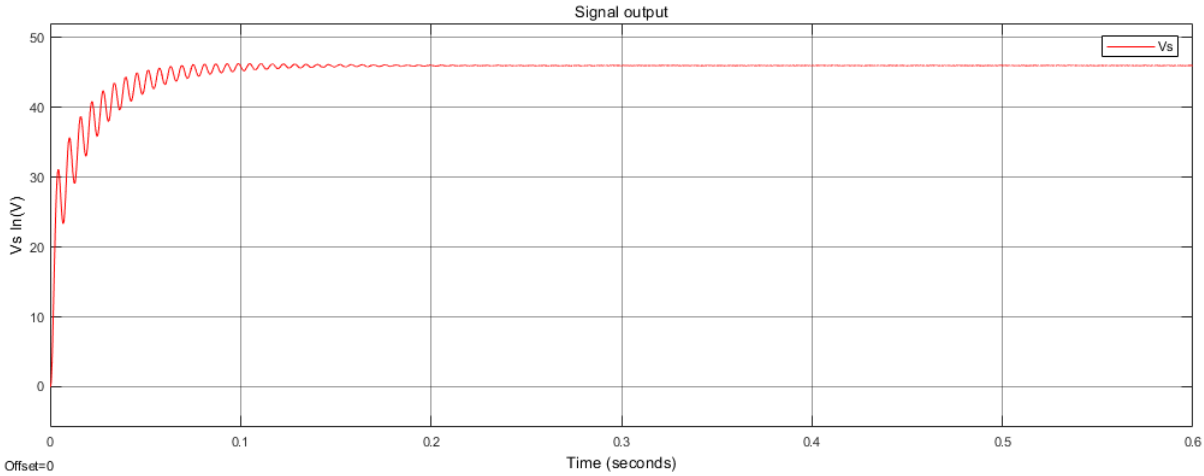


Fig II.22: voltage response of Z-source 2

And D=40%

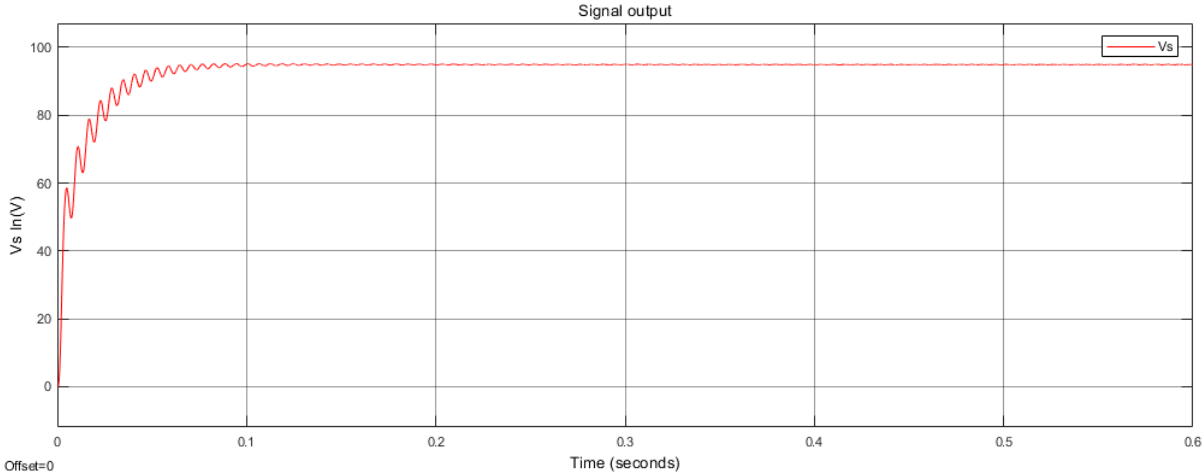


Fig II.23: voltage response of Z-source 3

And D=60%

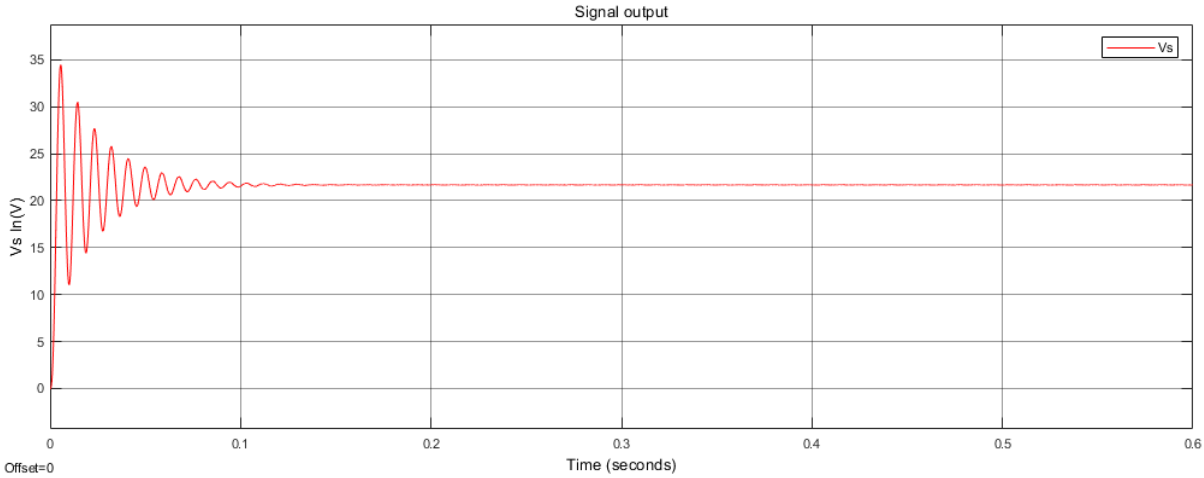


Fig II.24: voltage response of Z-source 4

II.6.1.2 Closed Loop Results:

Using PID controler:

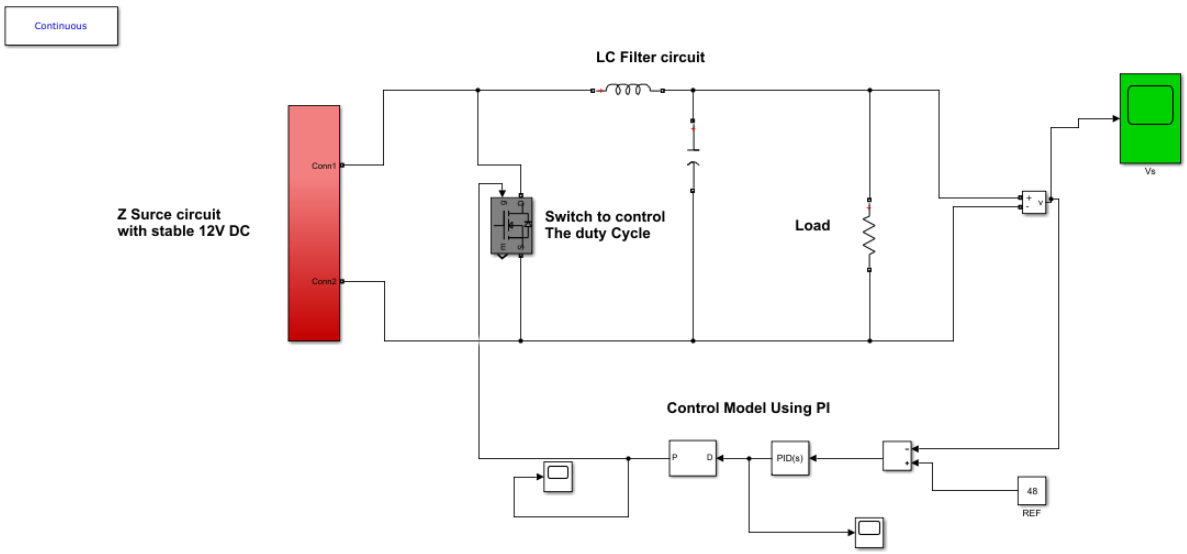


Fig II.25: Matlab Simulink block diagram of Z-source converting topology closed loop

For Ref= 48V Kp= 0.01149 Ki= 0.504

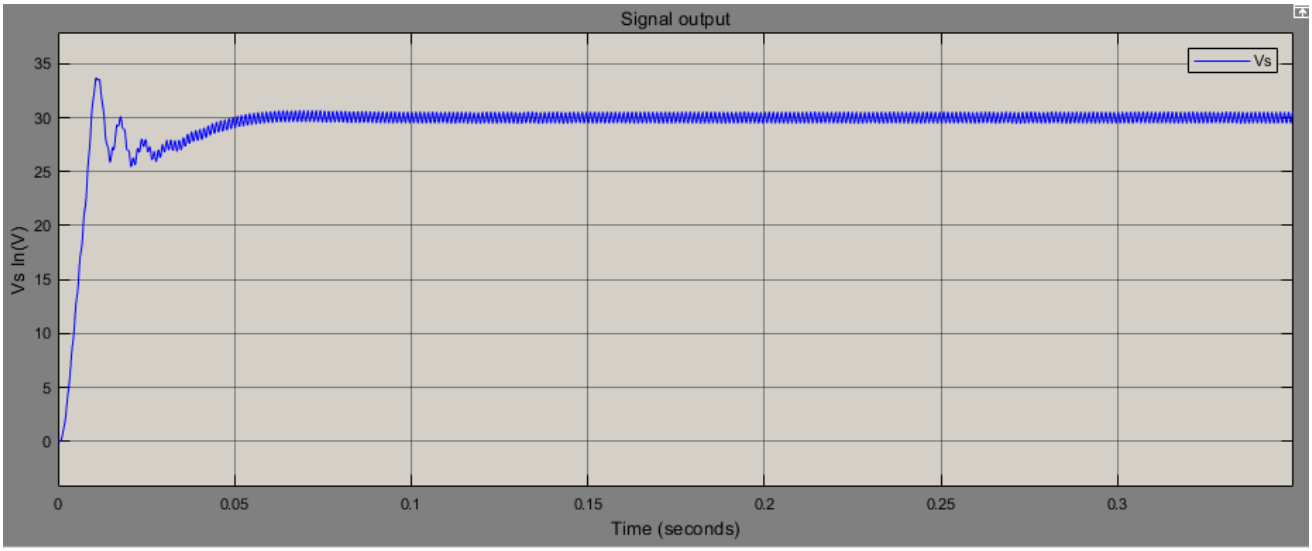


Fig II.26: voltage response of Z-source 5

For Ref = 30V ki= 01.354 kp= 0.01249

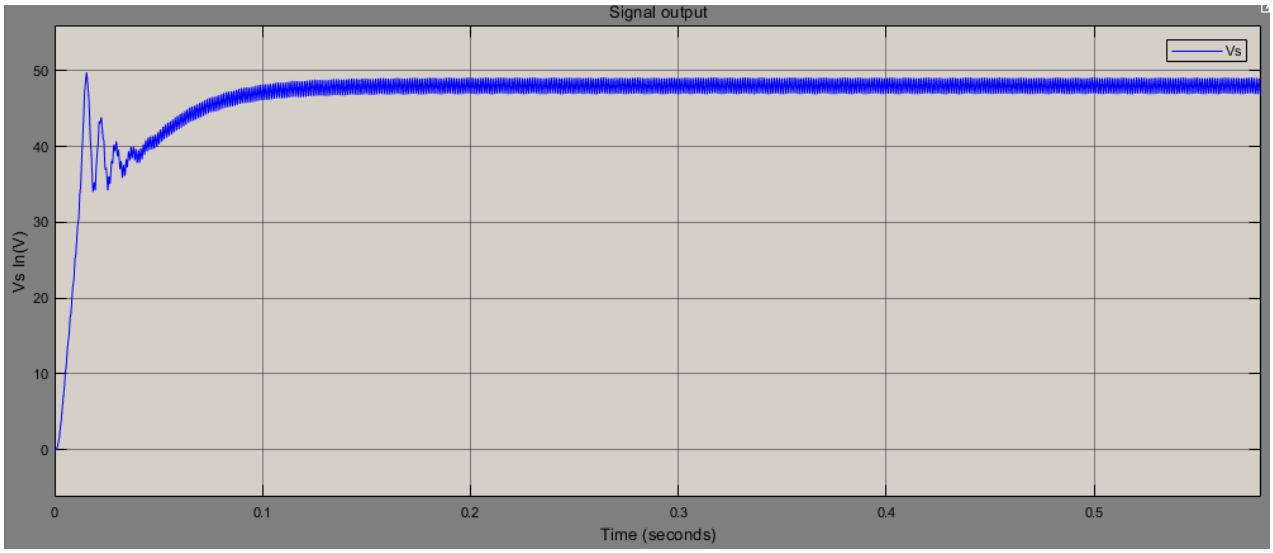


Fig II.27: voltage response of Z-source 6

II.6.2 Simple Boost Control (SBC)

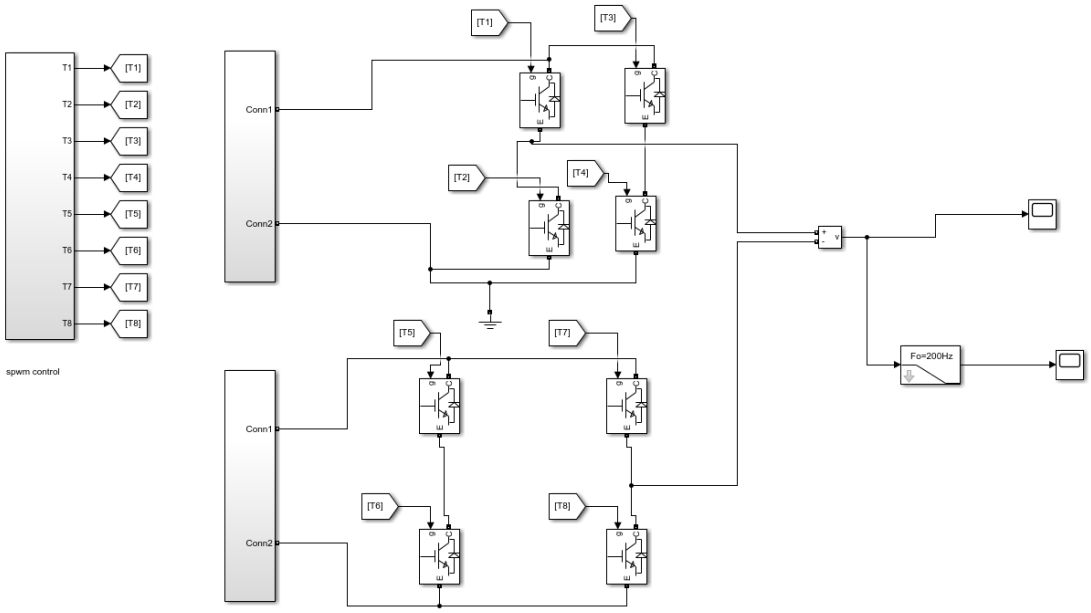


Fig II.28: Simulink model of SBC with z source

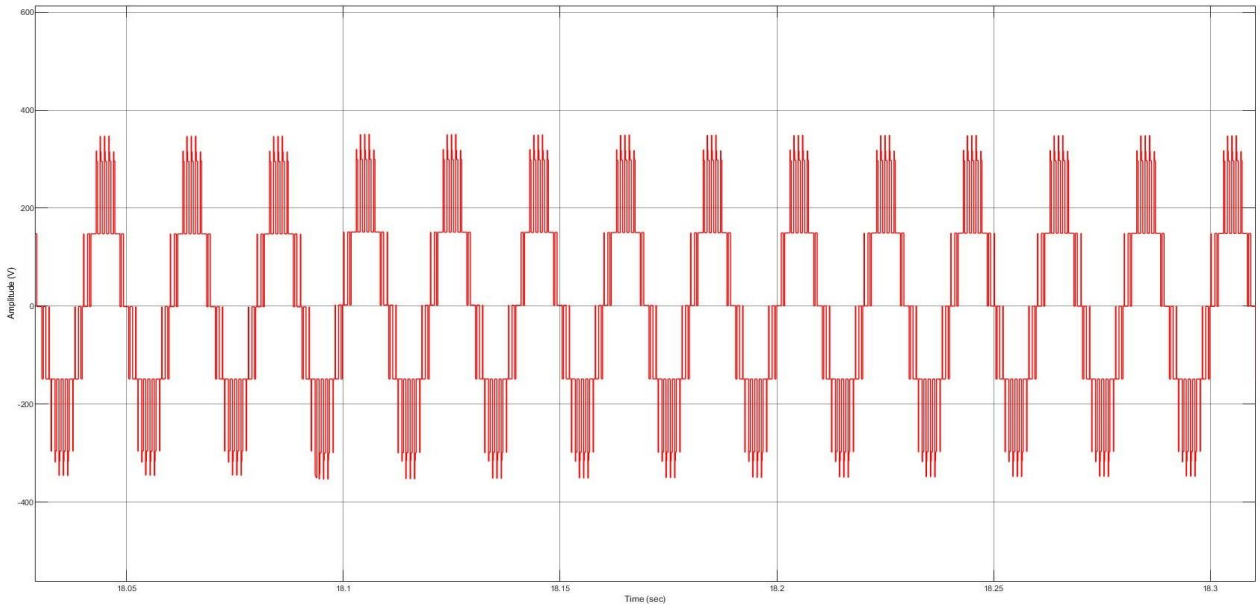


Fig II.29: Output for SBC Voltage Without filter

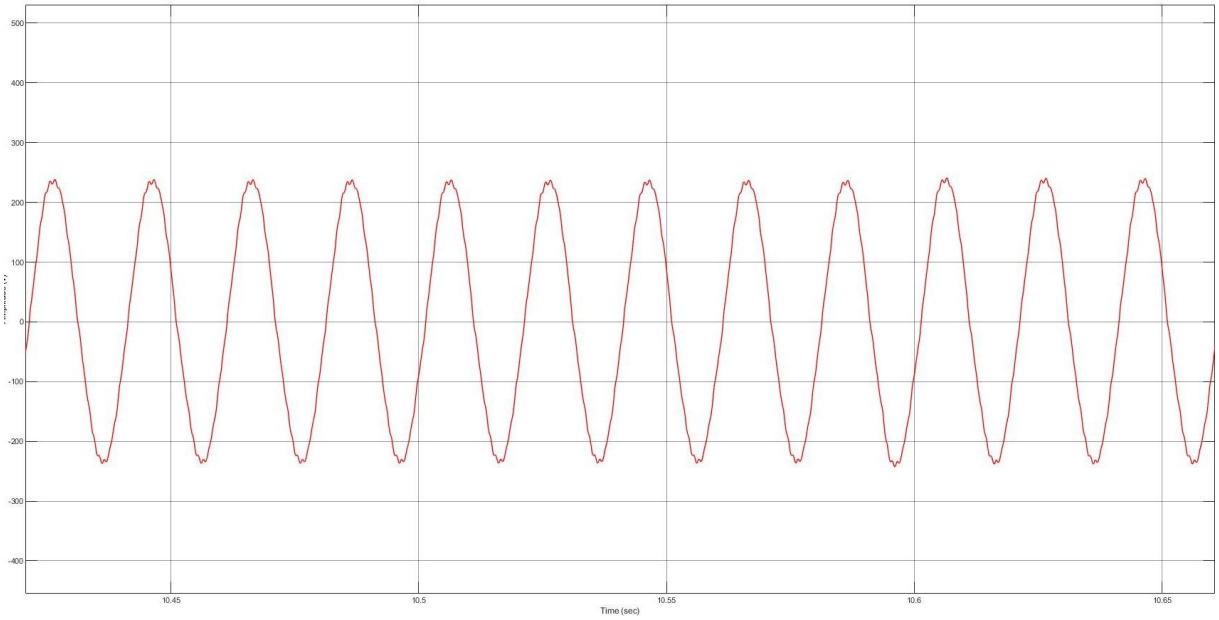


Fig II.30: Output for SBC Voltage With filter

II.6.3 Max Boost Control (MBC):

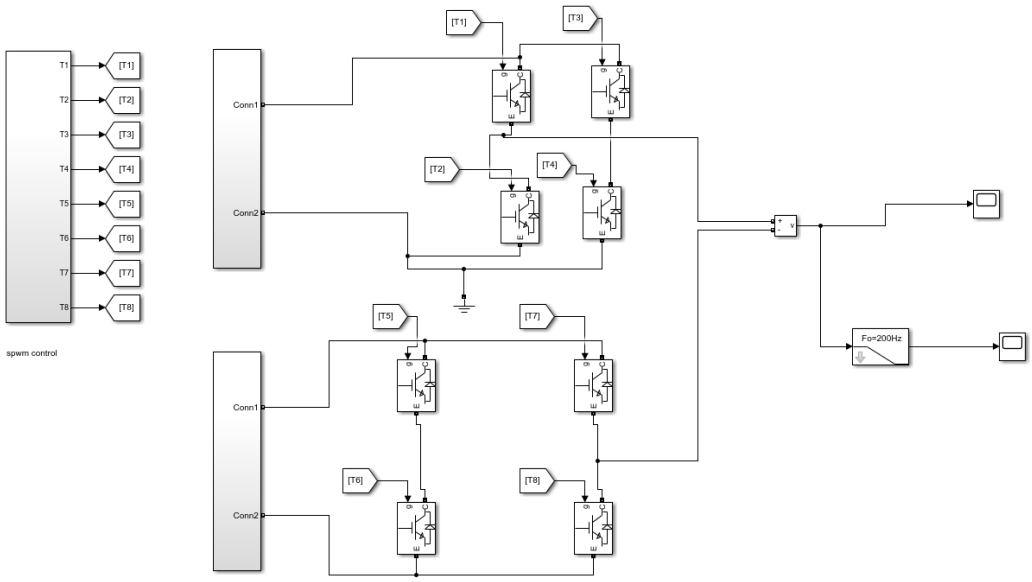


Fig II.31: Simulink model of MBC with z source

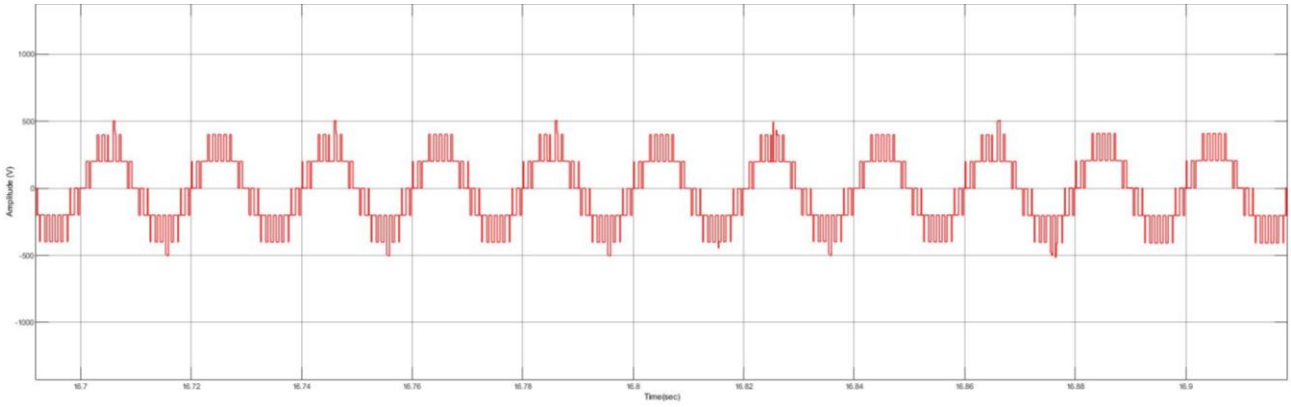


Fig II.32: Output for MBC Voltage Without filter

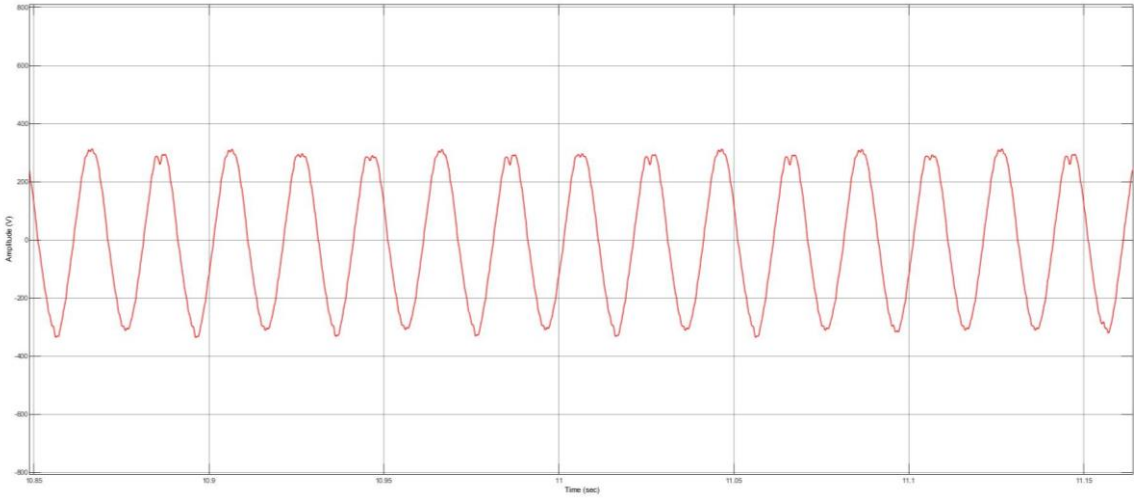


Fig II.33: Output for MBC Voltage With filter

II.7 Conclusion:

This chapter explored the realm of multilevel inverters and DC-DC inverters, highlighting the unique capabilities of the Z-source inverter. We delved into the theoretical framework of multilevel inverters, appreciating their ability to generate high-quality output waveforms with reduced harmonic distortion (THD) compared to traditional two-level inverters.

The Z-source inverter emerged as a game-changer, offering a distinct advantage with its integrated impedance network. This network empowers the Z-source inverter to achieve buck-boost functionality, enabling it to operate with a wider range of input voltages. This feature proves particularly valuable in systems powered by renewable energy sources, where the input voltage can fluctuate.

To solidify our understanding, we embarked on simulations of the Z-source inverter. These simulations not only provided a visual representation of its operation but also allowed us to compare the performance of two prominent control strategies: Simple Boost Control (SBC) and Maximum Boost Control (MBC). The simulations helped us grasp the trade-offs between these control methods, with SBC offering simplicity and MBC achieving higher voltage gain.

Chapter III:

Simulation results

IV.1 BLOCK DIAGRAM OF THE PROPOSED TOPOLOGY

A new topology of a cascaded three-phase inverter is proposed in order to improve the quality of output waveform and by reducing the harmonics at the output current and voltage.

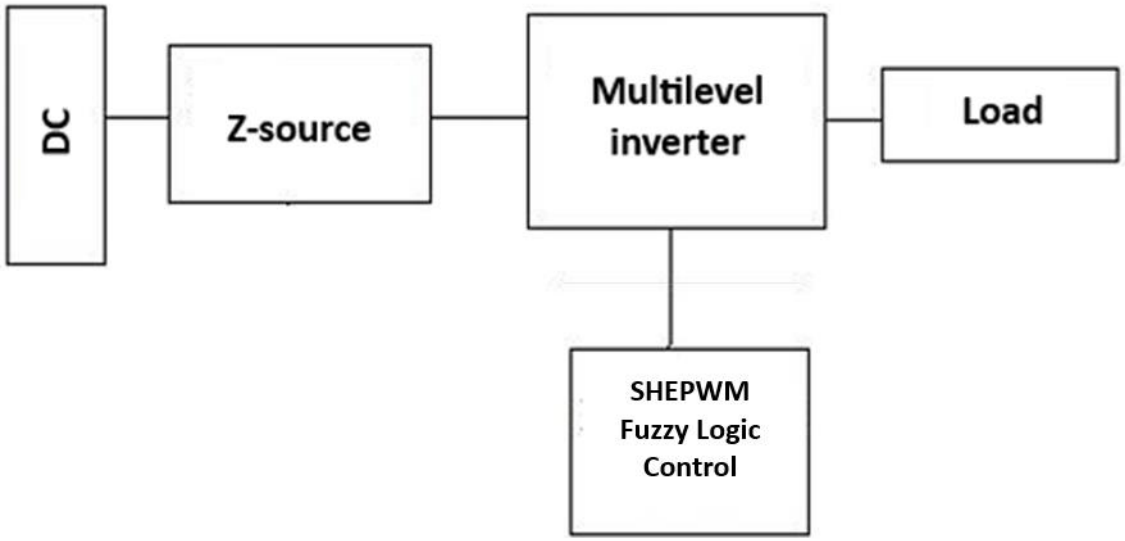


Fig III.1: Block diagram of the proposed model

A three-phase inverter system is built by connecting three identical sections, one for each phase (A, B, and C). Each section consists of two cascaded stages, like building blocks. These stages use H-bridge inverters (like HB1 and HB2 for phase A) and are powered by separate DC sources. A Z-shaped circuit made of capacitors and inductors sits before each stage. All six inverter circuits are independent and identical.

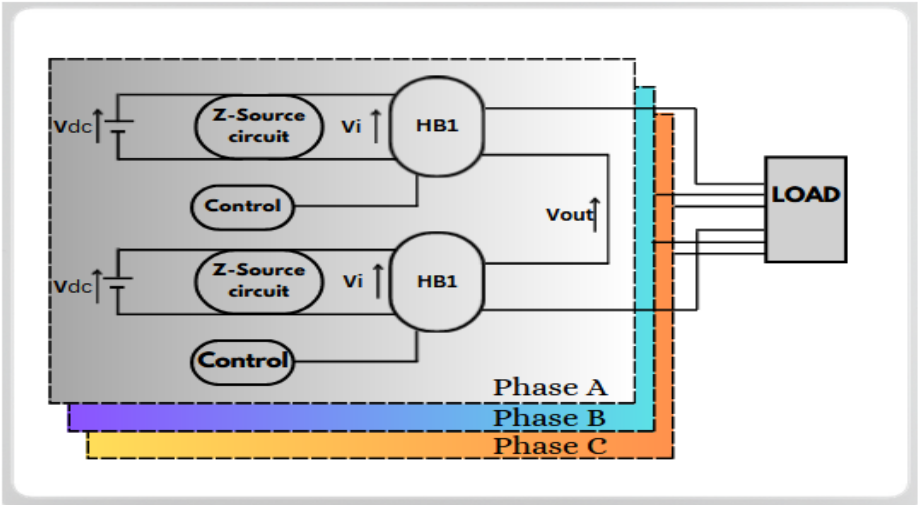


Fig III.2: Three-Phase System Generator

We can zoom in on one such stage, for instance HB1 in phase A. The voltage output from this stage is what we're interested in. This particular stage, which acts as a basic building block, includes a DC power source, a Z-shaped circuit, and a two-level H-bridge inverter. The

design of the inductors and capacitors in the Z circuit is crucial for the system to function properly.

The proposed inverter is connected with the system components as shown in the block diagram (Figure III.1) and the SHEPWM generator by using the Fuzzy logic controller has been implemented with a load connected at the inverter output.

IV.2 Selective Harmonic elimination SHE

Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) aims to eliminate specific harmonics from the output voltage waveform, ensuring only desired harmonic components are present. This is achieved by strategically determining the switching instants of the inverter switches, which results in a waveform meeting specified harmonic content requirements. By carefully selecting these switching angles, targeted harmonics can be suppressed, leading to a nearly sinusoidal output.

For example, consider applying SHEPWM to a three-phase inverter with the goal of eliminating harmonics such as n=3, 5, 7, 11, and 13 from the output voltage waveform. The method involves calculating precise switching angles that achieve this harmonic elimination.

The waveform generated by SHEPWM exhibits a quarter waveform with six edges and multiple levels. It represents the supply voltage of the H-Bridge inverter, which in this case corresponds to the output voltage Vi of the Z-impedance circuit.

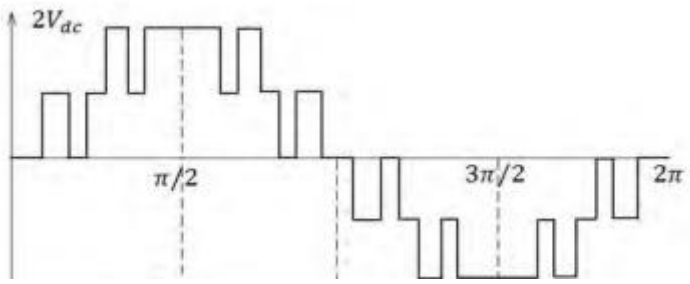


Fig III.3: Proposed Signal

The Fourier transform for the signal is given by equation ():

$$f(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t) \quad \textbf{(III.1)}$$

where the coefficients a_n and b_n are determined by equations (**III.2**) and (**III.3**):

$$a_n = \frac{1}{T}\int_0^T f(t)\cos n\omega t \, dt \quad \textbf{(III.2)}$$

$$b_n = \frac{1}{T}\int_0^T f(t)\sin n\omega t\, dt \quad \textbf{(III.3)}$$

Here, T represents the signal period. For our specific signal $f(t)$:

$$a_0 = 0,\ a_n = 0$$

b_n (given by (**III.4**))

exists for odd harmonics. The coefficient b_n is determined by:

$$b_n = 4E[\cos n\alpha_1 - \cos n\alpha_2 + \cos n\alpha_3 + \cos n\alpha_4 - \cos n\alpha_5 + \cos n\alpha_6] \quad \textbf{(III.4)}$$

Six switching angles can eliminate five specific harmonic components, or one angle degree is used to control the magnitude of the fundamental voltage. Incorporating additional switching angles can eliminate more harmonic components.

To eliminate harmonics $n = 3,5,7,11,$ and 13, SHEPWM involves solving a system of nonlinear equations to determine the optimal switching angles, given by (**III.5**):

$$\begin{cases} \cos\alpha_1 - \cos\alpha_2 + \cos\alpha_3 + \cos\alpha_4 - \cos\alpha_5 + \cos\alpha_6 = r\pi \\ \cos 3\alpha_1 - \cos 3\alpha_2 + \cos 3\alpha_3 + \cos 3\alpha_4 - \cos 3\alpha_5 + \cos 3\alpha_6 = 0 \\ \cos 5\alpha_1 - \cos 5\alpha_2 + \cos 5\alpha_3 + \cos 5\alpha_4 - \cos 5\alpha_5 + \cos 5\alpha_6 = 0 \\ \cos 7\alpha_1 - \cos 7\alpha_2 + \cos 7\alpha_3 + \cos 7\alpha_4 - \cos 7\alpha_5 + \cos 7\alpha_6 = 0 \\ \cos 11\alpha_1 - \cos 11\alpha_2 + \cos 11\alpha_3 + \cos 11\alpha_4 - \cos 11\alpha_5 + \cos 11\alpha_6 = 0 \\ \cos 13\alpha_1 - \cos 13\alpha_2 + \cos 13\alpha_3 + \cos 13\alpha_4 - \cos 13\alpha_5 + \cos 13\alpha_6 = 0 \end{cases} \quad \textbf{III.5}$$

Using PSO Algorithm and F-solve on Matlab we could solve this nonlinear equation to obtain good switching angles for the signal.

For r=0.868 We obtained:
α_1=12.8288; α_2=21.4745 ; α_3=33.5524 ; α_4=59.9027; α_5=60.8137 ; α_6=86.6198 ;

By carefully controlling the timing of the converter switches (represented by the angles), we can create an output voltage waveform that closely matches a desired signal. This technique allows us to eliminate specific harmonic frequencies that might be undesirable in the final output.

IV.3 Fuzzy Logic Controller

Fuzzy Logic Control (FLC) technique has been developed due to the reason; complex and nonlinear behavior of the structure. A new language was introduced to explain the fuzzy behaviors of reality, which are very difficult. Sometimes they are even unattainable to be illustrated by using conventional methods. Fuzzy set theory has been extensively used in the control area with some application to DC-AC inverter system. A simple fuzzy logic control is built by a set of rules to generate SHEPWM signals which are based on human knowledge of the system behavior. Matlab/Simulink model is built to study the performance of the proposed

controller to generate SHEPWM gate signals for controlling the output voltages. In addition to this, a design of fuzzy logic controller can provide a desirable output performance of SHEPWM signals which are not possible with the linear control techniques. As a result, a fuzzy logic controller has the potential to improve the performance. The proposed fuzzy logic controller is shown in Figure 3.2 and it consists of four major components such as: a fuzzifier which is used to convert input data into suitable linguistic values.

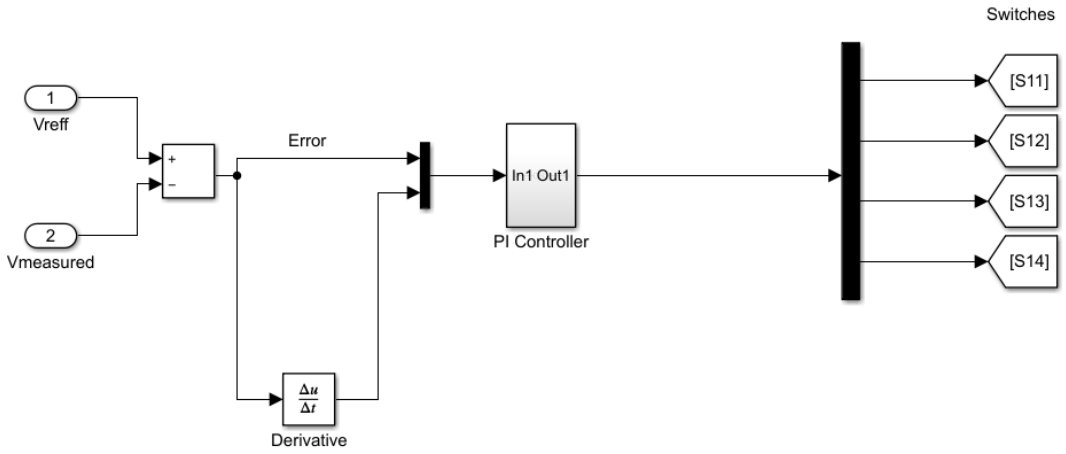


Fig III.4: Matlab structure of the proposed Fuzzy logic controller

A knowledge based logic which consists of a data base with the important linguistic definitions and the control rule set. A decision-making logic which is used for simulating a human decision making process and to infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions. A defuzzifier yields a non fuzzy control action from an inferred fuzzy control action.

The fuzzy control scheme is based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any mathematical model. Simulation has been conducted to verify the proposed fuzzy logic controller.

IV.3.1 Fuzzification Components

A fuzzy controller applies fuzzy rules and they are linguistic if-then statements involved the fuzzy sets, fuzzy inference and fuzzy logic. The Fuzzy rules play an important role in significance of expert control or modelling of knowledge and experience. It also used for connecting the input variables of fuzzy controllers to the output variables. Mamdani fuzzy rules are the major types of fuzzy rules exist and also it is widely used fuzzy inference system. The Mamdani type fuzzy inference system is performed in the following three steps[1]

- Fuzzification of the crisp input variables
- Decision making and Rule evaluation
- Fuzzy outcome

IV.3.2 Fuzzification of the Crisp

Input Variables The inputs and output of the fuzzy controller are not quantified in the traditional sense that each input or output is transferred a 'membership grade' to each fuzzy set. The universe of stated (range) input is divided into several fuzzy sets of required shapes. Each one input of fuzzy controller has several membership functions. The membership function is also called as label. A group of membership functions forms a fuzzy set. Here, five membership functions labeled as error negative high, negative medium, negative small,zero,positive small, positive medium and positive high. Basically, the seven membership functions have the labels as following. It means that the span from the data range's minimum point (negative high) to its maximum point (positive high):

- negative high (nh)
- negative medium (nm)
- negative small (ns)
- zero (z)
- positive small (ps)
- positive medium (pm)
- positive high (ph)

Output is also mapped into several fuzzy regions of desired shapes (for Mamdani type fuzzy systems). Here seven triangular fuzzy sets are chosen as shown in Figure.3.3 as input functions. These are defined by the fuzzy membership library functions for the error e and error derivative

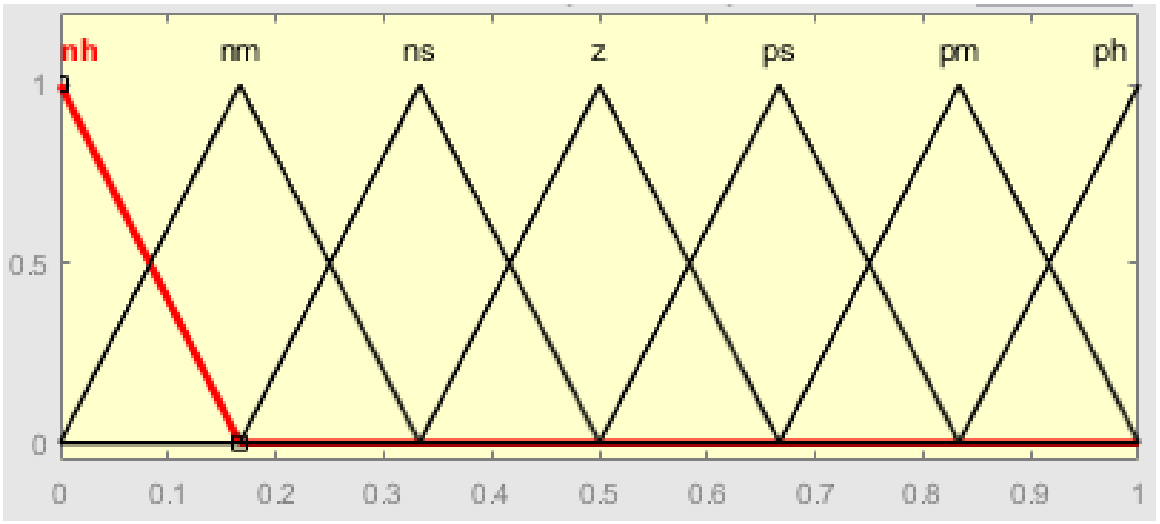


Fig III.5: Fuzzy membership functions for Input

IV.3.3 Decision making and Rule evaluation Mechanism of FLC

The fuzzy rules are in the form of Ri: If e is Ai and Ce is Bi, then Cs is Ci where Ai, Bi and Ci are fuzzy subsets in their universe of discourse. The formation of fuzzy control system for inverter is heuristic in nature and is based on the following conditions:

1. When the output of the inverter deviates far from the reference, the compensating signal/change of modulating signal must be large so as to bring the output to the reference quickly.
2. When the output of the inverter is approaching the reference, a small change of modulating signal is necessary. When the output of the inverter is near the reference and is approaching it rapidly, the modulating signal must be kept constant so as to prevent further deviation.
3. When the reference is reached and the output is still changing, the modulating signal must be changed a little bit to prevent the output from moving away.
4. When the reference is reached and the output is steady, the modulating signal remains unchanged.
5. When the output is larger than the reference, the amplitude of modulating signal must be decreased and vice versa.

Since the incidental output is a linguistic result, a defuzzification operation is performed to obtain a crisp result. The output of the inference mechanism is fuzzy output variables. The fuzzy logic controller must convert its internal fuzzy output variables into crisp values so that the actual system can use these variables. This conversion is called defuzzification. One may perform this operation in several ways. The max criterion method (MAX) is most commonly used control defuzzification strategy. The max criterion produces the point at which the membership function of fuzzy control action reaches a maximum value [2]

IV.3.4 Outcome of Fuzzy Controller

The inverter output voltage required for the proposed method is sensed and scaled to the value of per unit for 48 volt as base voltage and it calculates the error between actual value and the set value. This result decides the main fuzzy rules of the proposed system. The output of the fuzzy sets for the defined membership functions is shown in Figure 3.4. The Fuzzy logic controller operates with the help of these rules and they are related to the rate of change of the set or actual offset and it allows a very smooth regulation of voltage rating. Input data of the offset value has been calculated by taking relative voltage difference between the actual voltage and to the set value as described below: Error (E) = (Actual voltage of the system) - (Set value)

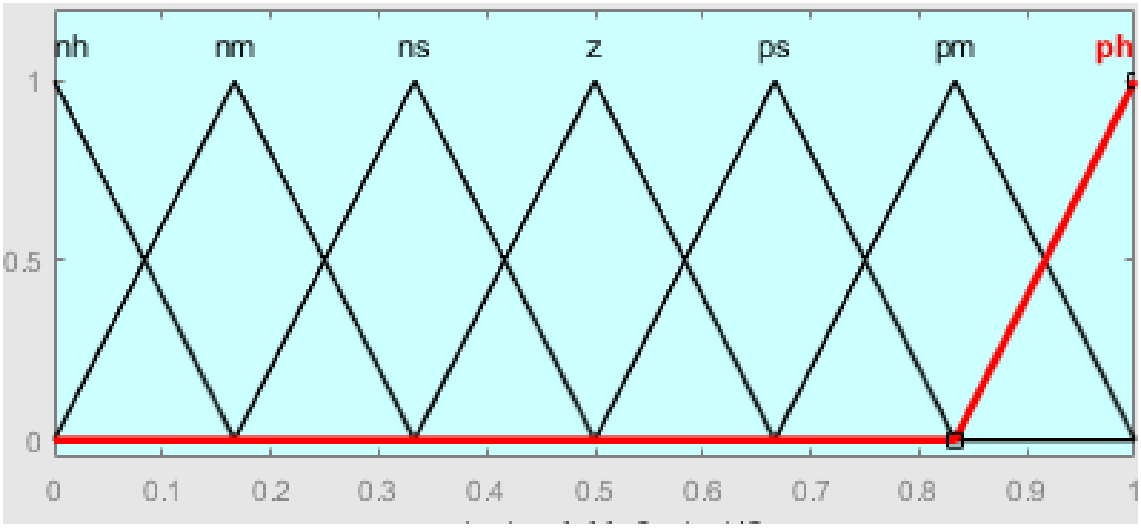


Fig III.6: Output Membership functions for change in modulating signal

Advantages of Mamdani Method

- It is well suited to human feeling
- It has widespread acceptance
- It is intuitive and simple to build
- It is widely used for second order systems with both linear and nonlinear characteristics.

IV.4 SUMMARY AND DISCUSSION:

IV.4.1 Simulink Model of the PI Controller

The Matlab /Simulink (2020a) design of the proposed PI controller is shown in Figure 3.5. The model consists of one H-bridge module, pulse width modulation with a PI controller. In this method, The reference voltage has a direct link with the amplification coefficient B. The control system is conventional, based on a proportional-integral (PI) controller. An output E from the PI controller will be compared with the triangular sequence that appears exclusively at the moment of short-circuit application. Now, the simulation was performed by implementing the PI controller. The output voltage for the resistive load is shown in Figure 3.6. It is obtained as the staircase waveform with a seven level output without using filter.

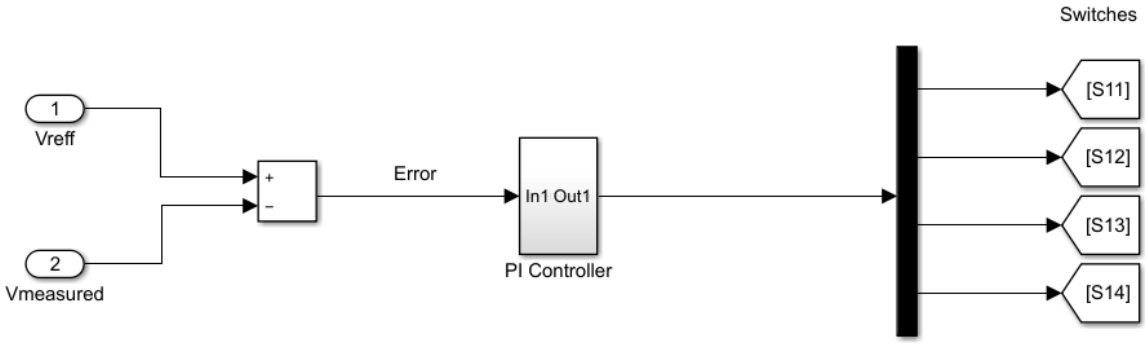


Fig III.7: Matlab model for PI controller

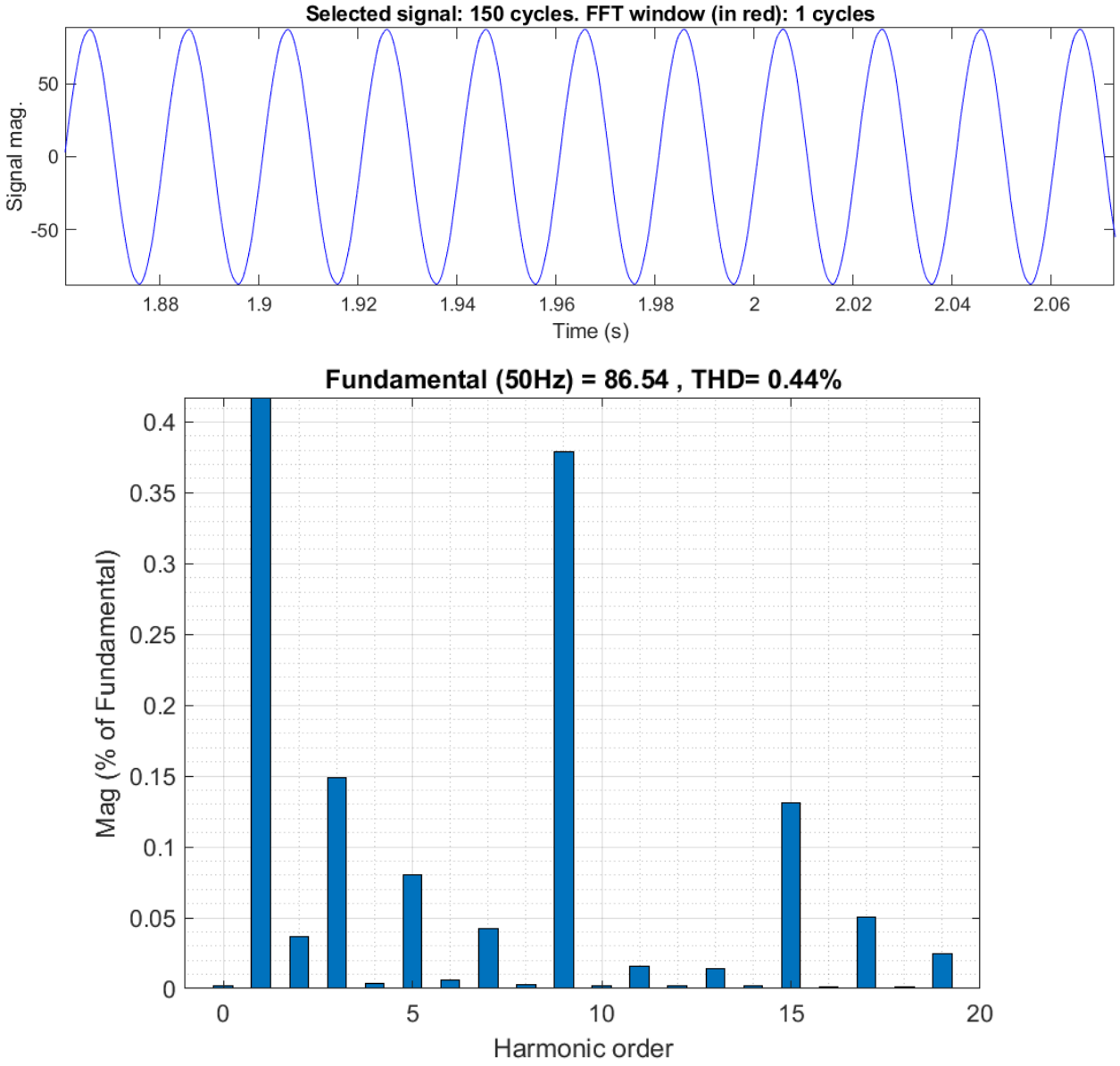


Fig III.8: Load voltage and FFT analyser with PI controller

The voltage THD of PI controlled inverter at the output is observed as about 0.44% for sine wave with 86.54 volts of peak output voltage equal to a frequency at 50 Hz. The Load voltage and FFT analyzer for full load of PI controlled inverter implemented with a LCL filter.

IV.4.2 Simulink of Fuzzy Logic Controller

The system is implemented by applying the fuzzy tools in Matlab 2020a, with fuzzy logic controller as shown in Figure 3.. The FLC is implemented with Mamdani style fuzzy inference system.

A simple fuzzy logic control is built by a set of rules to generate SHEPWM gate signals which are based on human knowledge of the system behavior. Matlab/Simulink model is built to

study the performance of the proposed controller to generate SHEPWM gate signals for controlling the output voltages.

The Matlab/Simulink block diagram is described as in the Figure 3.7 and the output voltage of the fuzzy controlled inverter for the load is shown in Figure 6.8.

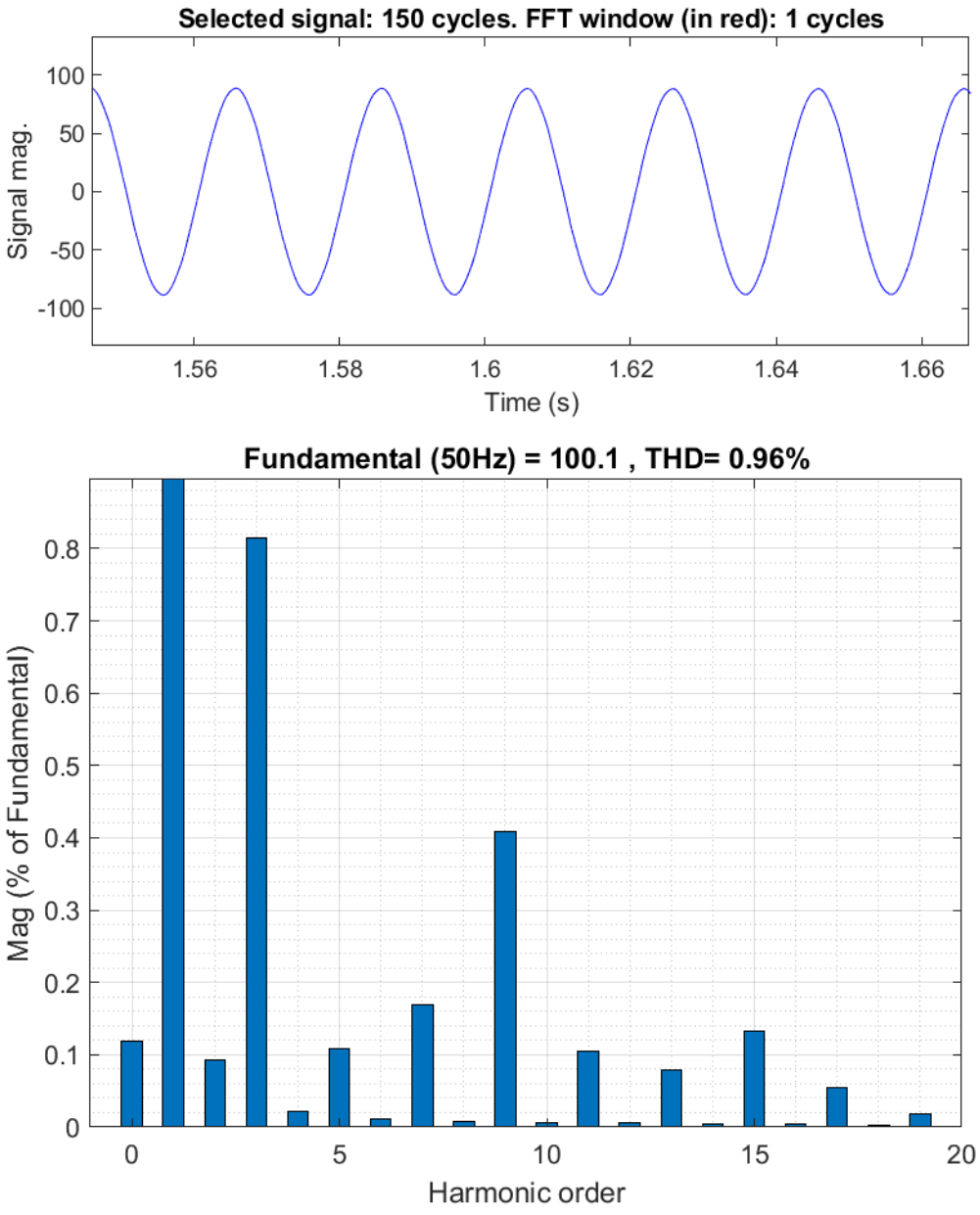


Fig III.9: Load current and FFT analyzer of inverter with fuzzy logic controller

The Figure 3.8 shows that the output of the inverter is a sinusoidal wave with a peak output voltage of 100.1 volts with the frequency of 50 Hz. It is also observed that the THD is 0.96 %

IV.5 Comparisons of output performance

	Methode of control	**THD %**
1	**Fuzzy Logic Controller**	**0.96**
2	**PI Controller**	**0.44**

Table 3.1 :Comparisons of output performance between PI controller and Fuzzy controlled inverter

From the observation and analysis mentioned in the Table 3.1, it is noted that the use of PI controller gave a good result which is better than the performance of fuzzy logic controller.

General Conclusion

This master's degree project focused on enhancing the performance, efficiency, and stability of an electric vehicle (EV) through innovative control strategies using a Z-source inverter with Sinusoidal Pulse Width Modulation (SHEPWM) technique. The study explored two distinct control approaches: a Fuzzy Logic Controller (FLC) and a Proportional-Integral-Derivative (PID) controller.

The study successfully demonstrated that the Z-source inverter, combined with the SHEPWM technique, offers significant advantages over traditional inverters by providing a single-stage power conversion with the capability to boost and invert the voltage. This unique feature significantly improves the overall efficiency and reliability of the EV's powertrain system.

The implementation of the Fuzzy Logic Controller provided adaptive control, showcasing its ability to handle the nonlinearities and uncertainties inherent in EV operations. The PID controller, on the other hand, offered precise control and stability, ensuring smooth and responsive performance.

Despite the successes, this study also identified several areas for future research. These include the need for further optimization of the FLC parameters for even better performance, and the exploration of real-time implementation challenges in practical EV systems. Additionally, integrating renewable energy sources with the Z-source inverter and extending the control strategy to multi-level inverters could further enhance the potential of this approach.

Overall, this project not only fulfills the academic requirements but also makes a significant contribution to the field of electric vehicle technology. The findings underscore the potential of advanced inverter and control technologies in paving the way for more efficient, reliable, and high-performance EVs. It is anticipated that this research will inspire further innovations and developments in the quest for sustainable and smart transportation solutions.

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