Control and Integration of Flywheel Energy Storage System

A

Thesis

Submitted in partial fulfillment of the requirements for the

Degree of

MASTER OF TECHNOLOGY

by

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June. 2024

Declaration

This is to certify that the thesis entitled "**Control and Integration of Flywheel Energy Storage System**", submitted by me to the Indian Institute of Technology Guwahati, for the award of the degree of M.Tech, is a bonafide work carried out by me under the supervision of **Prof. Harshal B. Nemade** and **Prof. Rajiv Tiwari**. The content of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree.

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Certificate

This is to certify that the work contained in this thesis entitled "**Control and Integration of Flywheel Energy Storage System**" is a bonafide work of **Satyam Mishra** (**Roll No. 224102108**), carried out in the Department of Electronics and Electrical Engineering, Indian Institute of Technology, Guwahati. We hereby accord our approval of it as a study carried out and presented in a manner required for its acceptance in partial fulfillment for the Post Graduate Degree for which it has been submitted. The thesis has fulfilled all the requirements as per the regulations of the Institute and has reached the standard needed for submission.

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Abstract

The Flywheel Energy Storage System (FESS) offers several significant advantages over traditional energy storage systems, such as battery energy storage systems. Notably, FESS exhibits a rapid dynamic response, making it highly suitable for applications requiring quick energy absorption and release. Its extended service life is another key benefit, with minimal degradation over time compared to batteries. Additionally, FESS allows for unrestricted charge and discharge cycles, ensuring continuous and reliable performance without the limitations seen in chemical-based storage systems.

This study presents the implementation of a two-stage power converter within a Flywheel Energy Storage System (FESS). The converter comprises an AC-DC converter with filter capacitance, a brake chopper, and a DC-AC converter interfaced with a motor load. Initial simulations of the open-loop operation of the converter with the motor were performed in MATLAB (2022b) Simulink. Following successful simulation results, a hardware setup was constructed, utilizing a Permanent Magnet Synchronous Motor (PMSM). The PMSM is integrated with the FESS, establishing a practical framework for energy storage and conversion. This research bridges the gap between theoretical modeling and practical implementation, providing a foundation for advanced energy storage solutions in grid and renewable energy applications.

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Chapter 1

Introduction

This chapter initially discusses the history of the flywheel energy storage system and the control strategy of Grid side converter (GSC) or (AC-DC) converter and Machine side converter (MSC) or (DC-AC) converter and also discusses the basic theory of Permanent magnet synchronous motor(PMSM) will also be introduced in this chapter. the motivation and goals of the work done and to be done during this study are then presented in the next section. After that open loop simulation of the converter and control of FESS and Hardware implementation is also discussed.

Flywheel energy storage system (FESS) and its plausible application within the power grid domain. In this context, FESS emerges as a promising and viable solution, primarily owing to its distinctive advantages over alternative energy storage systems. These advantages include its rapid dynamic response, prolonged service life, unrestricted charge and discharge cycles, and notably high power density.

Furthermore, the introduction sheds light on a fundamental component of the FESS, namely the GSC, delineating its pivotal role as the interface between the system and the power grid. Emphasizing its significance, the paper elaborates on the GSC's responsibility in managing the power flow between the FESS and the grid, as well as its crucial function in maintaining a stable and consistent DC voltage level within the FESS. [3]

The introduction provides an overview of the importance of FESS in modern power systems and the challenges it faces during grid-connected operations. It also highlights the need for an effective control strategy to ensure the stable and safe operation of FESS during grid voltage disturbances. [4]

1.1 Background

A flywheel energy storage system is a device that stores kinetic energy in the form of a rotating mass. It serves as a mechanical battery, where energy is stored in the form of rotational motion. When energy is needed, the flywheel releases its stored energy to perform useful work. Flywheels store energy by increasing the rotational speed of a spinning mass. The amount of energy stored is proportional to the square of the rotational speed (ω) and the moment of inertia (J) of the flywheel.

$$E = \frac{1}{2} J\omega^2 \tag{1.1}$$

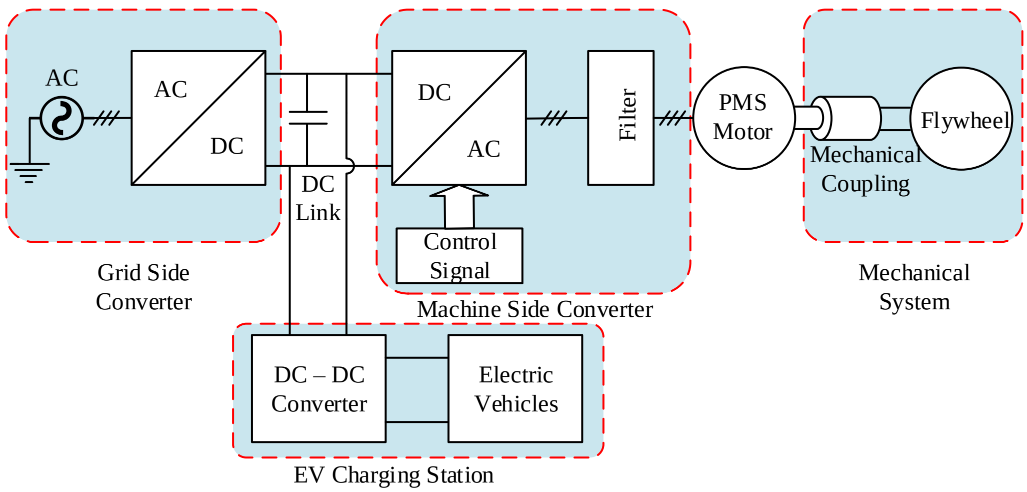


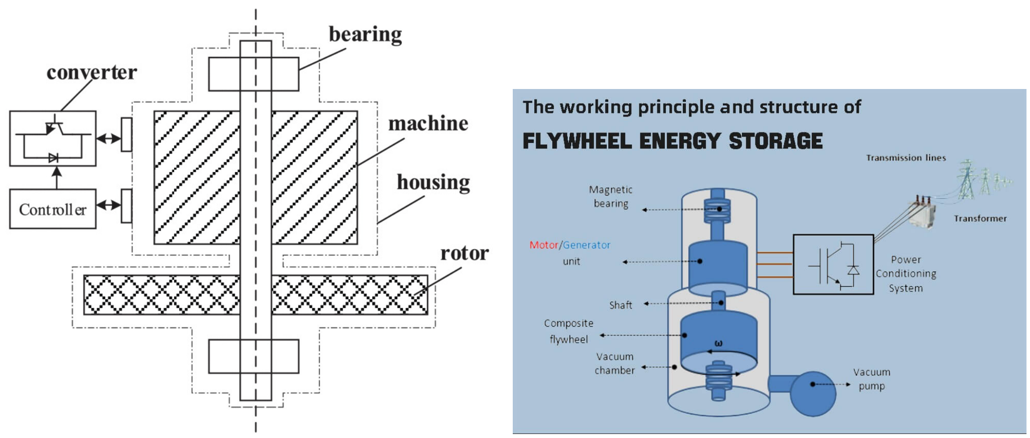
Figure 1.1: General block diagram for the Converter & control of Flywheel energy storage system.

1.2 Control strategy

The GSC control strategy serves as the power exchange interface between the FESS and the power grid. It maintains stable operation of the FESS during grid integration and minimizes grid impact by controlling DC voltage and reactive power output. The MSC control strategy, on the other hand, regulates active power to meet grid power requirements. It employs a power loop and a current loop for responsiveness and overcurrent protection. Both control strategies ensure high-frequency power regulation while maintaining stability and minimizing grid impact.

1.3 Flywheel Energy Storage System

Flywheel energy storage is a method of mechanical energy storage that utilizes the rotational energy of a spinning flywheel to store and release energy. It involves converting electrical energy into kinetic energy by accelerating a flywheel to high speeds, and then converting the kinetic energy back into electrical energy when needed.



(a) Structure of FESS (b) Application scenario of FESS

Figure 1.2: Flywheel. [1]

1.3.1 Applications:

Grid Stabilization: Flywheel systems can help stabilize electrical grids by providing rapid-response energy during fluctuations in demand.

Uninterruptible Power Supply (UPS): Flywheels are used in UPS systems to provide a short-term power backup in case of electrical grid failures.

Regenerative Braking: In transportation, flywheels can be used to store energy during braking and then release it to assist in acceleration, improving fuel efficiency. [5]

1.3.2 Skoda Citigo battery charging

Kinetic Power Booster Amplifying Electric Vehicle Charging Capabilities In areas where the local power grid struggles to deliver sufficient power, the innovative Kinetic Power

Booster (KPB) emerges as a game-changer for electric vehicle (EV) charging. This groundbreaking system taps into the grid during periods of excess energy consumption, utilizing this surplus to spin flywheels to exceptional speeds. This process effectively stores electrical energy in the form of kinetic energy.

When an electric vehicle connects to the KPB, the system harnesses the stored kinetic energy by gradually decelerating the flywheels, converting the rotational energy back into electricity. This efficient energy conversion enables the KPB to deliver double the charging power compared to what the local grid can provide.

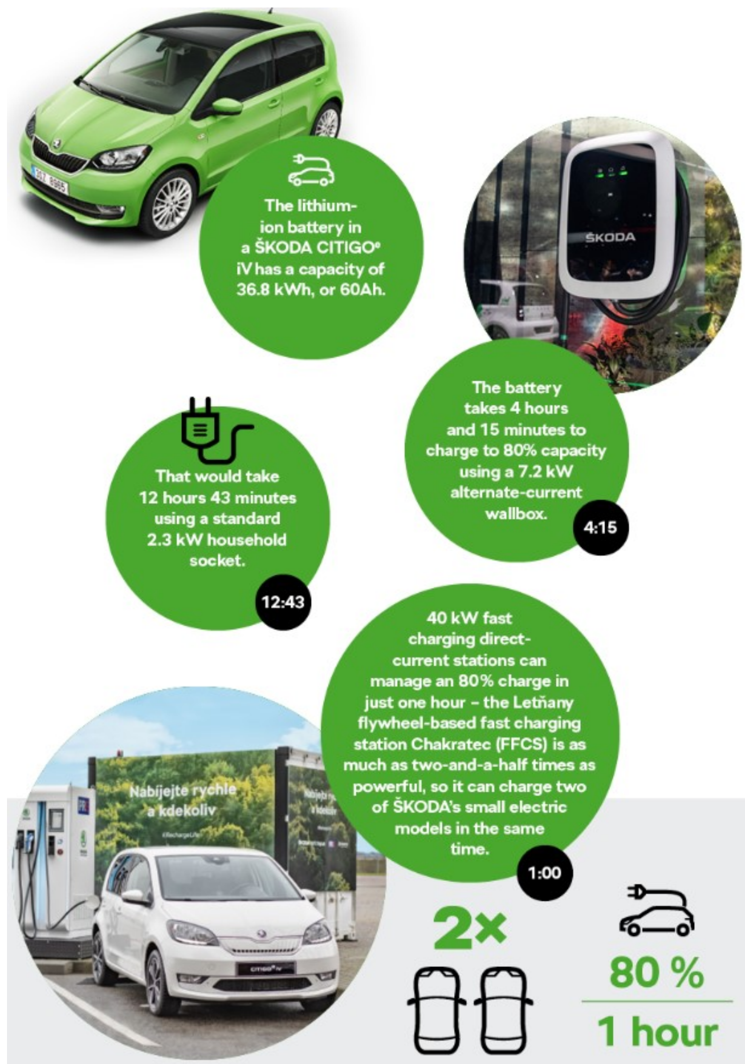


Figure 1.3: Skoda charging with different types of charger.
[4]

Chapter 2

Literature Review and Motivation

The history of the flywheel energy storage system is covered in this chapter, which is followed by a detailed introduction of AC-DC converter and DC-AC converter. Finally, some theoretical analysis of PMSM is represented.

2.1 Grid Side Converter (AC-DC converter)

The grid-side converter (GSC) plays a crucial role in ensuring the efficient and stable operation of the power grid. It maintains a constant DC voltage at a predetermined level, ensuring a reliable power supply to the grid. Additionally, the GSC regulates the active and reactive power to achieve unity power factor, minimizing losses and maximizing power transfer efficiency. This contributes to grid stability and efficient power utilization, making the GSC an indispensable component in modern power systems. [6]

To precisely quantify the expression of the grid-side active power formula:

$$P_g = 1.5 * U_{gd} * I_{gd} \tag{2.1}$$

Here, 'U_{gd}' represents the d-axis component of the GSC's output voltage, whereas 'I_{gd}' signifies the d-axis component of the GSC's output current.

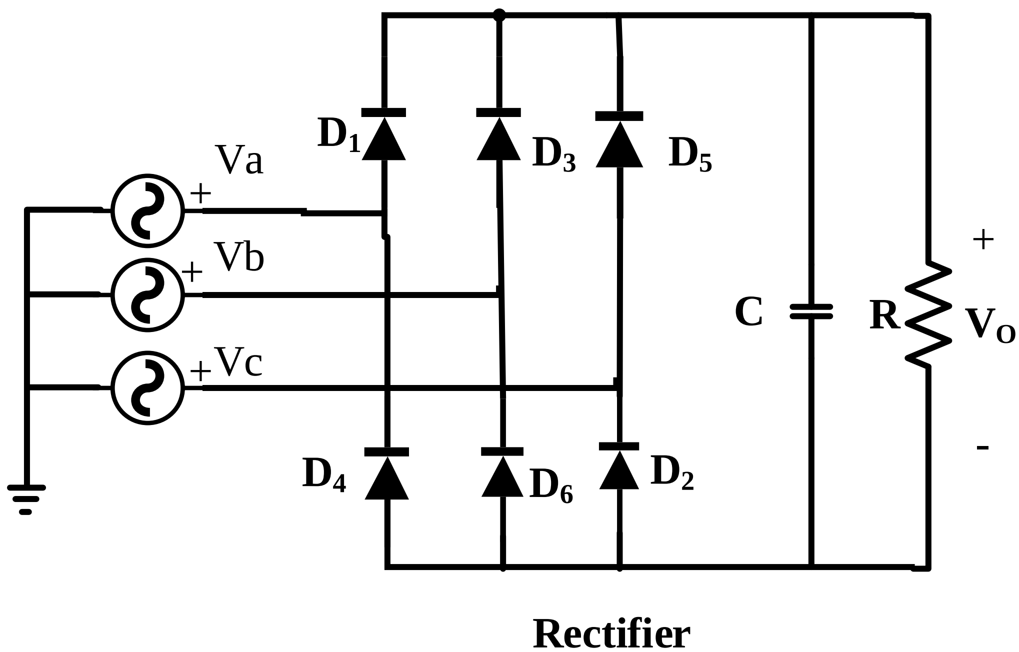


Figure 2.1: Circuit diagram of AC-DC converter with filter capacitance

2.2 Machine Side Converter (DC-AC converter)

The machine-side converter (MSC) plays a pivotal role in regulating the rotor speed during startup and enabling bidirectional power flow.

The MSC's ability to manipulate the rotor voltage and frequency stems from its bidirectional power conversion capability. By injecting or absorbing power from the rotor circuit, the MSC can either accelerate or decelerate the rotor, effectively controlling its speed. This bidirectional power flow also enables the FESS to operate in both generating and motoring modes, allowing for power transfer in both directions between the generator and the grid.

Key Functions of MSC in FESS Systems

1. **Startup Speed Control:** The MSC regulates the rotor speed during startup, ensuring a smooth and efficient transition to synchronous operation.

2. **Bidirectional Power Regulation:** The MSC enables bidirectional power flow, allowing the FESS to operate as both a generator and a motor.

3. **Reactive Power Compensation:** The MSC can adjust the reactive power output of the FESS to maintain grid voltage stability. [7]

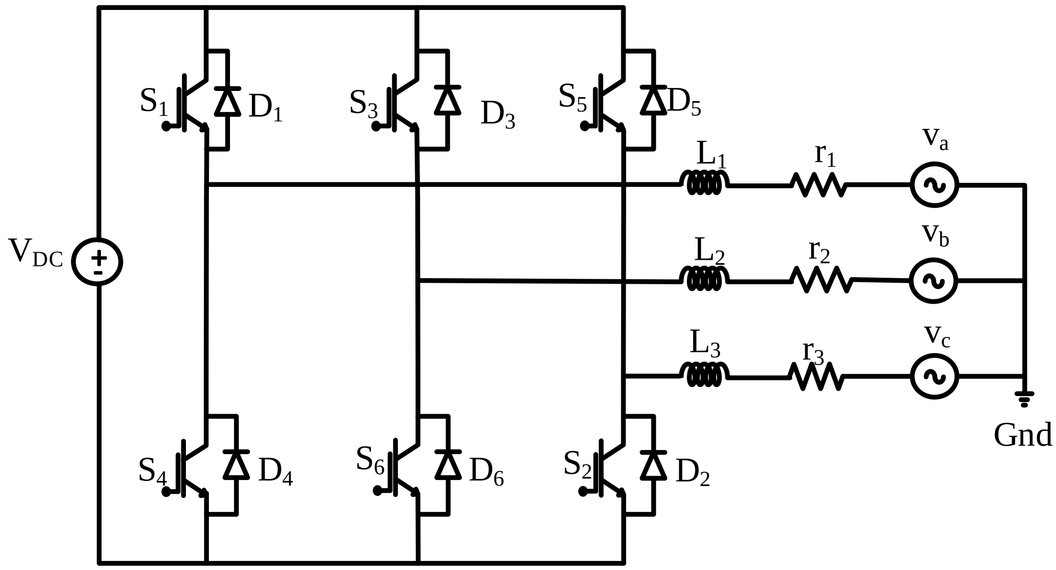


Figure 2.2: Circuit diagram of three phase AC-DC converter

2.3 Permanent Magnet Synchronous Motor (PMSM)

The PMSM is a rotating electrical machine that converts electrical power into mechanical power. It has permanent magnets embedded in the rotor that create a magnetic field that interacts with the rotating magnetic field of the stator, producing torque. A permanent magnet synchronous motor (PMSM) is a synchronous electric motor that uses permanent magnets instead of electromagnets to create the magnetic field in the stator. This makes PMSM more efficient and reliable than induction motors, and they are also often smaller and lighter.

The working principle of a PMSM is based on the interaction of two magnetic fields: the rotating magnetic field of the rotor and the stationary magnetic field of the stator. The rotor's magnetic field is created by permanent magnets, while the stator's magnetic field is created by coils of wire that are connected to an AC power source. When the two magnetic fields are aligned, the rotor is attracted to the stator and begins to rotate. [8]

2.4 Induction motor

Induction motors are fundamental to industrial applications, prompting extensive academic research aimed at improving their efficiency, performance, and reliability. Scholars focus on advanced control strategies such as sensorless control, model predictive control, and adaptive algorithms, which optimize motor performance without the need for physical sensors. Converter technologies, particularly matrix converters, are studied to enhance efficiency and power quality, especially in converting single-phase to three-phase power. Researchers also develop encoderless control methods for accurate speed estimation, reducing costs and increasing system robustness. Additionally, improving power quality in motor drives, especially from single-phase grids, by addressing harmonic distortion and ensuring stable operation is a significant area of investigation.

Addressing low-speed operation challenges, such as torque ripple reduction and precise speed control, is critical for optimizing motor performance. Academics also focus on enhancing the reliability and robustness of induction motors through fault detection algorithms, protection mechanisms, and fault-tolerant control strategies. This comprehensive research integrates control theory, power electronics, and motor design, forming a multidisciplinary approach that is essential for advancing the technology and application of induction motors. By addressing these various aspects, academic studies ensure that induction motors continue to meet the evolving needs of industrial sectors, enhancing their performance and reliability in diverse applications.

2.5 Flywheel Energy Storage System

Flywheel energy storage systems (FESS) offer unique advantages over other energy storage technologies, including high dynamics, long lifetime, and good efficiency. FESS devices excel in rapid response times, making them ideal for applications where power demand fluctuates. In microgrids, FESS can effectively manage peak load demands and store excess energy during low load periods. With increasing distributed energy sources, FESS can play a crucial role in maintaining grid stability by regulating voltage amplitude and frequency. Due to its ability to adapt to wind fluctuations, FESS is particularly wellsuited for wind energy storage. It also provides a reliable solution for critical load supply, ensuring short-term energy storage for local stability. While steady-state analysis of FESS has been extensively studied. [9]

2.5.1 Components of a Flywheel Energy Storage System

1. Flywheel: The core component, mainly a heavy rotor, that stores the kinetic energy.
2. Bearings: High-performance bearings minimize friction and allow the flywheel to spin with minimal energy loss.
3. Vacuum or Magnetic Enclosure: To reduce air resistance, flywheels are often enclosed in a vacuum or use magnetic levitation systems to minimize friction. [10]

2.5.2 Flywheel unit modelling

The rotational energy stored in the flywheel is defined as

$$E = \frac{1}{2} I \omega^2 \tag{2.2}$$

Where I is the moment of inertia. and I is directly proportional to the mass of the rotor by means of a constant that depends on the shape factor. ω is the angular velocity.

For a cylinder flywheel, the moment of inertia is determined by:

$$I = \frac{1}{2} \pi h \rho (r_0^4 - r_i^4) \tag{2.3}$$

Where the outer diameter and inner diameter are represented by r_0 and r_i, respectively. h is length and ρ is mass density. Thus

$$E = \frac{1}{4} \pi h \rho \omega^2 (r_0^4 - r_i^4) \tag{2.4}$$

The energy scales as ω^2. The flywheel with a larger angular velocity can store much more energy. But a small and light flywheel is preferable because it can operate at high stress levels.

2.5.3 Advantage & Disadvantage of FESS

Advantages of FESS	Disadvantages of FESS
Very high power density	Fatigue and mechanical stress limit
Very high cycle life	High losses in bearing if mechanical bearing is used
Can operates upto 20 years	Very hazardous if system fails
Can stores kilowatts to megewatts levels of energy	Very expensive
Very high tip efficiency	Short discharge time
No environmental impact	
Short recharge time	

Figure 2.3: Advantage and disadvantage of FESS [2]

2.5.4 Need for energy storage system

1. **Meeting peak demand:** Energy demand fluctuates throughout the cycle, with periods of high demand known as peak load. Traditionally, power plants have been designed to meet this peak demand by increasing generation. However, this approach is expensive and can lead to inefficient use of resources. Energy storage systems allow excess electricity generated during low-demand periods to be stored and released during peak demand, reducing the need for additional power generation capacity and ensuring a stable and reliable power supply.

2. **Integration of renewable energy:** Weather conditions have an impact on renewable energy sources like solar and wind power, which are unpredictable. They can produce sporadic amounts of power when the sun is shining or the wind is blowing.

3. **Grid stability and resilience:** Systems for storing energy contribute significantly to the stability and resilience of the grid. They can react quickly to shifts in the supply and demand for power, which helps to control the grid's frequency and voltage. [11]

4. **Electrification of transportation:** The need for energy storage systems is being driven by the increase in electric vehicles (EVs). Energy storage systems can effectively address the high power capacity needed for EV charging infrastructure.

2.6 Motivation

Motivation for Designing the Controller of Existing Flywheel Energy Storage System:

1. **Enhanced Energy Efficiency:**

   A dedicated controller provides the opportunity to fine-tune the operation of the Flywheel Energy Storage System, maximizing its energy efficiency and minimizing losses during charge and discharge cycles. This, in turn, contributes to a more sustainable and cost-effective energy storage solution.

2. **Grid Stability and Reliability:** The integration of an advanced controller aims to enhance the FESS's capability to support grid stability. By precisely managing the energy flow between the grid and the flywheel, the controller mitigates fluctuations, thereby contributing to a more reliable and resilient power supply.

3. **Adaptability to Grid Dynamics:** The design of a sophisticated controller enables the Flywheel Energy Storage System to adapt seamlessly to dynamic changes in the grid environment. This includes responding to sudden load variations, frequency fluctuations, and grid disturbances, ensuring a stable and uninterrupted power supply.

2.7 Control Strategy

During grid integration, the GSC maintains the FESS's DC voltage and regulates power flow, while the MSC controls active power to match grid requirements. The control strategy prioritizes seamless grid integration and stable FESS operation, enabling high-frequency power regulation without compromising grid stability.

2.7.1 Grid Side Converter and Control

The grid-side converter (GSC) control strategy represented in this file which serves a crucial function, aiming to offer vital reactive power support to the grid and facilitate the recovery of the grid-side voltage during instances of grid voltage disturbances.This strategy is meticulously devised to regulate the reactive current, thereby effectively managing and controlling the reactive power output of the flywheel energy storage system (FESS).

[12] Notably, the dynamic fluctuations in the active power of the machine-side significantly impact the control of the DC bus voltage by the GSC, necessitating adaptive adjustments in the control strategy of the machine-side converter (MSC). Consequently, the GSC's control strategy is tailored accordingly to accommodate these changes, ensuring optimal performance within the overall system framework. Moreover, the GSC's control strategy effectively modulates the reactive current to regulate the FESS's reactive power output, thereby contributing to the stabilization of the grid-side voltage and ensuring the uninterrupted operation of the system during grid voltage disturbances. This pivotal function plays a vital role in maintaining the system's resilience and stability, reinforcing its non-disruptive performance within the broader grid infrastructure.

Relation between Voltage (V_a, V_b, V_c) and Voltage (V_o, V_d, V_q) is $-$

$$\begin{bmatrix} V_o \\ V_d \\ V_q \end{bmatrix} = \sqrt{\frac{2}{3}} * \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ cos\theta & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin\theta & -sin(\theta - \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) \end{bmatrix} * \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2.5}$$

[13]

2.7.2 Machine Side Converter and Control

In the grid integration operation stage, the focus of the control strategy shifts towards the machine-side converter (MSC), which assumes the critical role of regulating the active power output of the flywheel energy storage system (FESS) to align with the power requisites of the power grid. The MSC control system adopts a dual-loop structure, with the power loop serving as the outer loop and the current loop functioning as the inner loop. This design choice facilitates enhanced responsiveness while effectively curbing any potential overcurrent occurrences within the motor winding. [14]

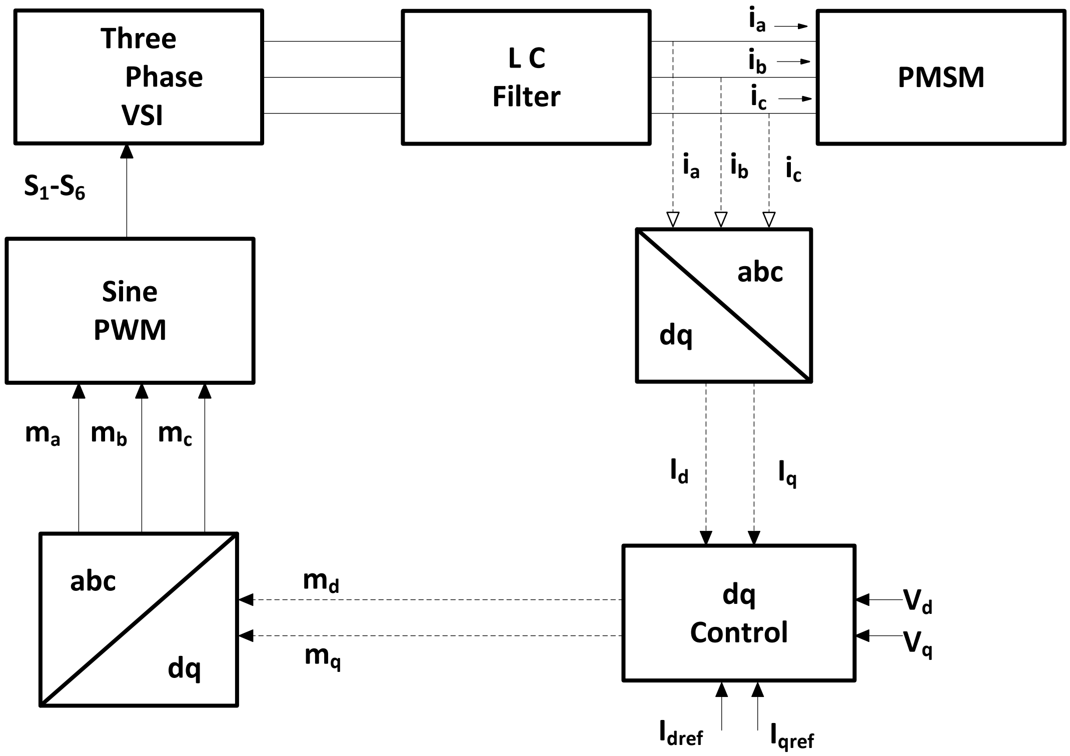


Figure 2.4: Closed loop control structural block diagram of MSC

The primary function of the power loop involves computing the active current of the flywheel machine, taking into account both the directives from the power grid and the operational status of the FESS. Simultaneously, the current loop operates to fine-tune the winding current to adhere closely to the reference instructions provided by the power loop. Importantly, the output limiting feature of the power loop serves to restrict the maximum output current flowing through the machine windings, thereby ensuring optimal operational safety measures. [2]

2.7.3 V/f control

V/F (voltage/frequency) control of Permanent Magnet Synchronous Motors (PMSMs) is a fundamental method used to regulate motor speed by maintaining a constant voltage-to-frequency ratio, ensuring stable magnetic flux and efficient operation. This approach is favored for its simplicity and cost-effectiveness, particularly in applications where precise speed and torque control are less critical. However, it is limited by less accurate performance at low speeds and slower dynamic response to load variations compared to advanced techniques like Field-Oriented Control (FOC) or Direct Torque Control (DTC). Despite these limitations, V/F control remains a practical solution for various industrial and commercial applications, such as HVAC systems, pumps, and household appliances, leveraging the inherent efficiency and consistent torque characteristics of PMSMs.

In V/F control, the frequency is varied using an Arduino through precise code adjustments. Specifically, in the Arduino code, we achieve frequency variation by systematically reducing the time interval for each cycle. For instance, if we decrease the time interval by 2ms increments, the frequency of the signal increases correspondingly. To maintain a constant voltage-to-frequency ratio (V/F), the supply voltage is also increased proportionally as the frequency rises, with the ratio maintained at 10 V/Hz. This ensures that for every 1 Hz increase in frequency, the voltage is increased by 10 V. By maintaining this V/F ratio, we ensure that the motor receives the appropriate voltage for each frequency, maintaining efficient and stable operation throughout the range of speeds. The Arduino-controlled adjustments enable precise and dynamic control of both the frequency and voltage, essential for effective V/F control of the induction motor.

Chapter 3

Simulation and results

Simulation is an invaluable tool for understanding, optimizing, and troubleshooting GSC and MSC. It's ability to predict performance, identify design flaws, and facilitate rapid prototyping makes it an indispensable asset in the development and deployment of these critical electronic components.

3.1 Permanent magnet synchronous motor

A three-phase diode AC-DC converter is an electrical circuit that converts three-phase alternating current (AC) into pulsating direct current (DC). It is commonly used in power electronics applications to provide a DC voltage source for various loads.

The working principle of a three-phase diode AC-DC converter based on the unidirectional conduction of diodes. Diodes allow current to flow in only one direction, from their anode to their cathode. Three-phase diode AC-DC converters are essential components in power electronics applications, providing a reliable and efficient means of converting three-phase AC power into pulsating DC power. Their higher output voltage, lower ripple, and improved efficiency make them a preferred choice for various applications

Here In my system, a rectifier converts the AC input to DC, which is then fed into a DC to AC inverter. The output of the inverter is filtered using an LC filter, comprising inductance and capacitance elements, to smooth the AC waveform and reduce harmonic distortion. This clean AC power is subsequently used to drive a permanent magnet synchronous motor (PMSM). The PMSM is mechanically coupled to a flywheel, which serves as an energy storage device, enhancing the stability and efficiency of the motor's operation. This configuration ensures efficient power conversion and stable operation of the motor-flywheel assembly, providing a reliable solution for energy management and mechanical drive applications

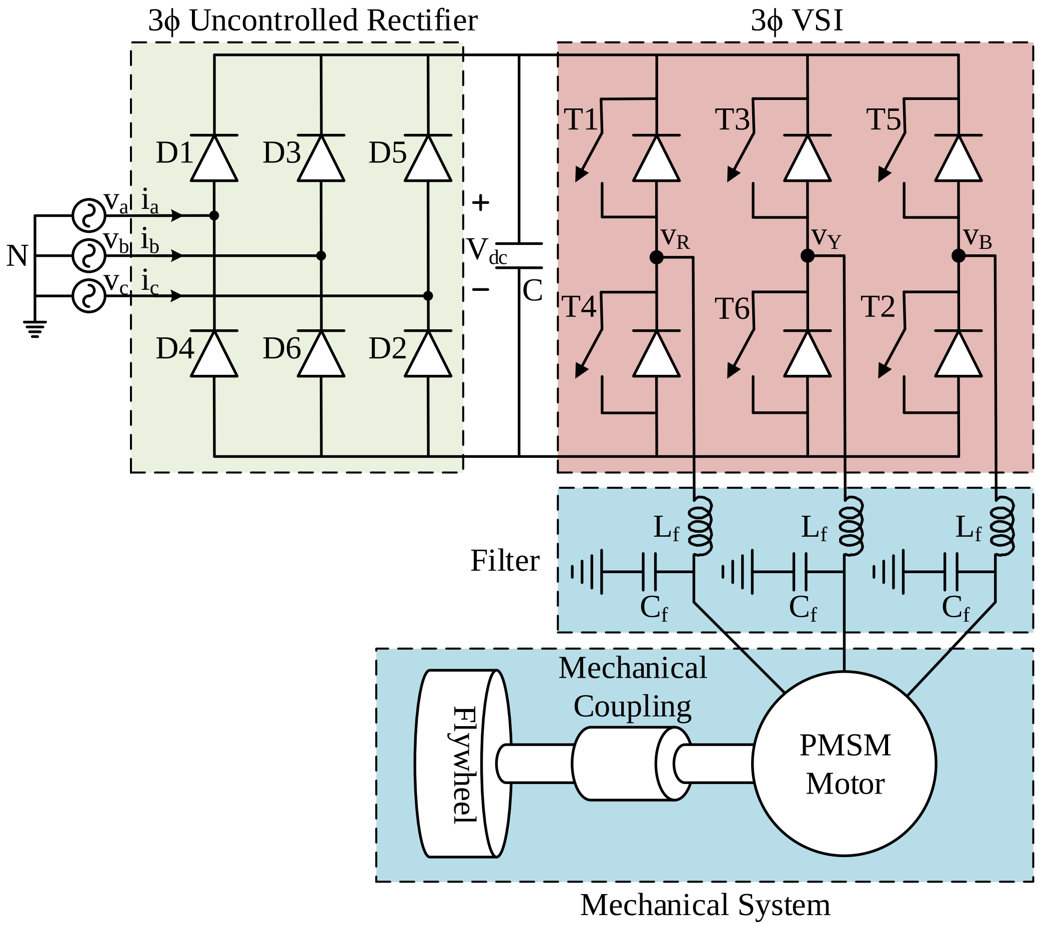


Figure 3.1: Schematic circuit diagram of PMSM

Parameters	**Value**	**Parameters**	**Value**
Grid line voltage	415 V	DC voltage	587 V
DC link capacitor	10 mF	Frequency	50 Hz
Inverter input voltage	587 V	Inverter RMS output voltage	479.3 V
Filter inductor of inverter	5 mH	Filter capacitor of inverter	2mF
THD without filter	31.22%	THD with filter	0.547%
Motor inertia	0.008 kg-m$\hat{2}$	Pole pair	2
Motor torque	5 N-m	Rotor speed	1500 RPM

Table 3.1: Open loop Simulation results

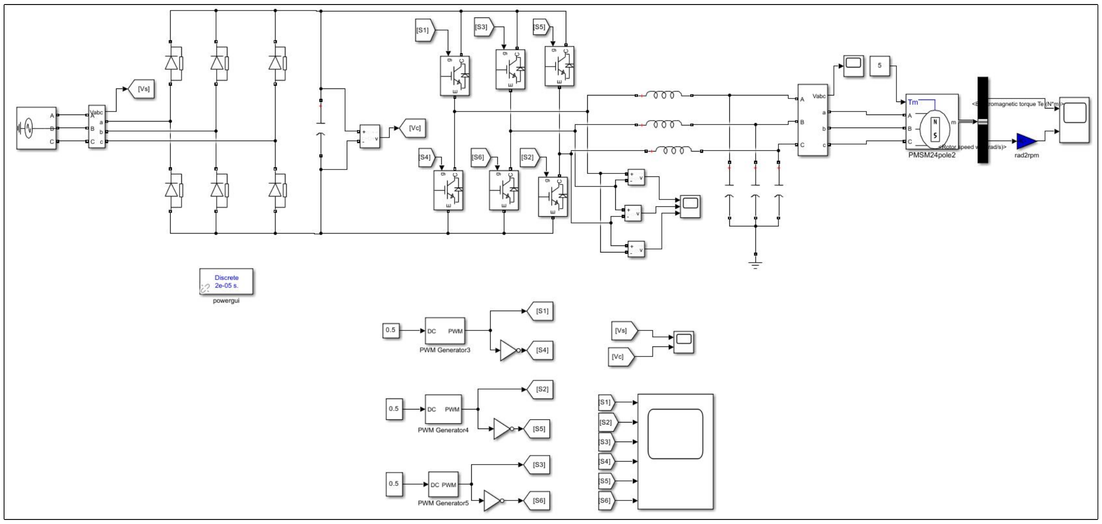


Figure 3.2: MATLAB simulation of PMSM

3.1.1 Rectifier (AC-DC converter)

AC to DC converter is to first rectify the AC voltage to a pulsating DC voltage. This is done by using diodes, which are semiconductor devices that allow current to flow in one direction only. The pulsating DC voltage is then smoothed out by a filter, which is typically a capacitor. [12]

$$V_{avg} = \frac{3V_{ml}}{\pi} \tag{3.1}$$

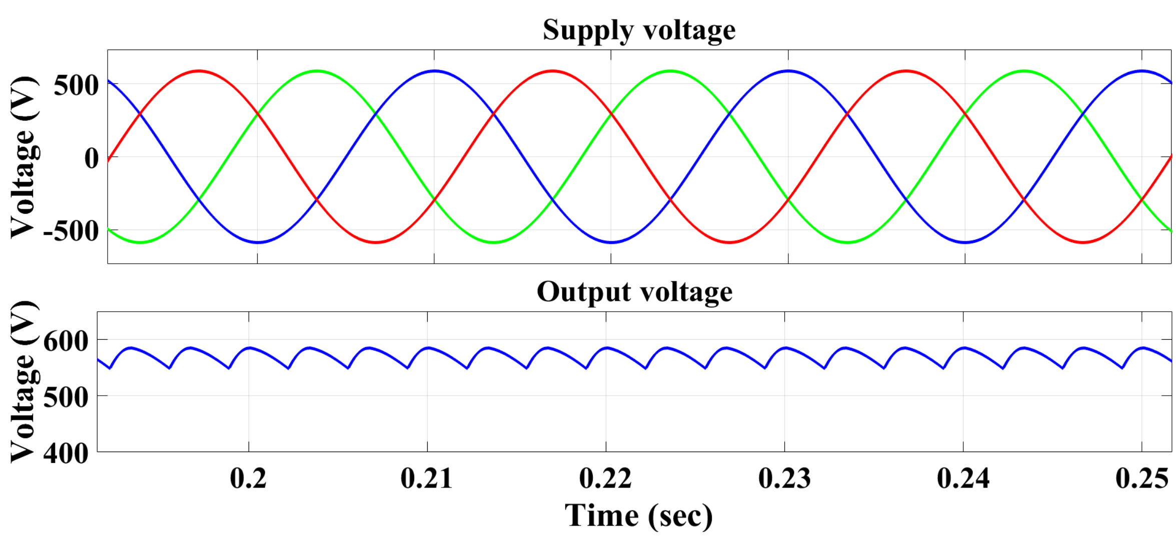


Figure 3.3: Rectifier output

$$I_{avg} = \frac{V_{avg}}{R} \tag{3.2}$$

Filter capacitors play a crucial role in AC-DC converter circuits by smoothing out the pulsating DC voltage produced by the AC-DC converter. The capacitor acts as a temporary storage device for electrical energy, charging during the positive half-cycle of the AC waveform and discharging during the negative half-cycle. This process effectively reduces the ripple voltage, which is the unwanted AC component in the DC output.

3.1.2 Inverter (DC-AC converter)

In 180-degree conduction mode is commonly used in three-phase DC-AC converter due to its simplicity and efficiency. In this mode, there are six switching devices, each con-

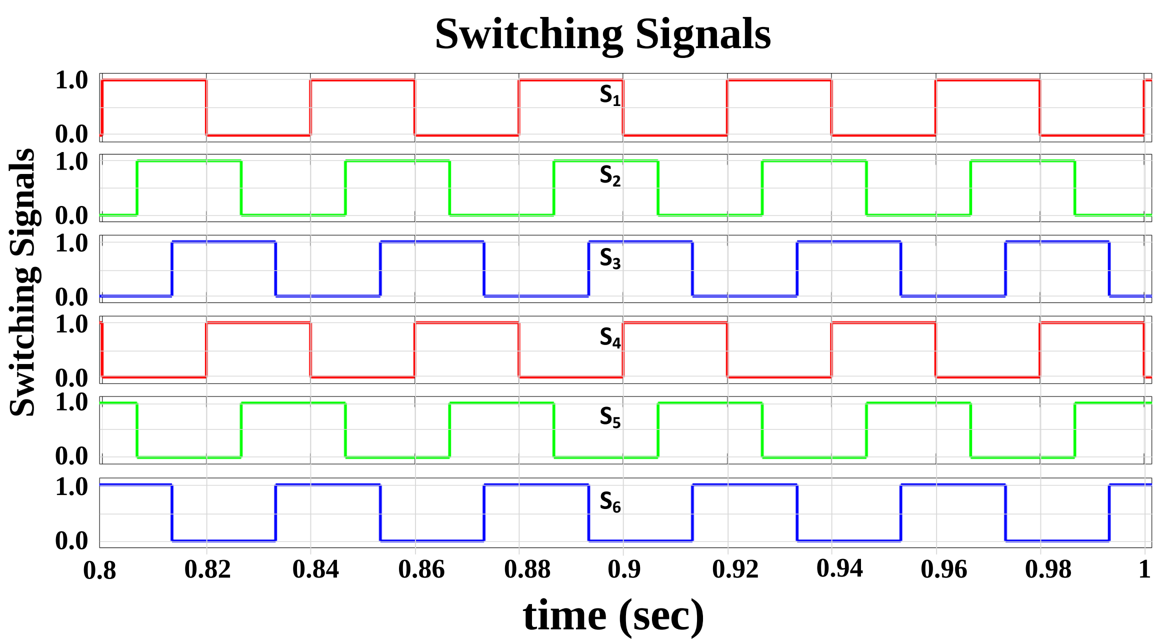


Figure 3.4: Switching pulse signal

nected to one of the three output phases. The switching sequence is controlled by a pulse width modulation (PWM) controller, which generates a set of control signals that determine the timing and duration of the switching actions. After providing a switching signal to each switch, at the terminal of each leg receives AC waveform frequency of the signal is the same as the switching frequency. Output waveforms have a frequency of fundamenatal component along with 5th, 7th, 11th, 13th and so on.shows the phase voltage of each leg of the DC-AC converter Figure 4.7 shows the total harmonic distortion of the three-phase

DC-AC converter con- ducting on 180o mode. For phase voltage total harmonic distortion of the DC-AC converter is 33% which is clearly shown by MATLAB approximately to 31.22%

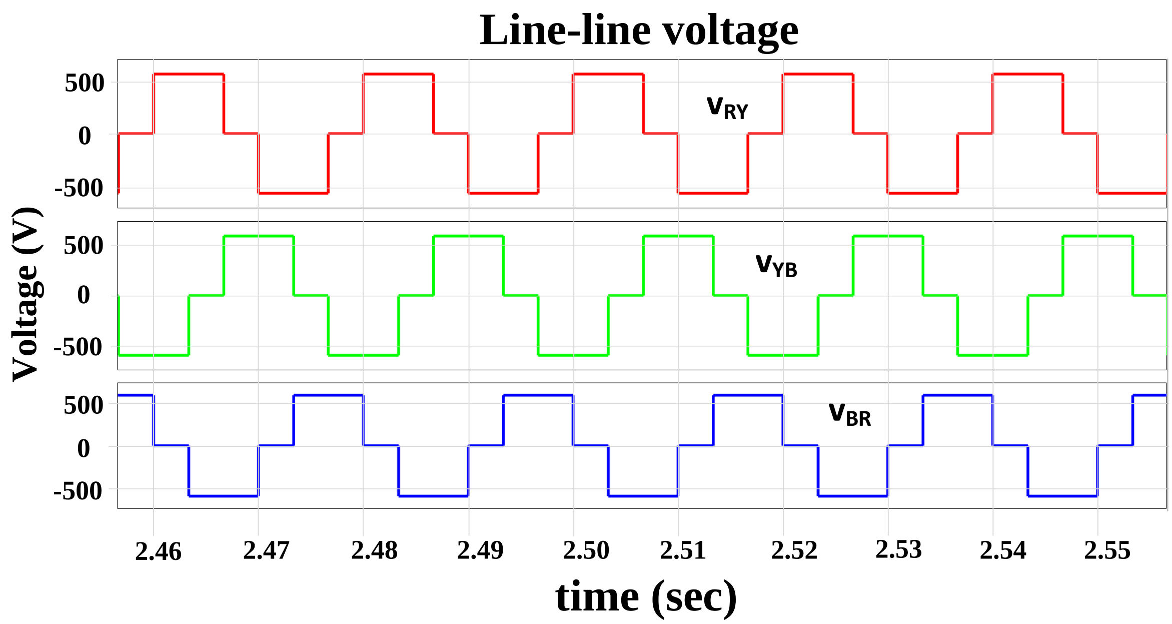


Figure 3.5: Inverter output voltage

3.1.3 Design of LC Filter

LC filter specifically designed for use in inverters, is a type of filter that employs both inductors (L) and capacitors (C) to reduce or eliminate harmonic distortion in the output voltage waveform of the inverter.

In an inverter, the output voltage waveform is typically a square wave or a modified sine wave, which can contain harmonics—integer multiples of the fundamental frequency—that are unwanted and can cause distortion in the waveform. These harmonics can lead to issues such as electromagnetic interference (EMI), equipment malfunction, and decreased efficiency.

LC filter is designed to mitigate these harmonics by providing a path for the high-frequency components of the output waveform to bypass the load, leaving only the fundamental frequency (desired) component to reach the load. The LC filter essentially acts as a low-pass filter, allowing the fundamental frequency to pass through while attenuating the higher frequency harmonics.

The configuration and parameters of the LC filter, such as the values of the inductor and capacitor, are chosen based on the specific requirements of the inverter system, including the frequency of operation and the level of harmonic distortion that needs to be mitigated.

By effectively removing or reducing the harmonics in the output voltage waveform, the LC filter helps to improve the quality of power delivered to the load, ensuring smooth operation of connected equipment and reducing the risk of electrical issues.

$$L = \frac{V_{dc}}{4hf_{sw}} \tag{3.3}$$

Where 2h = 40$\%$ of rated current. and for capacitor calculation

$$(P) = \frac{3 * V_{ph}^2}{X_C} \tag{3.4}$$

$$X_C = \frac{1}{2 * \pi * f_{sw} * C} \tag{3.5}$$

Whereas switching frequency

$$f_{sw} = \frac{1}{2 * \pi * \sqrt{LC}} \tag{3.6}$$

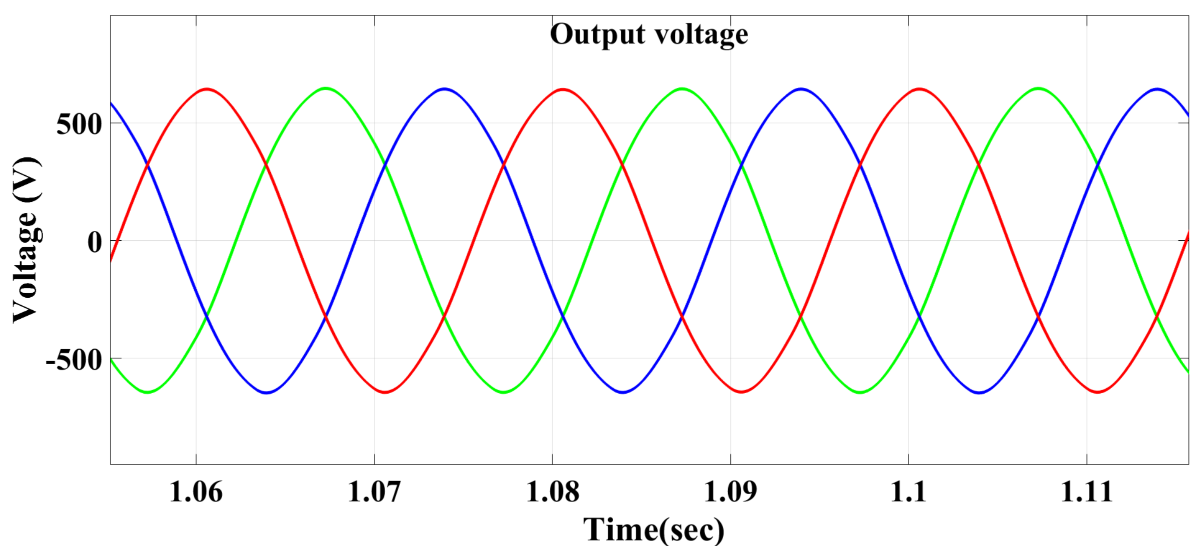
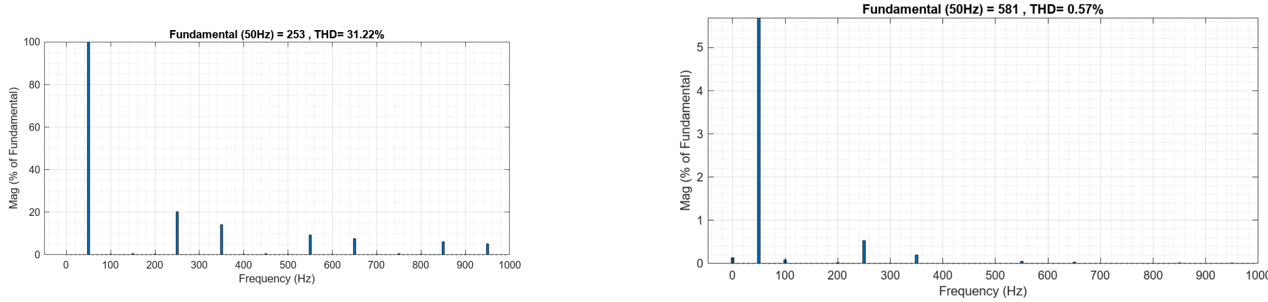


Figure 3.6: Inverter output with filter voltage



(a) THD without filter

(b) THD with filter

Figure 3.7: THD of Inverter

Figure 3.6 shows the output voltage of the Inverter after filter. It shows pure sinusoidal waveforms having less than 1% THD on AC side shown in Figure 3.7b.

3.1.4 Torque-speed

The Permanent Magnet Synchronous Motor (PMSM) plays a crucial role in the operation of Flywheel Energy Storage Systems (FESS) in electric vehicles due to its high efficiency, power density, and precise control capabilities. These attributes make the PMSM an ideal choice for applications requiring reliable and efficient energy storage and conversion. In this system, the output of a DC-AC inverter, which is equipped with an LC filter to

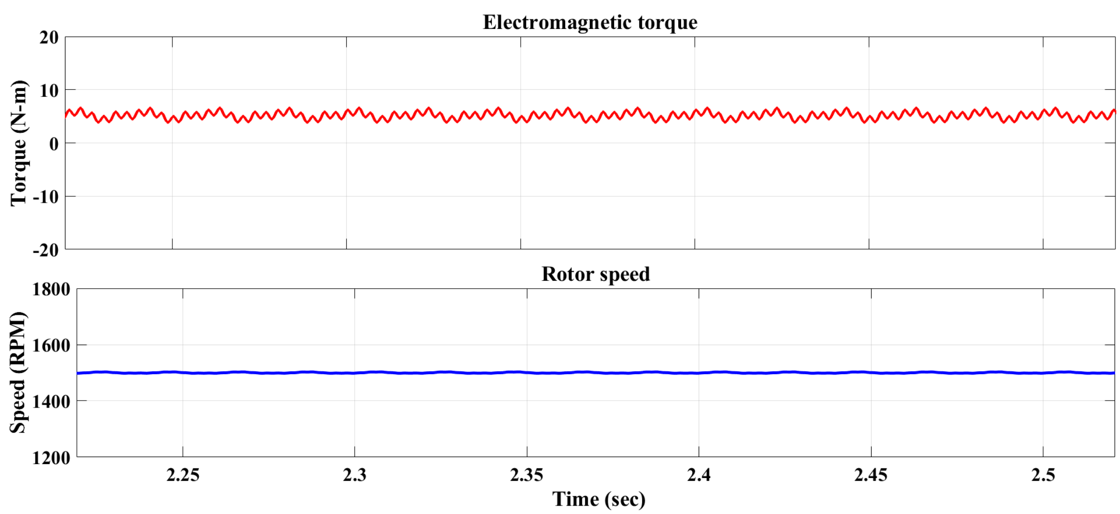


Figure 3.8: Torque speed

smooth the AC waveform, is connected to the PMSM. Additionally, the system incorporates a DC-DC boost converter for charging and a buck converter for discharging, ensuring optimal energy management. This configuration not only enhances the performance and efficiency of the electric vehicle but also ensures stable and reliable operation of the FESS. The integration of these components exemplifies advanced engineering solutions aimed at improving the energy efficiency and operational effectiveness of modern electric vehicles

After presenting and explaining all the open-loop parameter results and waveforms, I will detail the specific parameters used in the system and the corresponding results obtained. This will provide a clear and comprehensive understanding of the system's performance and the influence of various parameters on the results

3.2 Induction motor

In this section, I will elucidate the simulation circuit of an induction motor and the results derived from it. The simulation uses software like MATLAB/Simulink to model the stator and rotor windings with precise electrical and magnetic parameters. An AC power supply module energizes the stator, while control systems modulate the motor's operation under varying load conditions. Measurement tools capture performance metrics such as torque, speed, current, and voltage. The results reveal insights into the motor's start-up behavior, steady-state operation, and load response, aiding in design validation and control optimization.

Parameters	**Value**	**Parameters**	**Value**
Grid line voltage (RMS)	230 V	Output voltage of rectifier	325 V
Filter capacitor of rectifier	10 mF	Frequency	50 Hz
Input voltage of inverter	325 V	Inverter output RMS voltage	265.3 V
Motor inertia	0.05 kg-m^2	Poles	2
Motor torque	5 N-m	Rotor speed	2845 RPM

Table 3.2: Open loop Simulation results

3.2.1 Rectifier

AC to DC converter is to first rectify the AC voltage to a pulsating DC voltage. The analysis of a rectifier circuit with a 230V RMS AC supply, the output voltage is is ap-

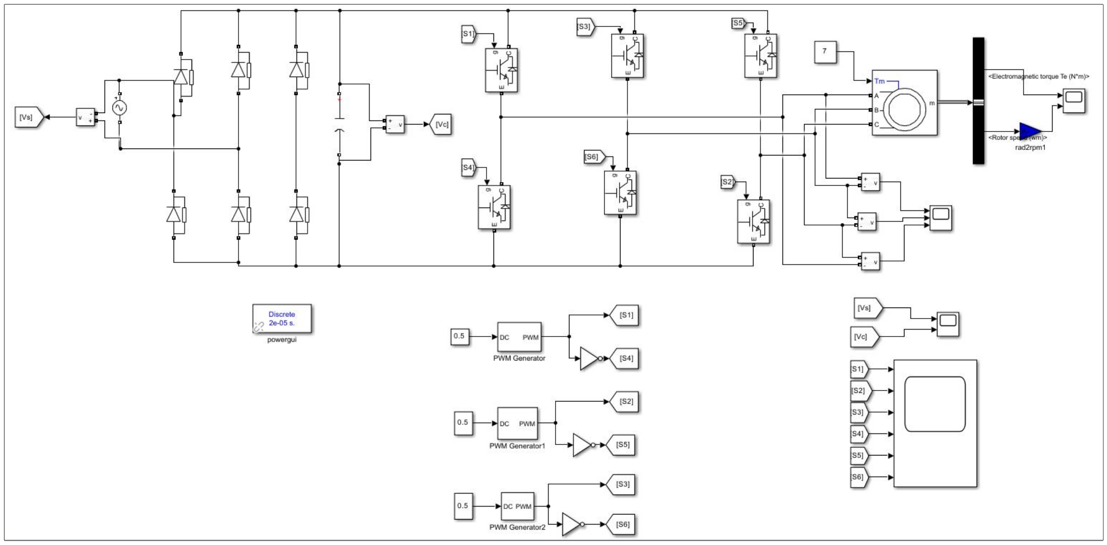


Figure 3.9: MATLAB simulation of induction motor

proximately 325V. the output is the peak of the input voltage because of capacitor whoose value is 10mF. so output voltage is

$$V_C = \sqrt{2}V_{in} = 1.414 * 230 \approx 325V \tag{3.7}$$

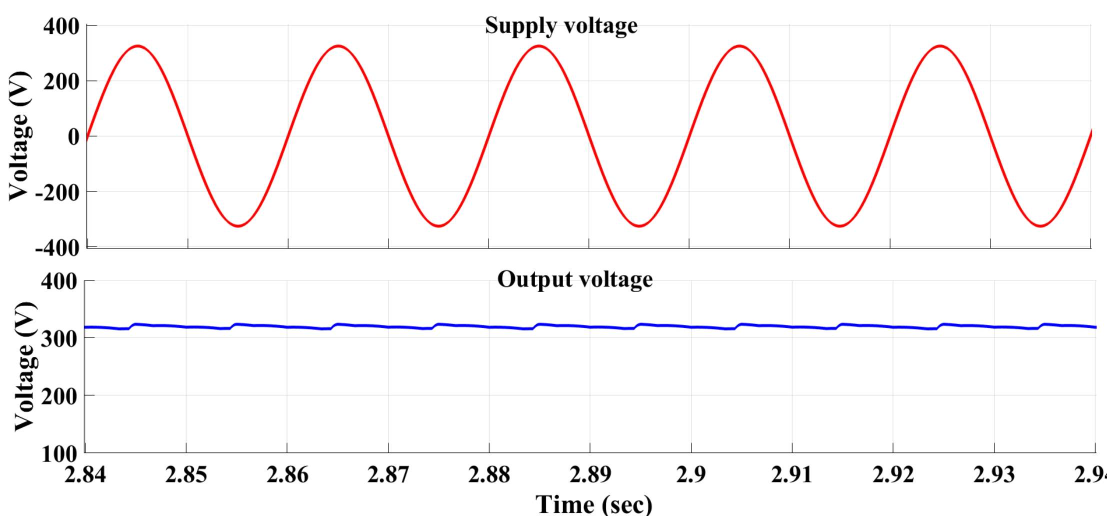


Figure 3.10: Rectifier output

3.2.2 Inverter

Three-phase DC-AC converters employ a 180°conduction mode. In this operating mode, six Insulated-Gate Bipolar Transistors (IGBTs) are utilized, upper each leg of IGBT are

120° a part and opposite leg of IGBTs are 180° apart. A pulse width modulation (PWM) controller governs the switching sequence by generating control signals that dictate the precise timing and duration of each IGBT's activation as shiwn in fig 3.11.

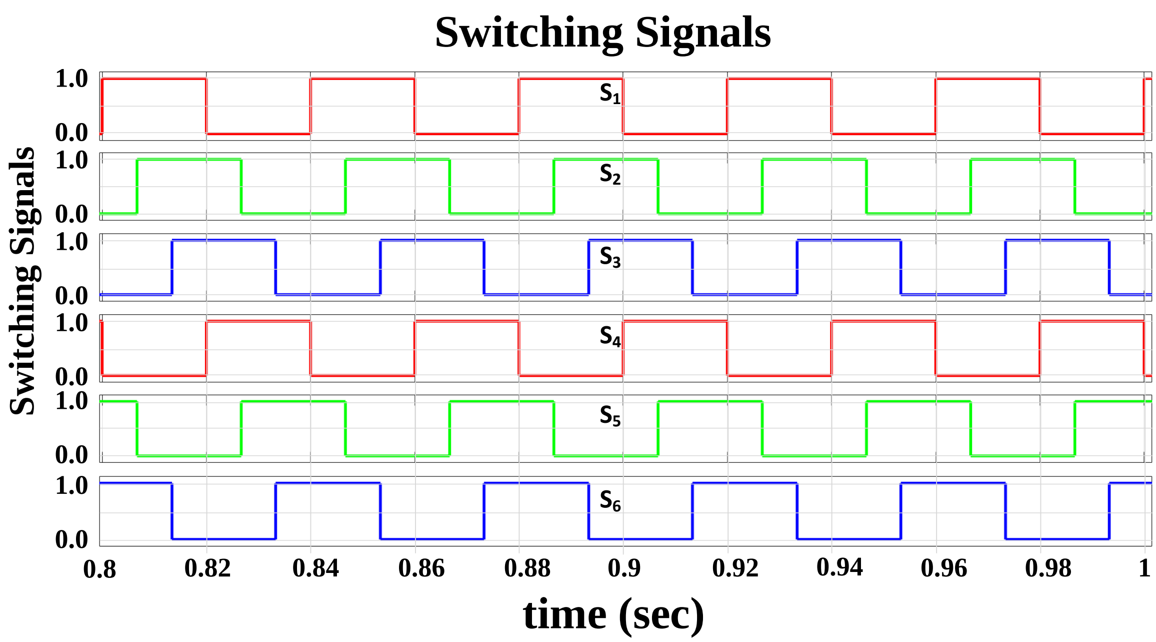


Figure 3.11: Switching pulse

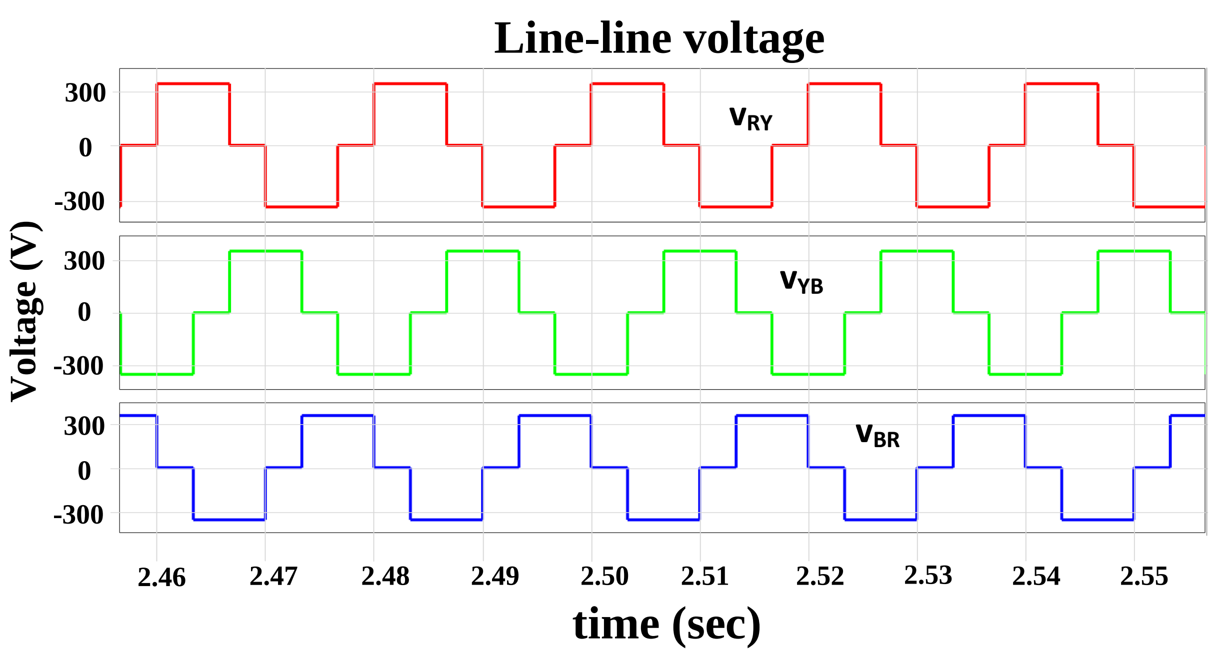


Figure 3.12: Inverter output voltage

The output voltage of the rectifier 325 V is connected to the inverter as shown in fig. 3.12.

And the line to line output RMS voltage of the inverter is 265.3V and peak to peak voltage of the inverter is 650 V.

3.2.3 Torque speed

Induction motor also known as an asynchronous motor, is a widely used type of electric motor that operates on the principle of electromagnetic induction. In an induction motor, the stator, which is the stationary part, is connected to an AC power supply and generates a rotating magnetic field. This field induces a current in the rotor, the rotating part, causing it to produce its own magnetic field and interact with the stator's field, resulting in torque and rotation.

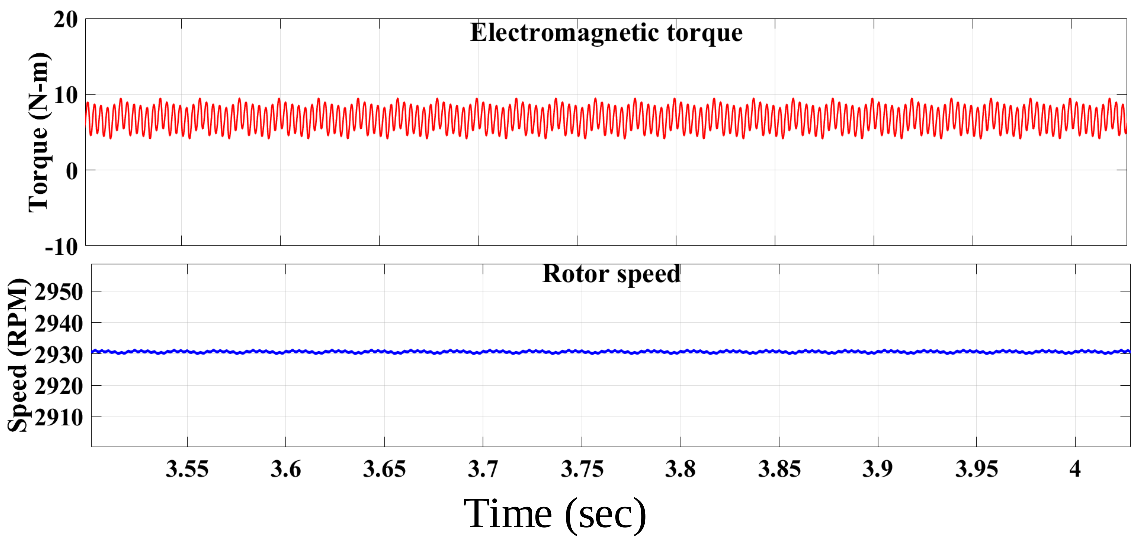


Figure 3.13: Torque speed

The inverter transforms the DC input into a controlled three-phase AC output at the desired frequency, driving an AC motor. In this motor, the moment of inertia is 0.05 kg-m² inertia, 2 poles, and the output of speed of the motor is 2845 rpm at a 50 Hz supply.

Chapter 4

Hardware Implementation and Analysis

In this hardware setup first three phase ac supply is converted in dc form using three-phase uncontrolled rectifier. At the output of rectifier dc link capacitor used to maintain constant dc voltage. Output of rectifier is fed to load through three phase inverter. Semikron converters refer to power electronic converters manufactured by Semikron, a leading manufacturer of power semiconductor components. These converters are used in various applications to convert electrical power efficiently and reliably. Semikron converters come in different configurations and are used in a wide range of industries.

4.1 Hardware setup of power converters of FESS

Semikron converters refer to power electronic converters manufactured by Semikron, a leading manufacturer of power semiconductor components. They often incorporate advanced semiconductor technologies such as insulated gate bipolar transistors (IGBTs) or silicon carbide (SiC) devices to achieve high efficiency and performance.Transitioning from computer simulations to real-world testing marked a significant mile stone in our project. This setup included key components such as a three-phase diode bridge rectifier, a brake chopper, and a three-phase IGBT-based PWM inverter. To facilitate interfacing with the power converter, an Arduino UNO board was integrated to supply the necessary control signals for the IGBT-based inverter. This configuration enabled us to effectively transition from theoretical models to practical implementation, validating our simulations through empirical testing. Complete hardware setup is shown in fig. 4.1

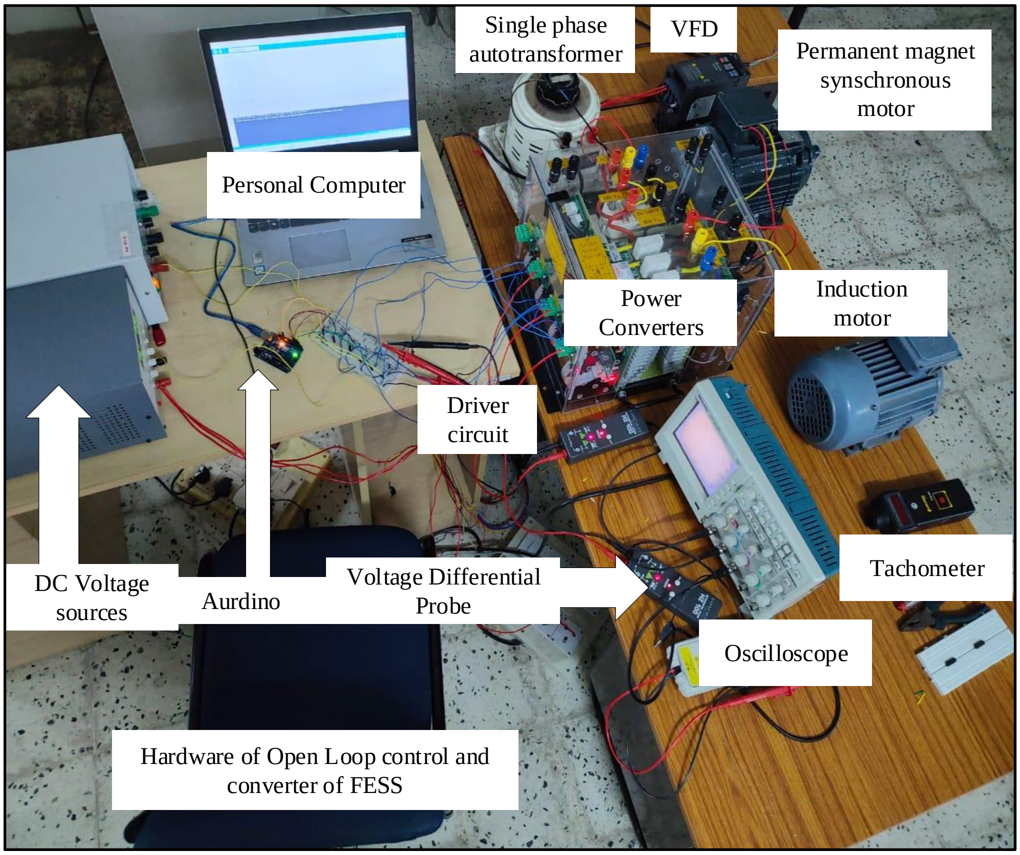


Figure 4.1: Hardware setup of power converters of FESS

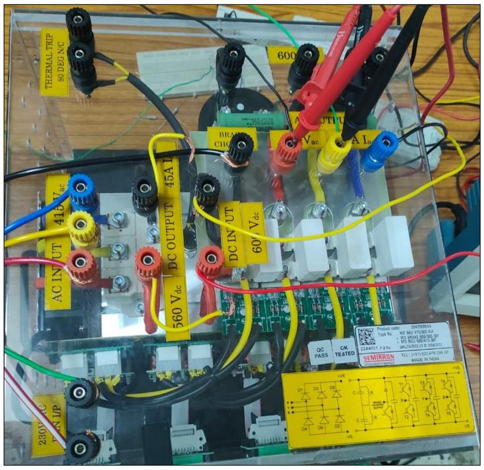
4.1.1 Power converters

In the hardware setup all three converters combined in single SEMIKRON power converter shown iN fig.4.14a. Semikron converter includes three phase uncontrolled rectifier, break chopper and three phase inverter.

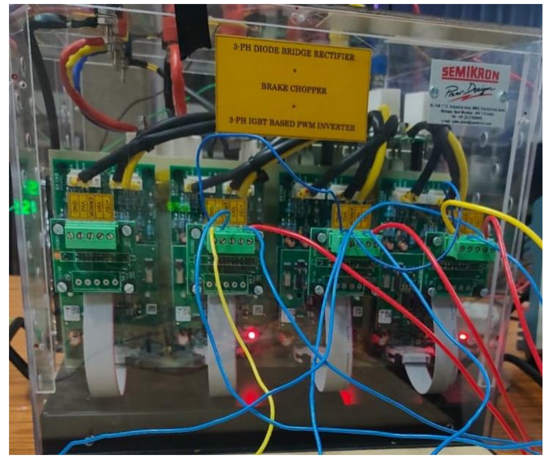
Three phase uncontrolled rectifier: In the power converter, two key operations occur: rectification and inversion. The rating of the rectifier is 415 V / 600 V to converts the three-phase AC signal into DC signal. To ensure a ripple-free output voltage, two capacitors are connected at the output of the rectifier. The DC output from the rectifier then serves as the input for the inverter, and the average output of the rectifier is:

$$V_{avg} = \frac{3V_{ml}}{\pi} \tag{4.1}$$

Where, V_{avg} shows the average voltage of the rectifier and V_{ml} is peak value of input line



(a) Power converters



(b) Power converters side view

Figure 4.2: Comparison of power converters and their side view

voltage. Here we are using DC link capacitor so, because of filter capacitor, the output value is:

$$V_C = \sqrt{2}V_{ml} = 1.414 * 408 \approx 576V \tag{4.2}$$

The output of the rectifier is connected to the Chopper (buck-boost converter) which is step up the voltage at charging time and step down the voltage at discharging time.

Brake chopper: The DC-DC Brake chopper converter or bidirectional DC to DC converter is a pivotal component in the Flywheel Energy Storage System (FESS) for electric vehicles, primarily tasked with regulating the DC voltage to the levels required by the inverter and the Permanent Magnet Synchronous Motor (PMSM). During braking operations, this regulation is crucial for charging the battery. In the charging mode, the brake chopper functions analogously to a boost converter, stepping up the voltage from the grid to match the requirements of the energy storage system. Specifically, when 415V is sourced from the grid and rectified to 560V, the brake chopper further elevates the voltage to 600V, optimizing energy transfer efficiency to the FESS inverter. Conversely, during discharging mode, the brake chopper's operation is akin to a buck converter, ensuring compatibility between the FESS's stored energy and the load requirements. Here, the brake chopper modulates the voltage from 600V to 560V, aligning with the desired output voltage for discharge. The relationship between the input voltage and output voltage of chopper is in Charging mode :

$$V_o = \frac{1}{1-D} * V_{in} \tag{4.3}$$

The relationship between the input voltage and output voltage of chopper is in discharging mode :

$$V_o = D * V_{in} \tag{4.4}$$

Three phase inverter: The inverter, which uses six Insulated Gate Bipolar Transistors (IGBTs). These IGBTs are controlled by switching pulses to regulate their turn-on and turn-off states. The inverter operates in a 180° conduction mode, meaning each IGBT conducts for 180°of the electrical cycle, ensuring a smooth and balanced three-phase AC output from the DC input and the output of inverter voltage is

- Expression of output line voltage (Quasi square wave):

$$v_L(t) = \sum_{n=1,5,7,11,12--}^{\infty} \frac{4V_{in}}{n\pi} sin(\frac{n\pi}{3}) sin(nwt + \frac{n*\pi}{6}) \tag{4.5}$$

- Expression of output phase voltage (Six stepped):

$$v_{ph}(t) = \sum_{n=1,5,7,11,13--}^{\infty} \frac{2V_{in}}{n\pi} sin(nwt) \tag{4.6}$$

- Expression for load current:

$$i_L(t) = i_{ph}(t) = \sum_{n=1,5,7,11,--}^{\infty} \frac{2V_{in}}{n\pi|Z_n|} sin(nwt - \phi_n) \tag{4.7}$$

- nth harmonic Current

$$i_{Ln}(t) = i_{phn}(t) = \frac{2V_{in}}{n\pi|Z_n|} sin(nwt - \phi_n) \tag{4.8}$$

Parameters	Value	Parameters	Value
3 ϕ AC supply	415 V	Rectifier output	587 V
fan Supply	230 V	Rectifier filter capacitance C	10 mF
Inverter input L-L	587 V	inverter output peak-peak	1200 V
inverter filter inductance	5 mH	inverter filter Capacitance	2 mF

Table 4.1: Power converter prameter

4.2 Control & Switching

In this section explains the switching signal provided to three phase inverter. Here for getting desired switching signal Arudino UNO used and command is given by pc. After genarating the desired switching signal there is need of amplification because the amplitude generated by arduino is 5 V which is not suitable to turn on IGBT. So for amplification purpose designed a driver circuit to get amplitude approximate 15 V and suitable to turn on IGBTs.

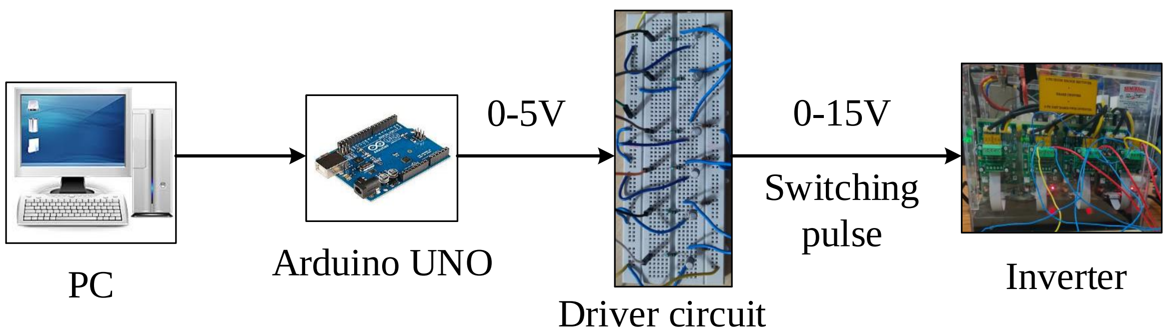


Figure 4.3: Switching pulse

4.2.1 Arduino UNO

The arduino pulse generation code is a crucial component of our experimental setup, directing the Arduino UNO board in transmitting signals to the inverter switches to control their operation. This code configures the arduino UNO board to utilize its digital pins for sending the appropriate control signals to the inverter, thereby regulating its functionality and ensuring precise operation within the system. For generating a switching pulse for the inverter Arduino UNO is used for which code is developed in Arduino IDE (software).Arduino Uno has 14 digital input/output pins (out of which 6 can be used as PWM outputs), 6 analog input pins, a USB connection, A Power barrel jack, an ICSP header and a reset button.Instead of all we use Only digital IO pins (2-7) along with ground pin is used for the application.

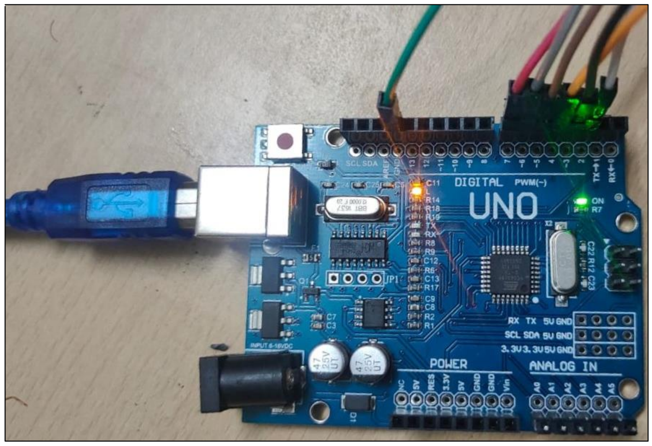


Figure 4.4: Arduino UNO

Parameters	Value
Output pulse	0-5
duty cycle	0.5
propagation delay	3333 μs
dead time	6 μs

Table 4.2: Driver circuit parameter

4.2.2 Driver Circuit

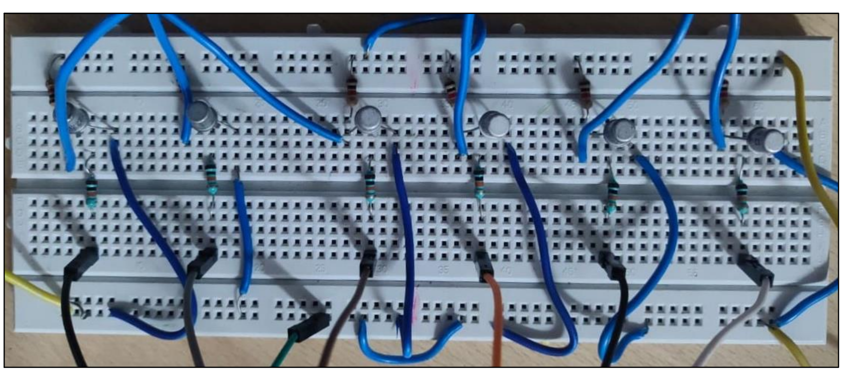


Figure 4.5: Driver circuit

Driver circuit is used to amplify the Arduino UNO output of amplitude 0-5V to 0-15V

mathmatical analysis of driver circuit

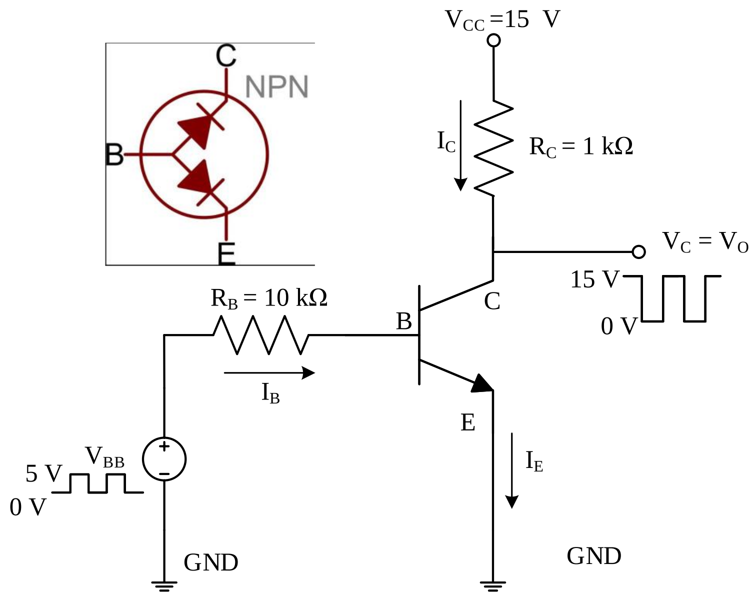


Figure 4.6: npn transistor

Case-1: when Arduino output is 0V: apply KVL in base side

$$V_{BB} - I_b R_B - V_{BE} = 0 \tag{4.9}$$

$$0 - I_b * 10k\Omega - 0.7 = 0 \tag{4.10}$$

$$I_b = (-0.7)/(10k) = -70muA \tag{4.11}$$

as I_b is negative,and current can not be negative, because current cannot flow in reverese direction in diode , transistor work in cut-off region and acts as a OFF switch. this results in 0V drop across collector resistance. hence the collector voltage is equal to supply voltage. i.e $V_c = V_{cc} = 15v$

Case-2: when Arduino output is 5 V: apply KVL in base side

$$V_{BB} - I_b R_B - V_{BE} = 0 \tag{4.12}$$

$$5 - I_b * 10k\Omega - 0.7 = 0 \tag{4.13}$$

$$I_b = (5 - 0.7)/(10k) = 0.43mA \tag{4.14}$$

again apply KVL in collector side

$$V_{cc} - I_c R_c - V = 0 \tag{4.15}$$

$$15 - 103.4 * 1 - V_c = 0 \tag{4.16}$$

$$V_c = -88.4V \ i.e. \ V_{CB} = -88.4 - 0.7 - 89.1v < 0$$

i.e transistor will work in saturation mode and act as a ON switch and in saturation region

$$V_{CE} = 0.2V \ and \ V_c = 0.2V \simeq 0V$$

Parameters	**Value**
Beta (β)	220
Base resistance (R_B)	10k Ω
Collector resistance (R_C)	1k Ω

Table 4.3: Driver circuit parameter

4.2.3 DC Supply

In this hardware setup I use 2 dc regulated power supply one supply is use to amplify the voltage pulse signal from 0-5V to 0-15V or 0-16V according to the requirement of IGBT breakdown Voltage and other dc voltage power supply is used as power supply to the gate driver circuit.

4.3 Permanent magnet synchronous Motor

The hardware setup involving a three-phase Permanent Magnet Synchronous Motor (PMSM) rated at 1.3 horsepower (HP), which corresponds to a power rating of approximately 1 kilowatt (kW). The PMSM operates with a current capacity of 2.9 amperes (A). The power factor (pf) of the motor is specified as 0.9, and it demonstrates an efficiency of 90% The

Figure 4.7: DC Supply

output of the inverter is configured to supply the necessary power to the PMSM. To ensure the quality and stability of the power being delivered, the inverter output is connected to a filter before interfacing with the PMSM. This filter serves to mitigate the effects of any unwanted harmonics and noise, thus ensuring a smoother and more efficient operation of the motor

Figure 4.8: PMSM motor

Parameters	Value	Parameters	Value
Voltage rating	220	Current rating	2.9A
Speed	3000 r.p.m	frequency	100 Hz
Efficiency	90%	power factor	0.91

Table 4.4: Motor parameter

4.4 Induction motor

The hardware setup involves a three-phase Induction motor rated at 1 horsepower (HP), which corresponds to a power rating of approximately 0.75 kilowatt (kW). The induction motor operates with a current capacity of 1.7 amperes (A). The power factor (pf) of the motor is specified as 0.84, and it demonstrates an efficiency of 73.5% The output of the inverter is configured to supply the necessary power to the induction motor. To ensure the quality and stability of the power being delivered, the inverter output is connected to a filter before interfacing with the induction motor. This filter serves to mitigate the effects of any unwanted harmonics and noise, thus ensuring a smoother and more efficient operation of the motor

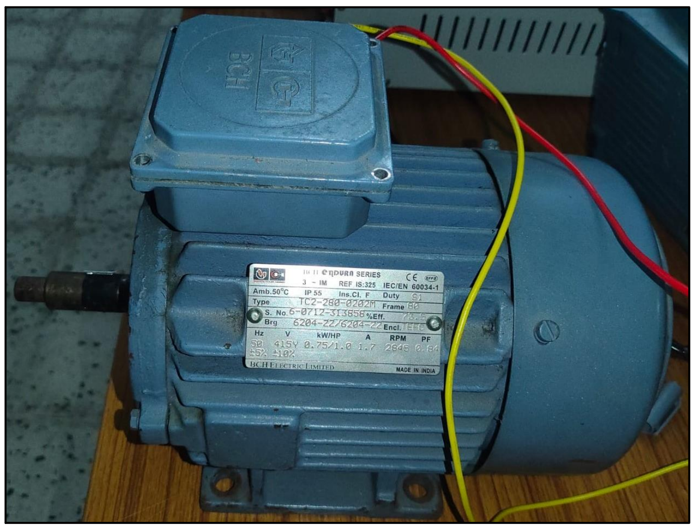


Figure 4.9: Induction motor

Parameters	**Value**	**Parameters**	**Value**
Voltage rating	415V	Current rating	1.7A
Speed	2845 r.p.m	frequency	50 Hz
Efficiency	73.5%	power factor	0.84

Table 4.5: Motor parameter

4.5 VFD (Variable frequency drive)

A Variable Frequency Drive (VFD) is a crucial electrical device that regulates the speed and torque of electric motors by varying the motor's input voltage and frequency. The VFD operates by converting the fixed frequency and voltage of the input power supply into variable frequency and voltage outputs, allowing for the adjustment of motor speed to meet specific application demands. This process involves rectifying incoming AC power to DC, then inverting the DC power back to a controlled AC output. Key components of a VFD include a rectifier, which converts AC to DC; a DC link, which stabilizes the DC power; an inverter, which converts the stabilized DC back to AC with the desired frequency and voltage; and a control unit, which manages the overall operation of the VFD

Figure 4.10: VFD

4.5.1 Tachometer

Tachometer measuring rotational speed in RPM, is crucial for monitoring and optimizing the performance of engines and machinery. Analog and digital types serve diverse applications, from automotive to industrial settings. Analog versions offer simplicity and reliability, while digital models provide precision and additional data. This instrument's evolution reflects technological advancements, enhancing efficiency and safety across various field

Figure 4.11: Tachometer

4.5.2 Single phase auto transformer

Variable single-phase auto-transformer provides a continuously adjustable output voltage from a single winding, enhancing efficiency and reducing material costs. Widely used in laboratories and industrial applications for precise voltage control, it allows fine-tuning of AC voltage through a movable brush on the winding.Its versatility and efficiency make it invaluable for voltage regulation and motor speed control and voltage is varring from 0-260V.

Figure 4.12: Single phase auto-transformer

4.6 Hardware testing

4.6.1 Testing of Induction motor

In 4.1 hardware model of the power converter is shown. A 1-ϕ supply voltage of 250 V input is given to the rectifier which rectifies to an average voltage of 225.1V. A filter capacitor of $10mF$ is connected at the output side of the rectifier to smoothen out the ripple content in the rectifier output which results in a constant DC voltage of 353.5 V. This constant DC voltage is fed to the inverter which gets its switching signal from Arduino UNO, which results in an alternating voltage As the output of the Arduino UNO not enough to drive the IGBT switches in the inverter, a driver is used to provide the switching signal. This driver takes input from the Arduino-Uno as a 0-5V pulse signal and amplifies to 0-15V. The PWM technique is used to generate a switching signal.

4.6.2 Generation of switching pulse

To generate the switching pulse we write a code and that code generates the pulse whose min. value is 0V and max value is 5V. Here i show all the upper leg of the IGBT signal(1,3,5). [12] Phase delay between 1 & 3 is calculated by

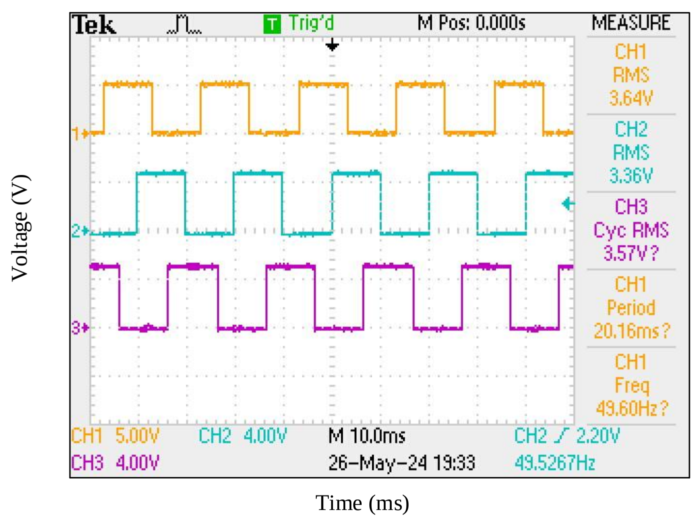
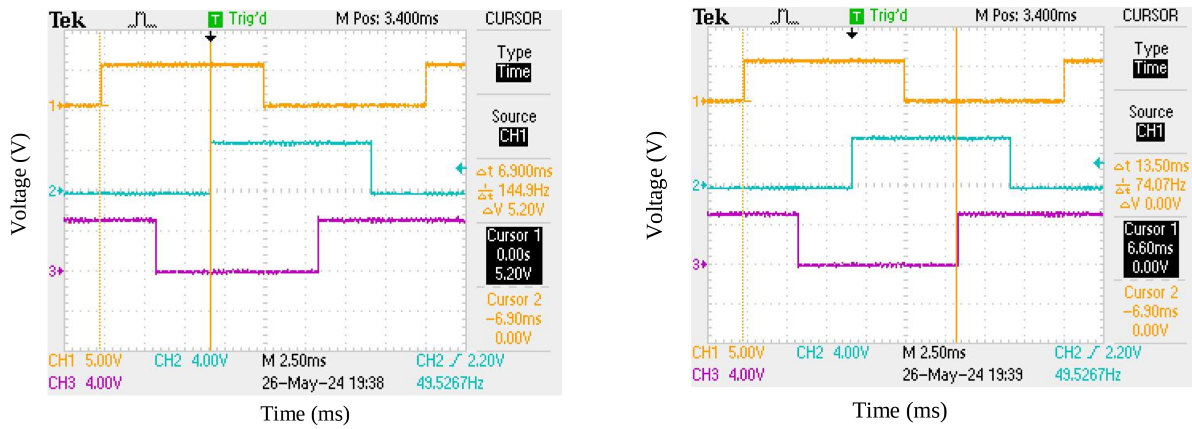


Figure 4.13: Switching signal of upper leg of inverter

$$\phi = \frac{6.9ms}{20.25ms} * 360^\circ = 122^\circ \tag{4.17}$$

Phase delay between 1 & 5 is calculated by

$$\phi = \frac{13.5ms}{20.25ms} * 360^\circ = 240^\circ \tag{4.18}$$



(a) Phase delay between 1 &3

(b) Phase delay between 1 & 5

Figure 4.14: Phase delay of IGBT

Driver circuit is used to amplify the Arduino UNO output of amplitude 0-5V to 0-15V

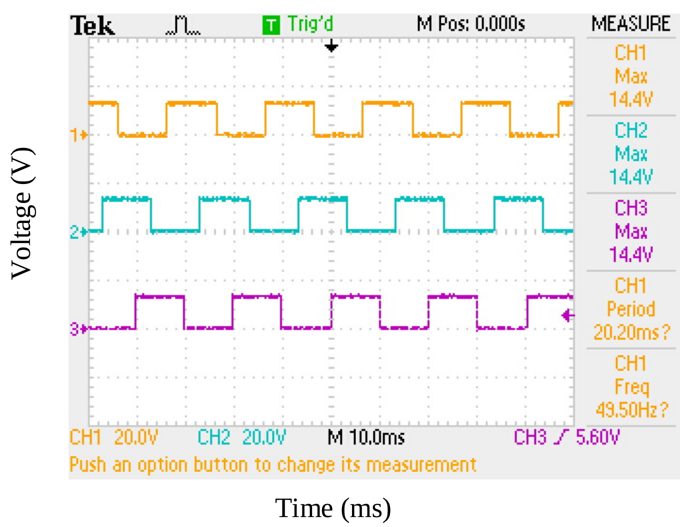
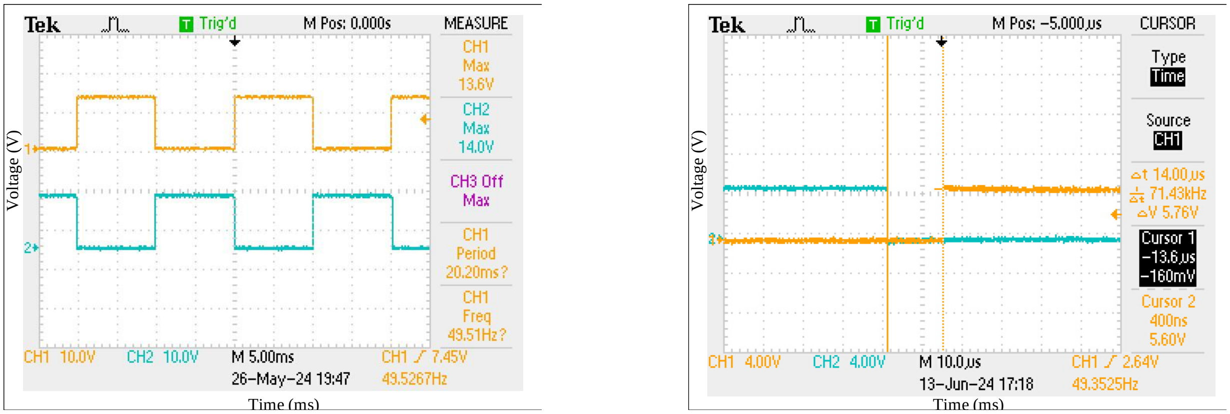


Figure 4.15: Amplified pulse signal



(a) Amplified pulse 1 &4 single leg

(b) Blanking time between 1 & 4

Figure 4.16: Amplified pulse and dead time of 1 & 4

4.6.3 Duty cycle and blanking time

Delay time For an output frequency (f) of 50 Hz, time period (T) would be 0.02 seconds.

$$T = \frac{1}{f} \tag{4.19}$$

So, we have 20 ms for one complete cycle. There are six phases in 20 ms hence one phase delay period would be

$$t_{pd} = \frac{20}{6} ms = 3333.3 \mu s \tag{4.20}$$

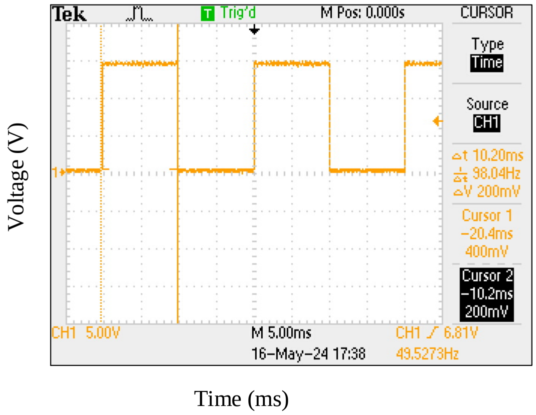
Duty cycle of the switching pulse is (D)

$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} \tag{4.21}$$

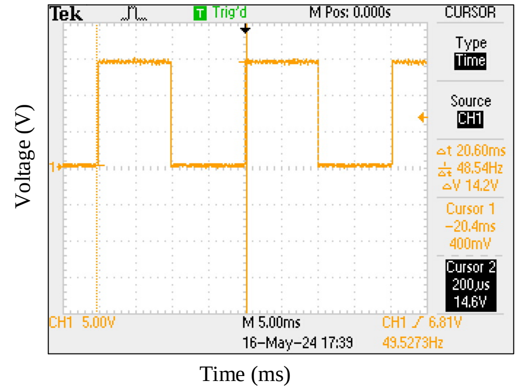
$$D = \frac{10ms}{20ms} = 0.5 \tag{4.22}$$

4.6.4 AC-DC input-output voltage

In Fig. 4.18, it is demonstrated that when a rectifier is supplied with an input voltage of 230 V RMS, the resulting output voltage is calculated to be approximately 325 V. This relationship is based on the conversion from RMS (Root Mean Square) voltage to peak voltage, where for a sinusoidal AC waveform, the peak voltage V_{peak} is given by



(a) ON time of switching pulse



(b) Total Pulse width of switching signal

Figure 4.17: Duty ratio ON time & OFF time

equation V$_{peak}$ =$\sqrt{2}$*V$_{rms}$ therefore with an input voltage of 230 V RMS, the peak voltage is 230*$\sqrt{2}$=325 V. This peak voltage represents the maximum voltage of the waveform and is typically the DC output voltage after rectification, assuming ideal components and negligible losses, illustrating the fundamental principle of AC-to-DC conversion in power electronics.

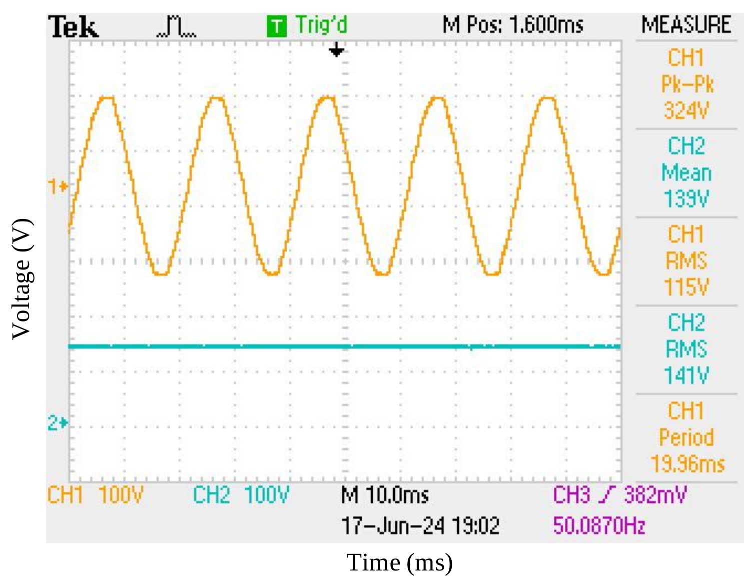


Figure 4.18: Rectifier input-output voltage

4.6.5 MSC output voltage

The inverter output voltage is peak to peak is 650 V (325V +325V) here i shows all three output line to line voltages (RY, YB, BR) all are 120° displacement.

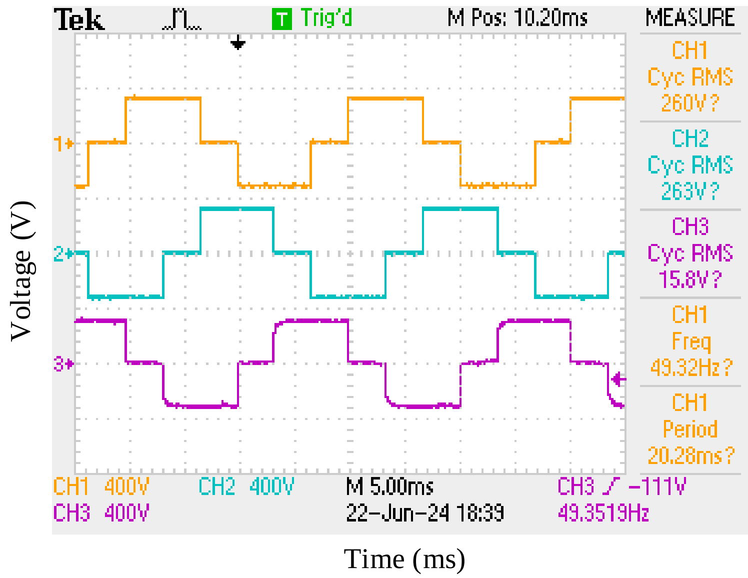


Figure 4.19: Inverter output line-line voltage waveform

In Fig. 4.20, the speed of the induction motor at a given voltage is measured using a digital tachometer. The voltage, supplied by the output of a power converter, is monitored using a multimeter. Under these conditions, the motor's speed is recorded as 2859 RPM. This setup ensures accurate measurement of both voltage and speed, providing reliable data for analyzing the motor's performance

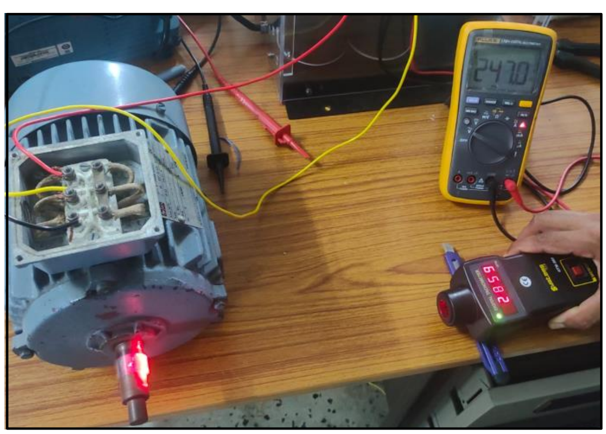


Figure 4.20: Induction motor speed

4.6.6 Testing of PMSM by using V/f control (V/f=10)

In hardware testing of the permanent magnet synchronous motor (PMSM), the performance metrics closely matched those predicted by simulations, validating the model's accuracy. Key parameters such as torque, speed, and efficiency were consistent across both testing environments. This confirms the simulation's reliability in predicting real-world performance

4.6.7 Switching pulse

In Fig. 4.21, the amplified pulse waveform of the upper leg of a three-phase voltage source inverter is depicted. For effective operation, the Insulated Gate Bipolar Transistor (IGBT) in the upper leg requires a gate voltage that exceeds the threshold voltage, which is more than 12V. The standard output signal from an Arduino typically provides a much lower voltage, insufficient to drive the IGBT directly. Therefore, it is necessary to amplify the Arduino pulse signal to achieve the required voltage level for the IGBT gate. This amplification ensures that the IGBT can switch properly, enabling the inverter to function effectively. The process of amplifying the pulse signal from the Arduino to meet the threshold voltage requirement of the IGBT is crucial for the reliable performance of the three-phase voltage source inverter, highlighting the importance of signal conditioning in power electronics applications

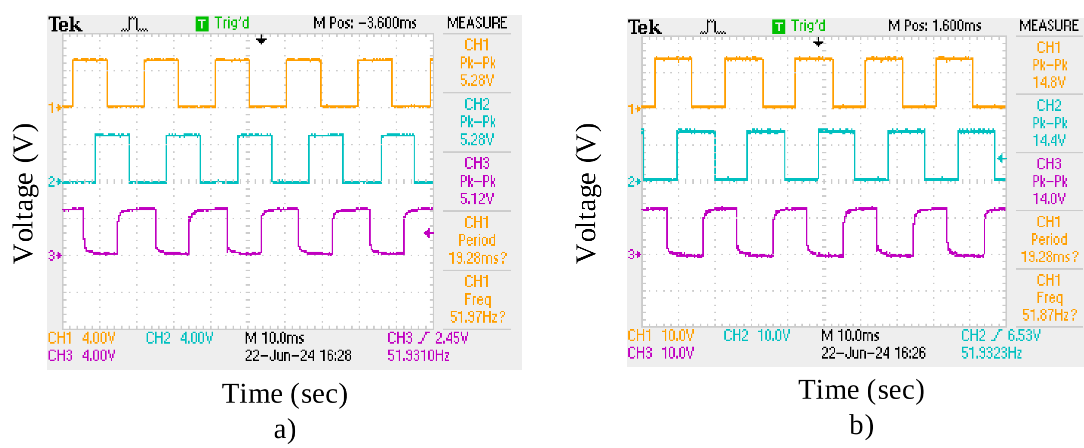


Figure 4.21: s) Aurdino generated pulse signal, (b) Amplified pulse signal

4.6.8 Generation of switching pulse

In fig.4.22 the switching pulse characteristics are illustrated, showing the on-time and total duration of the pulse. The duty cycle of a switching signal, which is a key parameter in pulse-width modulation (PWM) and other switching applications, is defined as the ratio of the pulse's on-time to its total period. In this case, the on-time is specified as 5 ms, and the total pulse width (or period) is 10 ms. Duty cycle of the switching pulse is (D)

$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} \tag{4.23}$$

$$D = \frac{10ms}{20ms} = 0.5 \tag{4.24}$$

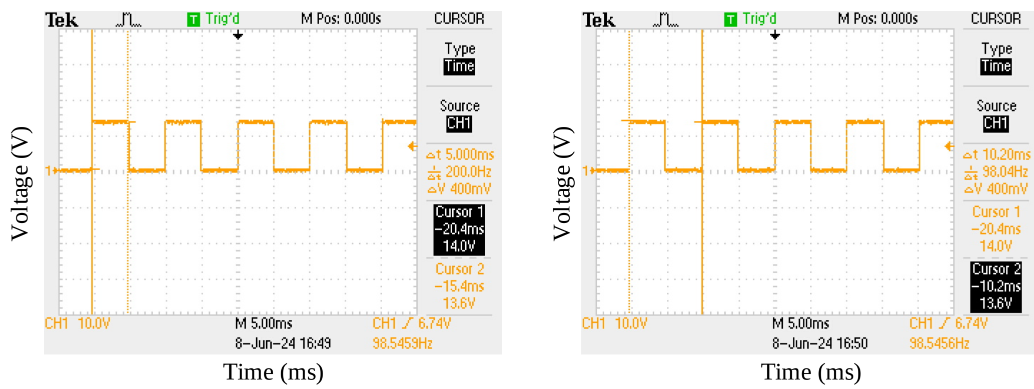


Figure 4.22: Duty cycle

4.6.9 AC-DC input-output voltage

In Fig. 4.23, it is demonstrated that when a rectifier is supplied with an input voltage of 256V RMS, the resulting output voltage is calculated to be approximately 362V. This relationship is based on the conversion from RMS (Root Mean Square) voltage to peak voltage, where for a sinusoidal AC waveform, the peak voltage V_{peak} is given by equation $V_{peak} = \sqrt{2} * V_{rms}$ therefore with an input voltage of 256 V RMS, the peak voltage is $256 * \sqrt{2} = 362$ V. This peak voltage represents the maximum voltage of the waveform and is typically the DC output voltage after rectification, assuming ideal components and negligible losses, illustrating the fundamental principle of AC-to-DC conversion in power electronics.

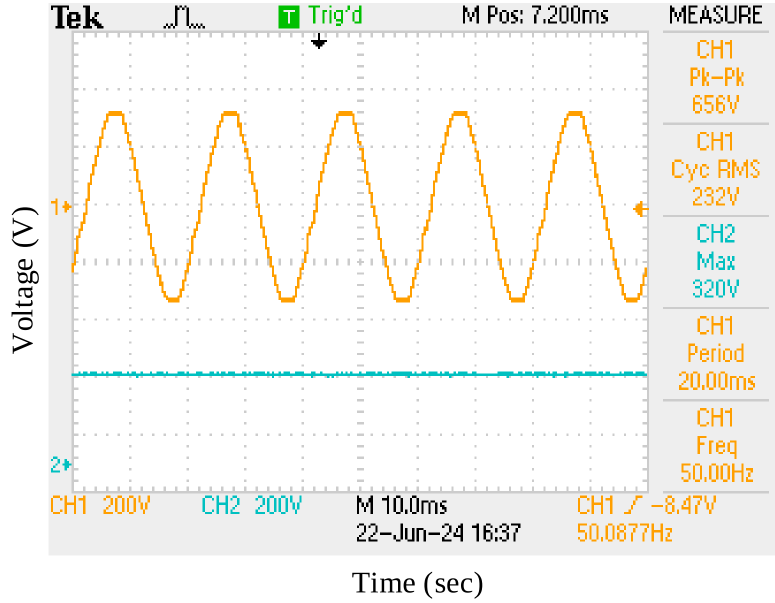


Figure 4.23: Rectifier input - output voltage

4.6.10 DC-AC output voltage

The inverter output voltage has a peak-to-peak value of 672 V, which corresponds to a maximum voltage swing of +336 V to -336 V. This output generates three line-to-line voltages: RY (Red to Yellow), YB (Yellow to Blue), and BR (Blue to Red). Each of these voltages is phase-shifted by 120 degrees with respect to each other, ensuring a balanced three-phase output. This 120° phase displacement is crucial for the proper operation of three-phase systems, providing consistent torque and smooth operation in applications such as motor drives and power distribution.

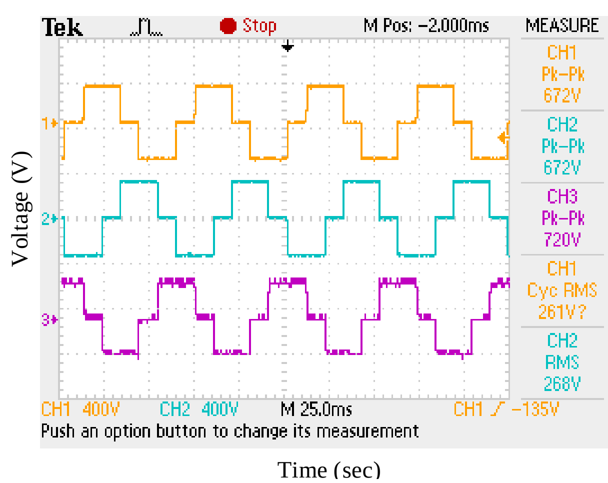


Figure 4.24: Inverter output voltage

4.6.11 Motor speed

In Fig. 4.25, the speed of the PMSM at a specified voltage is measured using a digital tachometer, while the voltage output from the power converter is monitored with a multimeter. Under these conditions, the motor's speed is accurately recorded as 1550 RPM. This setup allows for precise and reliable measurement of both the voltage and the motor speed, ensuring that the data collected is dependable for analyzing the motor's performance. The integration of the digital tachometer and multimeter in this configuration provides a comprehensive and accurate assessment of the motor's operational characteristics, facilitating detailed performance analysis.

Figure 4.25: PMSM speed

Chapter 5

Conclusion & Future scope

1. Open-loop simulation of the hardware setup was initially conducted. In this simulation, it was observed that,

   In case of PMSM when a 415V RMS supply was applied to the rectifier, the output, after being filtered by a connected capacitor of 10 mF, was 587V. Utilizing the square PWM technique in the IGBT, this 587V was supplied to the inverter, resulting in the inverter producing a square wave voltage in the line-to-line configuration. Upon adding filter inductance of 5 mH and capacitance of 2mF, the waveform was transformed into a sinusoidal form. This alternating sinusoidal wave was then supplied to the PMSM motor, which operated with a torque of 5 N-m and an inertia of 0.008 kg·m^2, achieving a speed of 1500 RPM.

   In case of Induction motor when a 230V RMS supply was applied to the rectifier, the output, after being filtered by a connected capacitor of 10 mF, was 325V. Utilizing the square PWM technique in the IGBT, this 325V was supplied to the inverter, resulting in the inverter producing a square wave voltage in the line-to-line configuration with r.m.s voltage of 265.3V. Induction motor is operated with a torque of 5 N-m and an inertia of 0.05 kg·m^2, with 2 poles achieving a speed of 2845 RPM.

2. In the experimental hardware setup, the induction motor exhibits a speed that aligns precisely with the simulated results. This congruence indicates that the induction motor is operating correctly and as expected, demonstrating the accuracy and reliability of both the simulation model and the physical implementation.

In the hardware setup, the permanent magnet synchronous motor (PMSM) shows a lower speed than in simulations, likely due to harmonics. Future research should focus on harmonic mitigation techniques, improved control algorithms like model predictive control (MPC) or AI, and hardware refinements. Implementing real-time monitoring and diagnostic systems to detect and compensate for harmonics is essential. Extensive real-world testing will be crucial to align hardware performance with simulations and advance motor control systems.

3. Future work could focus on optimizing control algorithms using predictive control or artificial intelligence, integrating the system with renewable energy sources for hybrid configurations, and enhancing fault detection methods for improved reliability and safety. Additionally, developing intelligent energy management strategies, refining hardware through real-world experiments, conducting cost-effectiveness analyses, and studying the impacts of grid integration are essential. These efforts will contribute to the progress in energy storage technology, improving system efficiency, reliability, and sustainability, thus paving the way for practical applications in the energy sector.

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Appendix A

Arduino Codes

A.1 Code for PMSM

```
int delayPd; // Variable to control the on-time delay
int deadtime; // Variable to control the off-time delay
int i=0;
void setup() {
  // Set the pins used for controlling the transistors as OUTPUT
  pinMode (2, OUTPUT);
  pinMode (3, OUTPUT);
  pinMode (4, OUTPUT);
  pinMode (5, OUTPUT);
  pinMode (6, OUTPUT);
  pinMode (7, OUTPUT);

  // Ensure all transistors are initially turned off
  digitalWrite (2, LOW);
  digitalWrite (3, LOW);
  digitalWrite (4, LOW);
  digitalWrite (5, LOW);
  digitalWrite (6, LOW);
  digitalWrite (7, LOW);
```

```
  // Initialize on-time delay to decrease
  delayPd = 15000; // Decreased from 1666.67

  // Initialize off-time delay to increase
  deadtime = 10; // Increased from 6
}

void loop() {
  if (i<400){
    delayPd = delayPd - 30;

  }
  delay(1);
  i++,
  // Turn on AH, BL, and CH
  digitalWrite(2, HIGH); //AH active
  digitalWrite(5, HIGH); //BL active
  digitalWrite(6, HIGH); //CH active
  delayMicroseconds(delayPd);

  // Turn off CH
  digitalWrite(6, LOW); //CH LOW
  delayMicroseconds(deadtime);

  // Turn on CL
  digitalWrite(7, HIGH); //CL active
  delayMicroseconds(delayPd);

  // Turn off BL
  digitalWrite(5, LOW); //BL LOW
  delayMicroseconds(deadtime);
```

```
  // Turn on BH
  digitalWrite(4, HIGH); //BH active
  delayMicroseconds(delayPd);

  // Turn off AH
  digitalWrite(2, LOW); //AH LOW
  delayMicroseconds(deadtime);

  // Turn on AL
  digitalWrite(3, HIGH); //AL active
  delayMicroseconds(delayPd);

  // Turn off CL
  digitalWrite(7, LOW); //CL LOW
  delayMicroseconds(deadtime);

  // Turn on CH
  digitalWrite(6, HIGH); //CH active
  delayMicroseconds(delayPd);

  // Turn off BH
  digitalWrite(4, LOW); //BH LOW
  delayMicroseconds(deadtime);

  // Turn on BL
  digitalWrite(5, HIGH); //BL active
  delayMicroseconds(delayPd);// Turn off AL
  digitalWrite(3, LOW); //AL LOW
  delayMicroseconds(deadtime);
}
```

A.2 Code for Induction Motor

```
int delayPd;
int deadtime;
void setup() {
  pinMode (2, OUTPUT);
  pinMode (3, OUTPUT);
  pinMode (4, OUTPUT);
  pinMode (5, OUTPUT);
  pinMode (6, OUTPUT);
  pinMode (7, OUTPUT);
  digitalWrite (2, LOW);
  digitalWrite (3, LOW);
  digitalWrite (4, LOW);
  digitalWrite (5, LOW);
  digitalWrite (6, LOW);
  digitalWrite (7, LOW);
  delayPd = 3333.3;
  deadtime = 6;
}
void loop() {
  // put your main code here, to run repeatedly:
  digitalWrite(2, HIGH); //AH active
  digitalWrite(5, HIGH); //BL active
  digitalWrite(6, HIGH); //CH active
  delayMicroseconds(delayPd);
  digitalWrite(6,LOW); //CH LOW
  delayMicroseconds(deadtime);
  digitalWrite(7, HIGH); //CL active
  delayMicroseconds(delayPd);
  digitalWrite(5,LOW); //BL LOW
```

```
delayMicroseconds(deadtime);
digitalWrite(4, HIGH); //BH active
delayMicroseconds(delayPd);
digitalWrite(2,LOW); //AH LOW
delayMicroseconds(deadtime);
digitalWrite(3, HIGH); //AL active
delayMicroseconds(delayPd);
digitalWrite(7,LOW); //CL LOW
delayMicroseconds(deadtime);
digitalWrite(6, HIGH); //CH active
delayMicroseconds(delayPd);
digitalWrite(4,LOW); //BH LOW
delayMicroseconds(deadtime);
digitalWrite(5, HIGH); //BL active
delayMicroseconds(delayPd);
digitalWrite(3,LOW); //AL LOW
delayMicroseconds(deadtime);

}
```

A.3 Code for SPWM Pulse

```
int pwmA = 9;
int pwmB = 10;
int pwmC = 11;
int pwmD = 3;
int pwmE = 5;
int pwmF = 6;
const int numPoints = 12; // Number of points in the sine wave
const byte sineWaveA[numPoints] = {127,191,238,255,238,
191,127,63,16,0,16,63};
```

```
const byte sineWaveB[numPoints] = {238,191,127,63,16,0,
16,63,127,191,238,255};
const byte sineWaveC[numPoints] = {16,0,16,63,127,191,
238,255,238,191,127,63};
const byte sineWaveD[numPoints] = {127,63,16,0,16,63,
127,191,238,255,238,191};
const byte sineWaveE[numPoints] = {16,63,127,191,238,
255,238,191,127,63,16,0};
const byte sineWaveF[numPoints] = {238,255,238,191,127,
63,16,0,16,63,127,191};
void setup() {
    pinMode(pwmA, OUTPUT);
     pinMode(pwmB, OUTPUT);
     pinMode(pwmC, OUTPUT);
    pinMode(pwmD, OUTPUT);
     pinMode(pwmE, OUTPUT);
     pinMode(pwmF, OUTPUT);
}
void loop() {
  // Output the sine wave points using PWM
  for (int i = 0; i < numPoints; i++) {
    analogWrite(pwmA, sineWaveA[i]);
      analogWrite(pwmB, sineWaveB[i]);
       analogWrite(pwmC, sineWaveC[i]);
    analogWrite(pwmD, sineWaveD[i]);
      analogWrite(pwmE, sineWaveE[i]);
       analogWrite(pwmF, sineWaveF[i]);

    delay(2);  // Adjust delay as needed for desired frequency
  }
}
```