TRANSFORMER LESS HYBIRD ACTIVE FILTER USING A THREE – LEVEL PWM CONVERTER FOR MEDIUM VOLTAGE MOTOR DRIVE

PROJECT PHASE-1

POWERING THE YOUTH
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BONAFIDE CERTIFICATE

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LIST OF FIGURE

LIST OF ACRONYMS (SYMBOLS) USED IN THE REPORT

Acronym/Symbol	Meaning
BTB	Back-to-Back
DSP	Digital Signal Processor
ECCE	Energy Conversion Congress and Expo
HVDC	High Voltage Direct Current
PC	Personal Computer
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion
AF	Active Filter
NPC	Neutral Point Clamped
STATCOM	Static Synchronous Compensator
VSD	Variable Speed Drive
IEEE	Institute of Electrical and Electronics Engineers

ABSTRACT

This project presents a transformer less hybrid active filter integrated into a medium-voltage motor drive for energy savings. This hybrid filter is intended for line harmonic-current mitigation of the three-phase diode rectifier used as the front end of the motor drive. It is based on direct connection of a passive filter tuned to the seventh-harmonic frequency in series with an active filter using a three-level pulse width modulated (PWM) converter. This paper provides a theoretical discussion on voltage-balancing control of two split dc capacitors of the active filter. The 400-V 15-kW motor drive system is designed, constructed, and tested, which can be considered as a downscaled model from a medium voltage motor drive without regenerative braking. Experimental results verify that the hybrid filter has the capability of satisfactory harmonic filtering and stable voltage balancing in all the load conditions

CHAPTER 1: INTRODUCTION

1.1 PROJECT DEFINITION:

The document presents a detailed exploration of a transformer-less hybrid active filter designed to improve energy efficiency and harmonic mitigation in medium-voltage motor drives. These motor drives are widely used in applications such as fans, blowers, pumps, and compressors, where fast speed control and regenerative braking are not required. Traditional systems employing three-phase diode rectifiers often introduce significant harmonic currents into the AC mains, resulting in non-compliance with established harmonic guidelines.

To address this challenge, the proposed hybrid active filter combines a passive filter tuned to the seventh-harmonic frequency with a three-level pulse width modulation (PWM) converter. This innovative configuration eliminates the need for bulky and costly transformers, while simultaneously achieving stable harmonic filtering and power factor correction for inductive loads in industrial environments.

The report provides theoretical analyses and experimental validations to demonstrate the efficacy of the hybrid active filter. A downscaled prototype rated at 400 V and 15 kW is utilized for testing, yielding results that validate the hybrid system's capability to balance voltages and mitigate harmonics under various load conditions. This work serves as a cornerstone for future advancements in medium-voltage motor drive systems, offering both cost efficiency and enhanced performance.

CASE STUDY :

Background: In a large manufacturing plant specializing in the production of textiles, medium-voltage motor drives were extensively used to operate high-power machinery such as looms and dyeing equipment. The plant experienced significant issues with power quality, including high levels of harmonic distortion, leading to inefficient energy use, overheating of equipment, and non-compliance with regulatory standards.

The primary source of these power quality issues was the three-phase diode rectifiers integrated into the motor drives. These rectifiers generated substantial harmonic currents, causing voltage distortion in the AC mains. The plant's management sought a cost-effective and space-saving solution to mitigate these harmonics and improve overall power quality.

Solution: The engineering team introduced a transformerless hybrid active filter to address these challenges. The hybrid filter combined:

1. **Passive Filter**: Tuned to the seventh-harmonic frequency to remove specific harmonic currents effectively.
2. **Active Filter**: A three-level neutral-point-clamped (NPC) pulse-width modulation (PWM) converter that dynamically adjusted to manage harmonic currents and balance DC voltages.

The absence of a transformer in the hybrid filter design reduced installation complexity and costs. The active filter's low DC-link voltage (20% of the AC voltage) enabled the use of standard insulated gate bipolar transistors (IGBTs), making the solution affordable and scalable.

Implementation: A 400 V, 15 kW prototype of the hybrid active filter was tested in one section of the plant. The system was configured to operate alongside the existing motor drives without requiring significant modifications. The installation process took two days, minimizing downtime.

Results: After implementation, the hybrid active filter achieved the following results:

- **Harmonic Reduction**: The total harmonic distortion (THD) of the current was reduced from 28% to 3.5%, well below the regulatory limit.
- **Improved Power Factor**: The system maintained a near-unity power factor, reducing reactive power losses.
- **Energy Savings**: The reduction in harmonics and improved efficiency led to a 7% decrease in energy consumption.
- **Equipment Longevity**: Lower harmonic currents reduced stress on motors and electrical components, extending their operational lifespan.

Conclusion: The successful deployment of the transformerless hybrid active filter in the textile manufacturing plant demonstrated its effectiveness in mitigating harmonic distortion, enhancing power quality, and improving energy efficiency. The plant is now scaling the solution to other sections, aiming for comprehensive power quality management.

Future Scope: Further studies are planned to explore the hybrid filter's performance under varying load conditions and during voltage sags or interruptions, ensuring robustness in all operational scenarios.

1.2 PROJECT OBJECTIVES:

1. **Harmonic Mitigation:**
   To effectively reduce harmonic distortion in medium-voltage motor drive systems, ensuring compliance with international harmonic standards and improving power quality.

2. **Energy Efficiency:**
   To enhance energy savings by optimizing power factor and reducing reactive power losses through the integration of transformerless hybrid active filters.

3. **Cost-Effective Solution:**
   To implement a scalable and economically viable system by eliminating the need for bulky transformers and utilizing commercially available components like IGBTs.

4. **System Reliability:**
   To improve the operational reliability and longevity of electrical equipment by minimizing the negative impacts of harmonic currents and voltage imbalances.

5. **Flexibility and Scalability:**
   To design a flexible solution capable of adapting to various load conditions, with potential for future scaling to higher voltage levels and diverse industrial applications.

1.3 PROJECT SPECIFICATIONS:

Here are the specifications of the transformer less hybrid active filter system as listed in Table 1.1.

Specification	Value/Description
Rated Voltage	400 V
Rated Power	15 kW
Diode Rectifier Voltage	380 V for induction motor drive
Induction Generator Voltage	190 V
DC-Link Voltage	80 V (20% of the rated 400 V)
Switching Devices	- Twelve 600-V IGBTs for the motor and generator drive - Twelve 100-V MOSFETs for the active filter
Filter Type	Hybrid (Passive + Active)
Passive Filter	Tuned to the 7th-harmonic frequency
Active Filter	Three-level NPC PWM converter
Control System	Digital signal processor (DSP) and field-programmable gate arrays (FPGAs)
Switching Frequency	10 kHz carrier frequency (5 kHz for each MOSFET)
Harmonic Mitigation	Reduced Total Harmonic Distortion (THD) from 31% to 3.8%

1.4 APPLICATIONS:

- **Medium-Voltage Motor Drives:**
  - Used in industrial motor drive systems operating fans, blowers, pumps, and compressors, particularly where regenerative braking is not required.
  - Suitable for systems relying on three-phase diode rectifiers to ensure harmonic mitigation and energy efficiency.
- **Industrial Power Systems:**
  - Applicable in industrial environments for improving power quality by reducing harmonic currents and maintaining voltage stability.
  - Provides power factor correction, benefiting other inductive loads connected to the same power distribution network.
- **Energy Conservation in High-Power Applications:**
  - Reduces power losses and optimizes energy use in industries such as manufacturing, textile production, and heavy-duty processes.
- **Harmonic Regulation Compliance:**
  - Ensures compliance with international harmonic standards for large-scale electrical systems by mitigating harmonic distortion to permissible levels.
- **Scalable Design for High-Voltage Systems:**
  - Designed for potential scalability to higher voltage applications, such as 6.6 kV motor drives, with modular components like NPC PWM inverters and passive filters.

CHAPTER 2: LITERATURE REVIEW

2.1 PROJECT BACKGROUND AND HISTORY OF HYBRID FILTER:

The research presented in the document builds upon decades of advancements in active and passive filtering technologies for improving power quality in industrial applications. Key developments and prior works cited in the paper provide the foundation for the proposed transformer - less hybrid active filter.

1. Early Developments in Active Filters:

Pioneering work by researchers such as Akagi and Nabae (1990) introduced the concept of combining passive filters with active components to mitigate harmonics. Their work demonstrated that hybrid systems were more efficient than purely active or purely passive systems.

- Reference: Akagi et al. (1991, 1996) discussed practical implementations of harmonic compensation using combined filter systems.

2. Evolution of PWM Converters:

Neutral-point-clamped (NPC) PWM converters emerged as a critical advancement in power electronics, enabling better voltage control and harmonic mitigation in medium-voltage applications.

- Studies such as those by Nabae and Takahashi (1981) introduced three-level NPC inverters, which later became essential for hybrid active filter designs.

3. Hybrid Active Filters in High-Power Applications:

The integration of hybrid active filters in high-power systems, such as HVDC and large industrial plants, gained traction in the late 1990s and 2000s.

- Works like Bhattacharya et al. (1997) highlighted the viability of hybrid solutions for damping resonance and improving power quality.
- Detjen et al. (2001) further explored combining passive components with active

filters for industrial power systems.

4. Challenges in Voltage Balancing:

A notable challenge in using three-level NPC PWM converters is maintaining voltage balance across split DC capacitors.

- Celanovic and Boroyevich (2000) analyzed neutral-point balancing problems and proposed solutions, which informed the control strategies used in this study.
- Matsui et al. (1995) introduced voltage injection methods to stabilize capacitor voltages, which were refined further in this project.

5. Advances in Harmonic Mitigation:

Recent works before the publication of this document focused on harmonic guidelines compliance and the optimization of filtering techniques for medium-voltage systems.

- Akagi and Hatada (2009) provided graphical explanations for voltage-balancing mechanisms in three-level converters, laying the groundwork for the theoretical and experimental analyses in this project.

Gaps Identified and Addressed:

While earlier research established the principles and components of hybrid filters, gaps remained in adapting these technologies for transformerless configurations in medium-voltage motor drives. The following challenges were addressed:

- **Eliminating the Transformer:** Traditional hybrid systems relied on transformers, which increased cost and complexity.
- **Scalability:** Most prior solutions were not easily scalable to medium-voltage applications.
- **Voltage Balancing:** Few studies focused on voltage balancing for hybrid systems with NPC PWM converters under non-sinusoidal current conditions.

2.2 PREVIOUS WORK:

1. Combination of Active and Passive Filters (1990s):

Initial research combined passive filters with active filters for harmonic compensation in industrial power systems. Early works by Akagi, Nabae, and Fujita highlighted the advantages of hybrid systems over standalone active or passive solutions:

- **Passive filters** provided low-cost harmonic mitigation tuned to specific frequencies.
- **Active filters** dynamically adjusted to suppress higher-order harmonics and address reactive power compensation.
    - *Key Reference*: Akagi et al. (1990) introduced a combined shunt passive and series active filter system for harmonic compensation.

2. PWM Rectifiers and Converters:

The development of pulse width modulation (PWM) rectifiers and converters provided the foundation for harmonic filtering in medium- and high-voltage systems.

- Three-level neutral-point-clamped (NPC) PWM converters were introduced by Nabae and Takahashi (1981), enabling efficient voltage balancing and low harmonic distortion.
- These converters became critical in hybrid filter designs for improving voltage control and dynamic harmonic mitigation.

3. Hybrid Filters for High-Power Systems:

In the late 1990s and early 2000s, hybrid active filters were adopted in high-power applications, such as HVDC systems and industrial motor drives.

- Bhattacharya et al. (1997) demonstrated that hybrid filters could effectively dampen resonances and reduce harmonic currents in power distribution systems.
- Detjen et al. (2001) explored the use of hybrid filters for harmonic mitigation in industrial setups with high power factor correction demands.

4. Challenges in Voltage Balancing:

Neutral-point voltage balancing in three-level converters became a significant focus in the 2000s.

- Research by Celanovic and Boroyevich (2000) analyzed the inherent balancing issues in NPC inverters and proposed space vector control methods for improvement.
- Matsui et al. (1995) introduced voltage stabilization techniques using harmonic injection methods.

5. Early Hybrid Filters in Motor Drives:

Several studies explored hybrid filters in motor drive systems but faced challenges related to:

- Dependency on transformers for isolation and impedance matching.
- Inadequate scalability for medium-voltage applications.
    - *Key Reference*: Akagi and Hatada (2009) provided critical insights into voltage-balancing mechanisms and hybrid filter performance in motor drives.

Figure 2.2: Passive and active filter

2.3 COMPONENTS

This section is a general description of the functions of the main parts that are involved in abicycle movement.

Component	**Description/Function**
Three-Level NPC PWM Converter	Used as the active filter for harmonic mitigation and dynamic voltage balancing.
Passive Filter	Tuned to the seventh-harmonic frequency for removing specific harmonic currents.
IGBTs (Insulated Gate Bipolar Transistors)	600-V IGBTs for the three-level NPC PWM inverter and BTB systems.
MOSFETs	100-V MOSFETs employed in the active filter for fast switching operations.
DC-Link Capacitors	Two split DC capacitors for maintaining balanced voltages across the NPC PWM converter.
Digital Signal Processor (DSP)	Central processing unit for controlling the active filter and implementing voltage-balancing algorithms.

Component	Description/Function
Field Programmable Gate Arrays (FPGAs)	Used for implementing high-speed control logic and PWM generation.
Induction Motor	15 kW, 380 V motor used for testing the system.
Induction Generator	15 kW, 190 V generator mechanically coupled to the motor for load testing.
Voltage Sensors	Measure DC voltages across the capacitors for real-time control adjustments.
Current Sensors	Monitor harmonic currents and provide feedback to the control system.

2.3.1 MICROCONTROLLER:

The family of microcontroller is 8051 which has same member of family is 89c51, 89c52 etc. There are different packages such as dual in line packages (DIP), quad flat packages (QFP), lead less chip carrier (LLC). The microcontroller family such 89c51, 89c52 consists of 40 pin which consists of four I/O ports. The supply vtg is applied to 40^{th} pin of controller and grounded by 20^{th} pin. Crystal oscillator is used to generate frequency which is connected to 18^{th} and 19^{th} pin of the controller.

RESET is used to reset the controller which is normally low, 9^{th} is used for reset. When the high pulse is applied to reset, it will reset the controller and all the activities will be terminated, counter will reset to zero and all values in the register will be lost. It also called as POWER ON RESET.

Port 0 consists of 8 pin which is used for interfacing or I/O port. normally P0-P3 has value FFH to them. Port 0can is used as address and data (AD0-AD7). Port 0 does not contain any external resistor, so pull up resistor (10k) is connected with port0 which can be used simple I/O port. But, Interfacing the LCD display is connected with the port 0 of the controller which pin details of LCD display is given below.

Port 3:

Port 3 is used for serial communication which transfers the data from controller to PC and vice versa. Pin 3.1 is connected to the 11^{th} pin of the max 232 which is used for transmit the data to pc through max232 and vice-versa. Pin 3.0 is connected to the 12^{th} pin of the max 232 which is used for receive the data from pc and vice-versa through max232. Pin 11 and 12 of microcontroller is used for interrupts 0 and interrupts 1. The interrupt o and 1 is select according to user. Pin 14 and 15 of microcontroller is used for timer/counter 0 and 1. There are different timer namely timer 0 and timer 1 which is used for delay purpose and as well as counter. If (C/T=0), it is used as timer for time generation. If (C/T=1), it is used as counter which is used for counting purpose such as pulse. If serial application is not needed that the port 3 can be used as I/O port.

Port 1 and Port 2:

Port 2 and port 1 can be used as I/O ports. Depending upon the user, either of this port can used as input or output.port2 must be used along with the port 0 to provide the address for external memory which is used for LCD display. The port pin used for external memory rather pin is used for I/O operation. Depending upon the application, controller port is used.

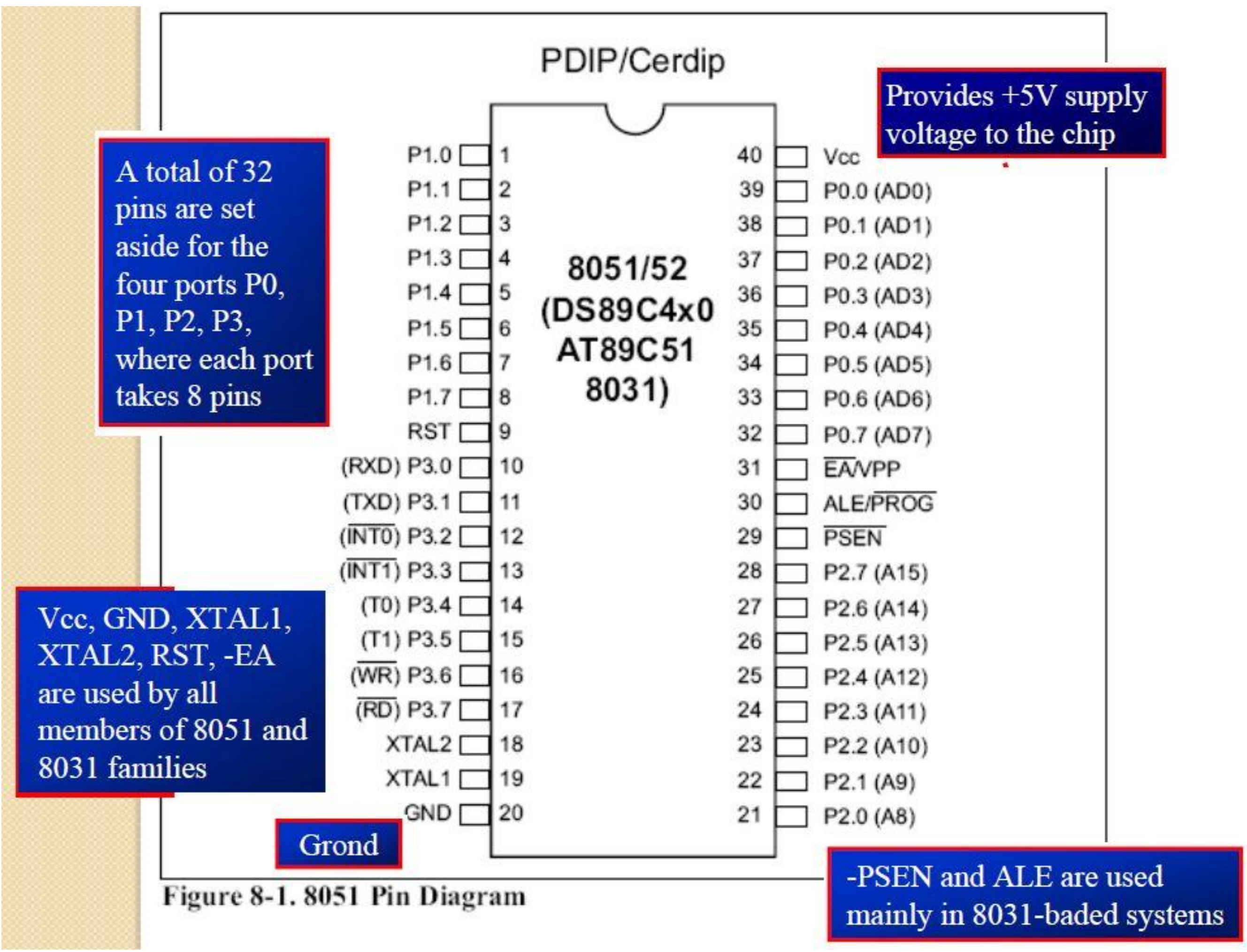


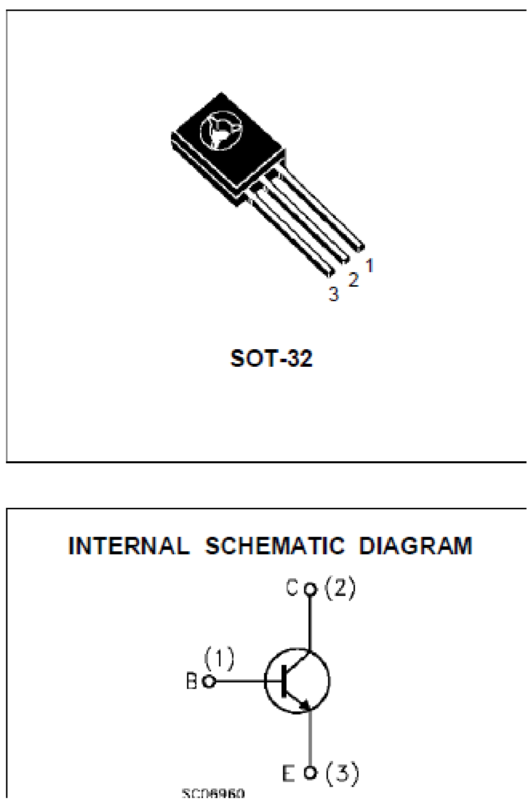
Figure 2.3.1: MICROCONTROLLER

2.3.2 BD135, BD137, BD139:

- **Voltage Ratings:** 45V, 60V, 80V (depending on the model).
- **Applications:** Suitable for audio amplifiers and other driver circuits.
- **Thermal Management:** Includes dissipation ratings and thermal resistance for durability in high-power applications.

These components, particularly the transistors, PWM converters, and passive filters, collectively enable efficient harmonic mitigation, voltage control, and power quality improvement in the hybrid active filter system. Let me know if you'd like a more detailed explanation of any component

Figure 2.3.2 : Transister



2.3.3 OPTOCOUPLER:

The **4N35** is an optocoupler designed to provide electrical isolation between an input signal and an output circuit. Below are its key specifications and applications based on the provided document:

Key Features

- **Optical Coupling:** Uses a gallium-arsenide infrared LED optically coupled to a silicon NPN phototransistor.
- **High Electrical Isolation:** Provides isolation ratings up to 3.55 kV, making it ideal for separating high-voltage and low-voltage circuits.
- **High-Speed Switching:** Typical switching times of 7 µs for both turn-on and turn-off.
- **Direct-Current Transfer Ratio:** Efficient current transfer between input and output.

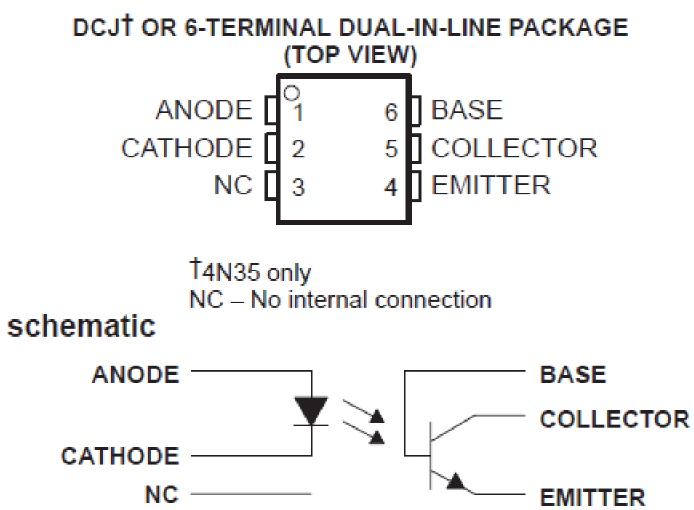


Figure 2.3.3: OPTOCOUPLER

2.3.4 MOSFET:

MOSFETs play a critical role in the three-level NPC PWM converter of a transformer less hybrid active filter, primarily through their high-speed switching capabilities. Acting as the switching elements, MOSFETs provide precise control over the switching states, enabling the generation of accurate output voltage waveforms essential for counteracting harmonic currents. Their high switching speed ensures efficient modulation, maintaining optimal system performance under varying load conditions. Additionally, MOSFETs facilitate harmonic mitigation by enabling the active filter to inject compensating currents into the system, effectively canceling unwanted harmonics introduced by the motor drive's front-end diode rectifier, ensuring compliance with harmonic regulations.

In the context of voltage balancing, MOSFETs are instrumental in stabilizing the split DC-link capacitors of the NPC converter. Through controlled switching, they manage current flows that equalize the capacitor voltages, ensuring stable and reliable operation. Moreover, MOSFETs contribute to reactive power compensation by dynamically adjusting to supply reactive power, enhancing the power factor and overall energy efficiency of the motor drive system. This dual role in reducing harmonic distortion and improving energy efficiency underscores their importance in ensuring the hybrid active filter's effectiveness and reliability in medium-voltage motor drive applications.

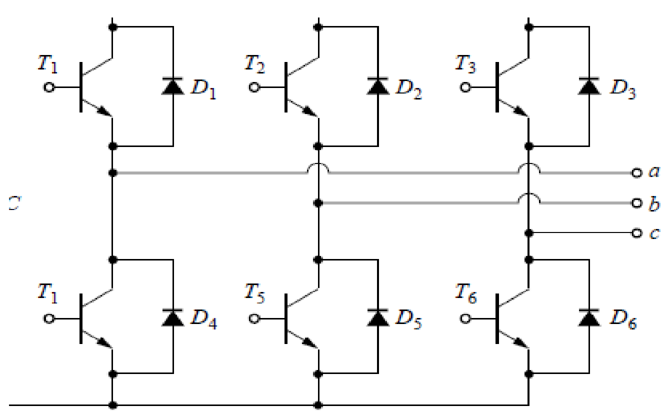


Figure 2.3.4: MOSFET

2.3.5 PWM INVERTER:

1. **Pulse-Width Modulation (PWM):**
   - PWM is a technique used to control the width of pulses in a pulse train in direct proportion to a control signal. The width of the pulses increases with the control voltage.
   - By using a sinusoidal control voltage, PWM can generate a high-power waveform with an average voltage that varies sinusoidally, making it suitable for AC motor applications.
2. **PWM Inverter Circuit:**
   - The document describes a single-phase PWM inverter circuit that utilizes Insulated Gate Bipolar Transistors (IGBTs).
   - It explains the role of comparators in the circuit, which compare the input voltage to reference signals and control the states of the IGBTs accordingly.
3. **Operation of the PWM Inverter:**
   - The document outlines how the inverter operates under different control voltage conditions:
     - With a control voltage of 0 V, the output voltage is zero.
     - With a constant positive control voltage (half of the peak reference voltage), the output voltage has a 50% duty cycle.
     - With a sinusoidal control voltage, the pulse width varies sinusoidally, resulting in a high-power output waveform.
4. **Harmonics and Motor Control:**
   - **While the output waveform contains harmonic components, they are generally not a concern for motor control applications. However, they can cause additional heating in motors, which can be managed by using specially designed motors or derating standard motors.**
5. **Three-Phase PWM Inverter:**
   - A complete three-phase PWM inverter consists of three single-phase inverters with control voltages that are sinusoidal and phase-shifted by 120°.
   - Frequency control is achieved by varying the frequency of the input control voltage.
6. **Switching Frequency and Component Requirements:**
   - PWM inverters switch states rapidly, with reference voltages reaching frequencies as high as 12 kHz, requiring components that can handle high-speed, high-power switching.
   - IGBTs are highlighted as the preferred components for building PWM inverters due to their advantages in high-speed applications.

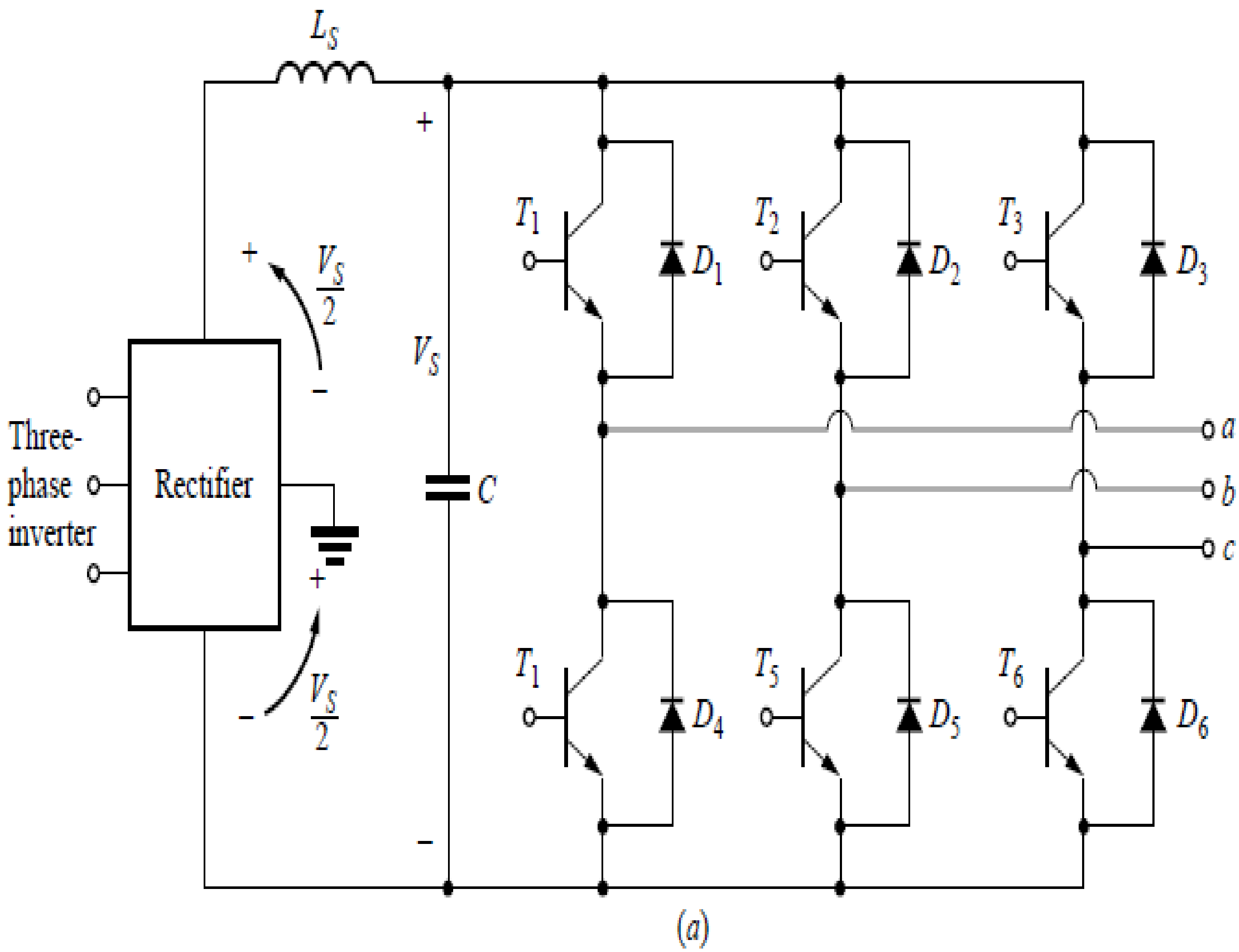


Figure 2.3.5: PWM INVETER

CHAPTER 3: SYSTEM DESIGN

3.1 DESIGN CONSTRAINTS:

Voltage Ratings: The system must handle voltages up to 6.6 kV, as indicated in the context.

Power Ratings: The active filter should be designed to work effectively with a motor drive system rated at 15 kW.

Harmonic Mitigation: The design should effectively reduce total harmonic distortion (THD) to comply with relevant guidelines, such as the Japanese harmonic guidelines.

Voltage Balancing: The design must ensure stable voltage balancing between the two dc capacitors in the system.

Load Conditions: The system should perform well under various load conditions, from no load to full load.

Transient Response: The active filter should have a quick response time to changes in load conditions and should be able to handle transient events without instability.

Control Strategy: The design must incorporate a control strategy for the active filter that can manage the injection of harmonic voltages effectively.

3.2 DESIGN METHODOLOGY:

1. **System Requirements Definition**:
    - Identify the application requirements, including voltage levels (6.6 kV), power ratings (15 kW), and the need for harmonic current mitigation.
    - Establish performance criteria such as acceptable total harmonic distortion (THD) levels and voltage balancing between dc capacitors.
2. **Theoretical Analysis**:
    - Conduct theoretical analysis to understand the behavior of the hybrid filter system, including the interaction between the passive and active components.
    - Analyze the effects of injecting second-harmonic negative-sequence voltages and sixth-harmonic zero-sequence voltages on the system performance.
3. **Component Selection**:
    - Select appropriate components, such as IGBTs rated for 1.2 kV, that can handle the operational requirements of the system.
    - Choose passive filter components tuned to the seventh-harmonic frequency to complement the active filter.
4. **Control Strategy Development**:
    - Develop a control strategy for the active filter that includes voltage-balancing control for the two dc capacitors.
    - Implement algorithms for harmonic current detection and compensation to ensure effective filtering under varying load conditions.

5. **Simulation and Modelling**:
    - Create a simulation model of the hybrid active filter system to predict its performance under different operating conditions.
    - Use numerical analysis to evaluate the waveforms and system responses to various harmonic injections.
6. **Prototype Development**:
    - Build a prototype of the hybrid active filter based on the design specifications and selected components.
    - Ensure that the prototype includes the necessary circuitry for voltage balancing and harmonic compensation.
7. **Experimental Testing**:
    - Conduct experimental tests to validate the performance of the hybrid filter under different load conditions, including no load and full load.
    - Measure key parameters such as dc capacitor voltages, ac input power, and harmonic current contents to assess the effectiveness of the design.
8. **Performance Evaluation**:
    - Analyze the experimental results to evaluate the filtering performance, voltage balancing, and overall system stability.
    - Compare the measured THD values and harmonic current contents against the established performance criteria

3.3 CIRCUIT DIAGRAM:

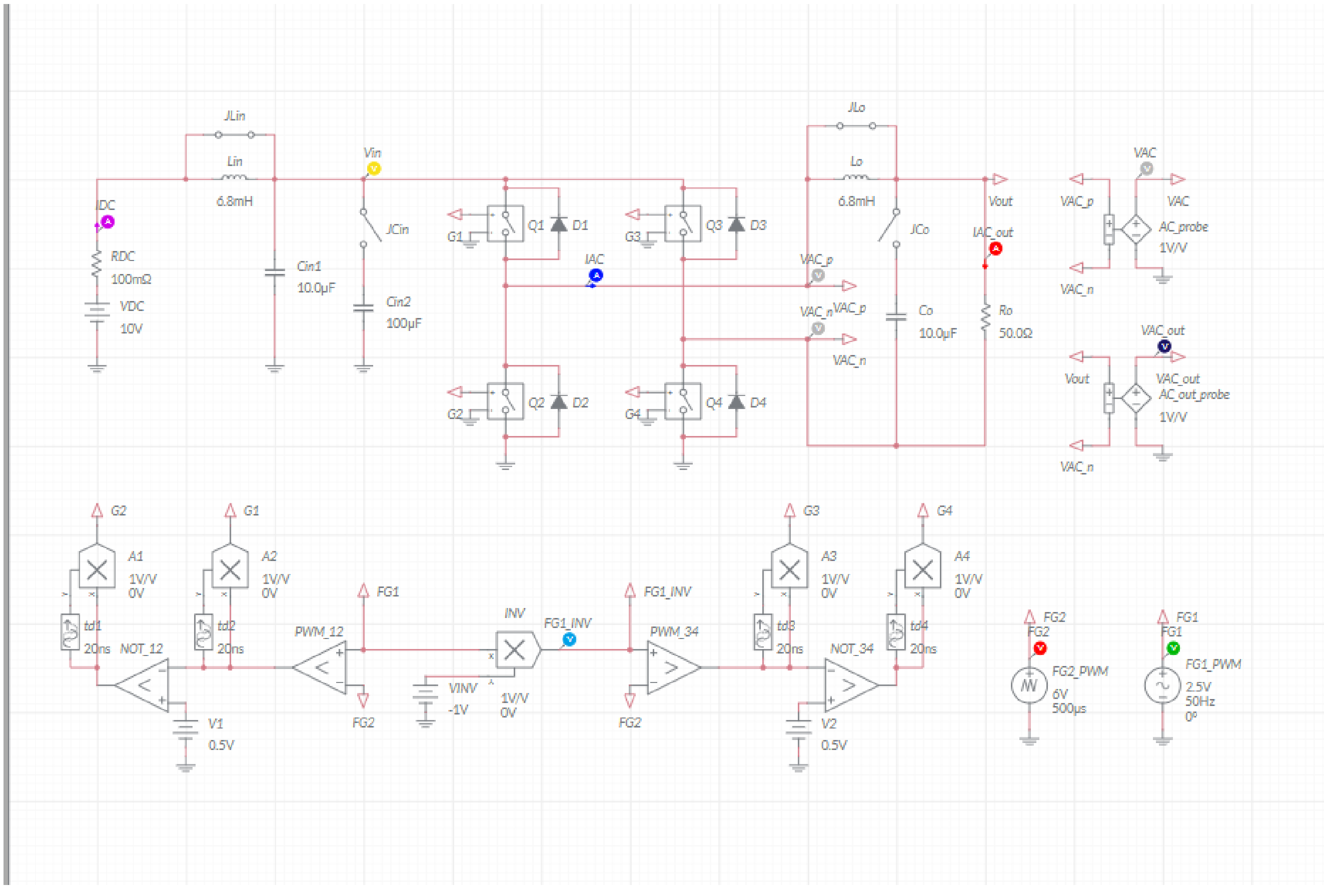
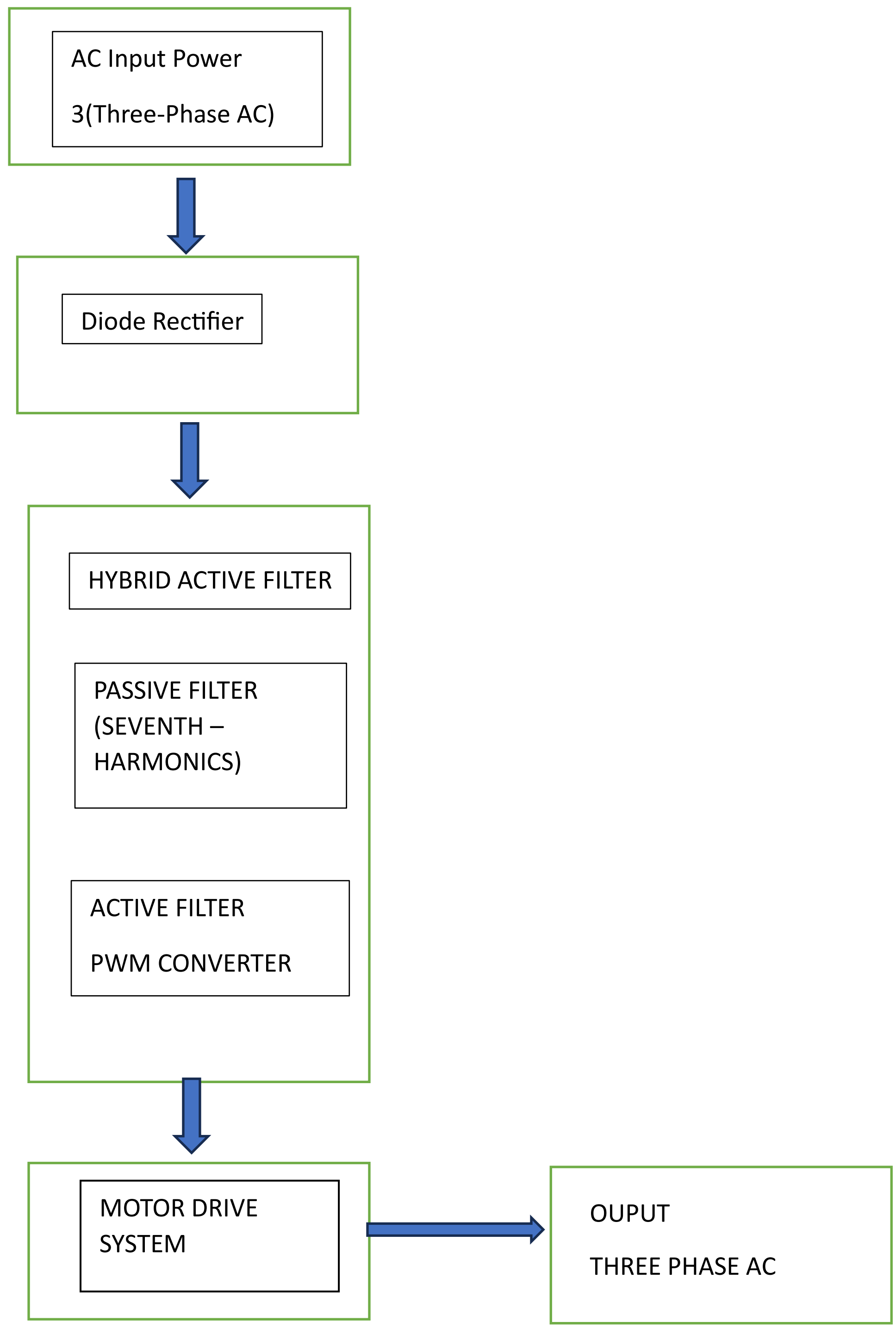


Figure 3.3: CIRCUIT DIAGRAM

3.4 BLOCK DIAGRAM:



CHAPTER 4: SYSTEM TESTING AND ANALYSIS

4.1 Configuration of the MVDC Testbed

The operation of ANGLE-DC is demonstrated by a scaled-down MVDC testbed. The experimental platform .which aimed to resemble the real practical configuration as much as possible. There are two converter cabinets, labelled Stations 1 and 2, which constitute the back-to-back converter system. The power of each cabinet is supplied by a power amplifier (PA-3*3000-AB/260/2G) which emulates the AC grid, shown shows the internal structure of the cabinet as well as the hardware board within each SM. Figure 3.5(a) shows the twelve 3L-NPC cascaded SMs, a high-level main controller and the isolation transformers. The main controller is used to coordinate and monitor the operation of the SMs. shows the top layer components of a single SM, which includes three-phase IGBT power modules, SM controllers based on DSP 28335 and the power supply to the microcontroller. Other components such as the inductor, relay and cooling fans are under the bottom layer.

Figure 4.1: TEST BED

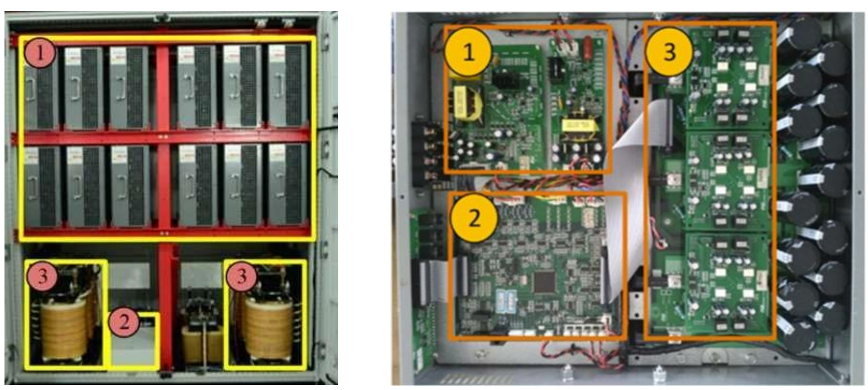
The leakage inductance of the transformer in real system can provide filtering of the harmonics. Since the leakage inductance of the transformer for the testbed is significantly smaller than that of the real system, an additional L-type grid-connected inductor is used. The values of the Lfilter and DC capacitors are calculated as:

$$L_{..} = \frac{}{} \quad \frac{}{}\,./ \quad = \quad \_\,./$$

$$= 0.22 \text{ p. u.} \qquad (3\text{-}2)$$

$$C_{..} \quad \frac{C_{dc}\ 12}{C_{base}} = \frac{C_{dc}\ 12}{\frac{1}{\omega_{base} Z_{dc\ base}}} \quad / \quad / \quad == 5.5 \text{ p. u.} \qquad (3\text{-}3)$$

where $Z_{\_} = \frac{}{}\,(S = S,\ V_{\_} = V)$, $\omega = \omega$, and N is the turns ratio of the isolation transformer.



(a) (b)

Figure 4.1.1 Internal structure of the MVDC station and each SM. (a) MVDC station: 1) twelve

3L-NPC SMs, 2) high-level main controller, and 3) isolation transformers. (b) Each SM: 1) power supply to the microcontroller, 2) DSP28335 controller board, and 3) three-phase IGBT power modules.

A parameter comparison between the experimental testbed and the real ANGLE-DC system is provided in Table 3.1. As illustrated, except for the DC capacitance, the selected parameters of the testbed in per unit values are similar to those of the real system.

TABLE 4.1. PARAMETER COMPARISON BETWEEN THE ANGLE-DC CONFIGURATION AND THE EXPERIMENTAL TESTBED [96].

Parameters	ANGLE-DC station	Per unit value	MVDC testbed
Power rating S	33 MVA (2.75 MVA*12)	1 p.u.	30 kVA (2.5 kVA*12)
AC voltage V (rms of $v_{,}$)	33 kV	1 p.u.	415 V
DC link voltage V	±27 kV	1 p.u.	±540 V
Transformer rating	2×17 MVA (Y-33 kV/Δ-2.1 kV)	1 p.u.	2×15 kVA (Y-415 V/Δ-41.5 V)
Transformer impedance	0.2 p.u.	0.2 p.u.	—
Filter inductance (per	—	0.22 p.u.	0.5 mH

VSC)			
DC capacitance (per VSC)	2300 mF	5.32 p.u./ 5.5 p.u.	5400 mF
Switching frequency	750 Hz	—	10 kHz

4.2 Signal Measurement and Hardware Protection

Representative block diagrams summarising signal measurement and hardware protection are provided in Figure 3.6. The current and voltage of each SM are detected by the SM controller. Once the maximum value limit is reached, the SM protection is triggered. At the same time, the PWM driving signals are blocked immediately and the relay at the AC side is opened. As the sampling of the Analogue-to-Digital Converter (ADC) is not quick enough (the signal is sampled once per PWM period, which is 100 μs), an edge detection method is used. At the comparator, if the measured signal is greater than the reference voltage, the output voltage changes from low to high. This method can detect the fault signal within 10 μs, thereby improving the speed of response of the protection scheme.

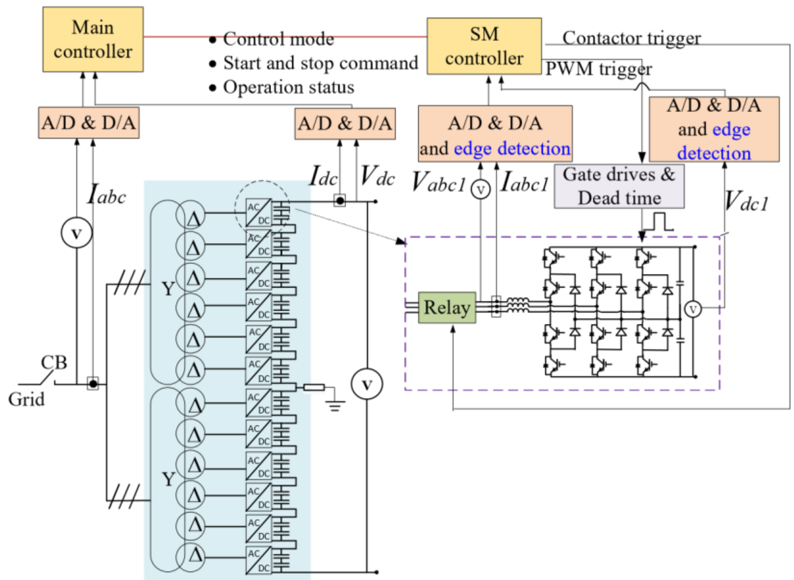


Figure 4.2. Signal measurement and hardware protection diagram.

4.3 Communication

The communication diagram for the MVDC experimental testbed is shown in Figure 3.7. The main controller dispatches control commands and sends suitable references to each SM. Data communication is achieved using an RS485 cable and the Modbus protocol. Also, a digital signal is sent to the SMs for PWM carrier synchronisation. The main controller additionally communicates with a PC in real time to monitor the status of the system operation. To facilitate implementation, the control system (including the ADC sampling, phase-locked loop, Proportional-Integral (PI) controller and protection) was built in MATLAB/Simulink. Then, executable Code Composer Studio (CCS) codes were translated from this MATLAB/Simulink model and downloaded to the DSP 28335 based microcontrollers.

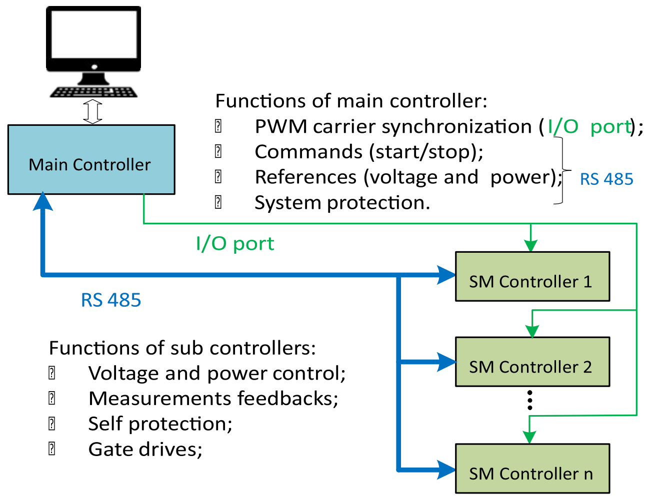


Figure 4.3. Communication diagram.

4.3 Simulation and Experimental Validation

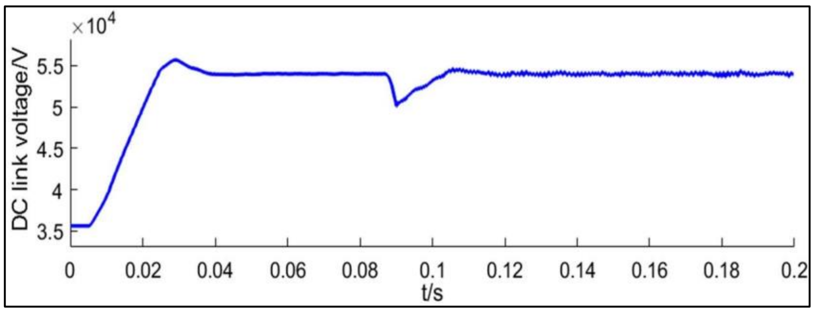
4.4 Simulation Results :

The simulation results are shown .The references of DC voltage active and reactive power are set as the rated value of the real ANGLE-DC project. Figure 3.8 shows the results of the step change of active power. The DC voltage is first increased to 5400 V after 0.03 s. At time 0.1 s, the reference of active power is changed from zero to 30 MW (i.e., 1 p.u.). The total current at the primary side of the transformer is shown .show the individual AC current and DC voltage of each SM. It can be seen that the power and DC voltage of SMs can be shared equally.

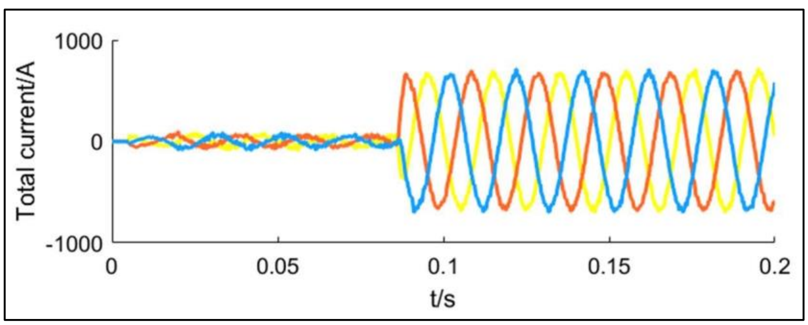
Figure 3.9 shows the condition when power factor is set as zero (i.e., the system is operated with only reactive power). It is seen that the system can work well under reactive power control mode.

Figure 3.10 shows the results under unbalanced grid voltage. A 0.1 p.u. negative-sequence component is added in the grid voltage To control the current as balanced sinusoidal waveform, the dual current controller in is used. As seen in Figure the output current has been balanced. Due to the interactions between the positivesequence current and the negative grid voltage, there is a slight 2^{nd} order ripple in the DC voltage .

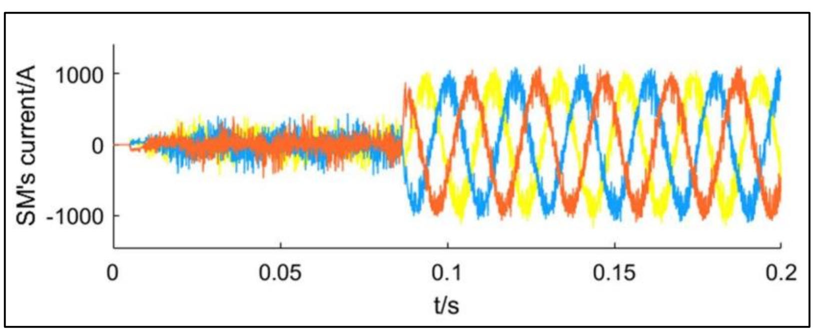
shows the results when droop control is adopted in the two-terminal converter stations. At time 0 s to 0.07 s, the system is operated at the desired operating points. At 0.07 s, one converter station is blocked due to a contingency. The DC voltage is increased to another steady-state point according to the droop curve. Thus, the droop control can ensure the regulation of DC voltage when a converter station encounters fault condition.



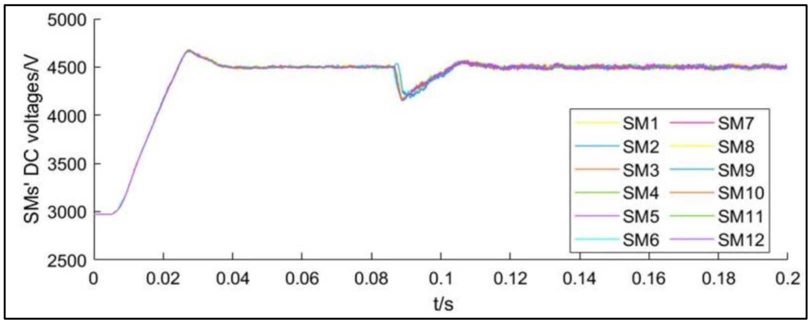
(a)



(b)

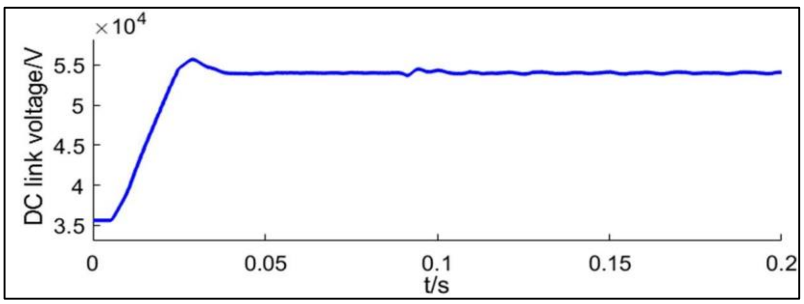


(c)

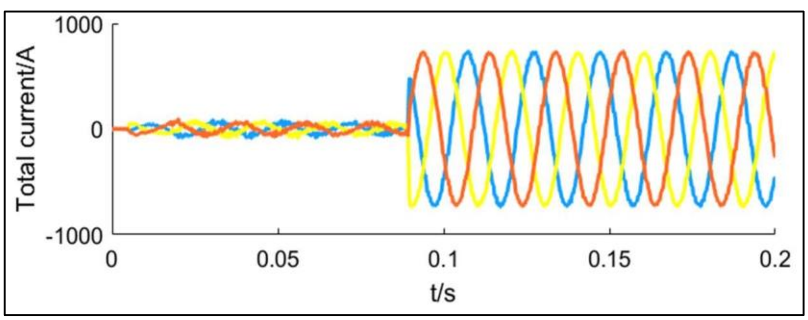


(d)

Figure 4.4 Step reference change of the active power under unit power factor: (a) DC link voltage; (b) Total AC current; (c) Current of SM 1; (d) SMs' DC voltages.



(a)



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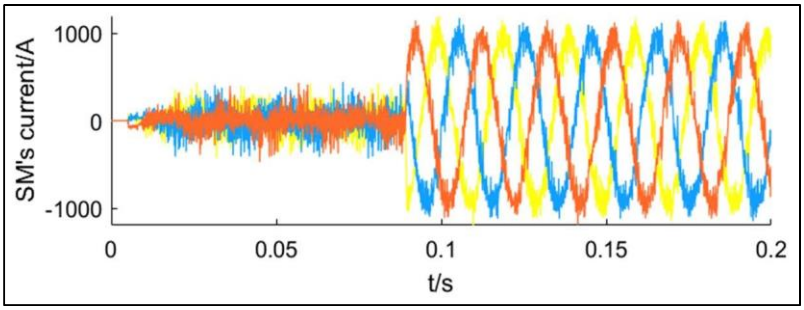
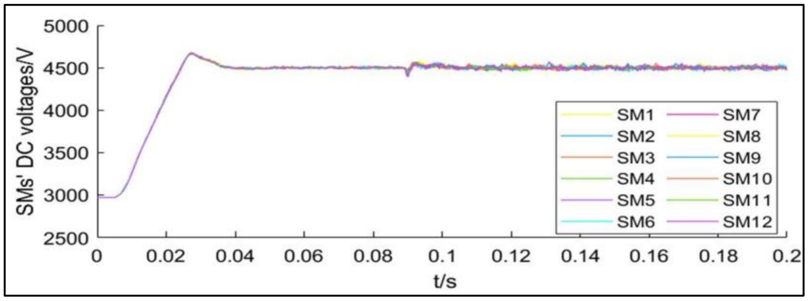
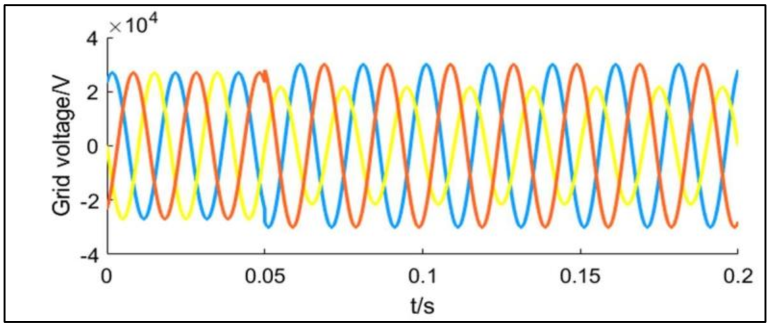


(c)

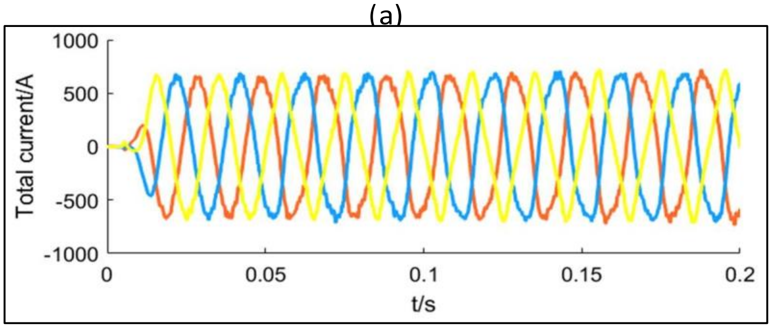


(d)

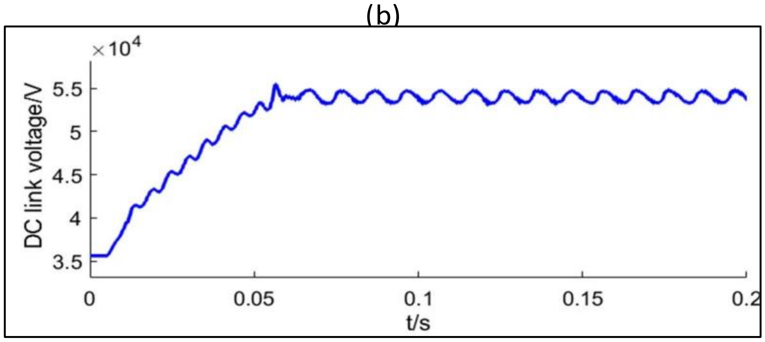
Figure 4.4.1 Step reference change of the reactive power under zero power factor: (a) DC link voltage; (b) Total AC current; (c) Current of SM 1; (d) SMs' DC voltages.



(a)



(b)



(c)

Figure 4.4.2. Performance under unbalanced grid voltage with 20% negative-sequence voltage.

(a) Grid voltage; (b) Total AC current; (c) DC link voltage

CHAPTER 5: PROJECT MANAGEMENT

5.1 Project Plan:

Table 5.1 shows the items that were needed to be purchased from the market to be assembled in our prototype. After research and looking through the market, we have found all of the items except for the PEM CONVERTER. We had to buy it from online. We have searched online for the motorwith an exact performance that fulfills our need for the project. Regarding the rest of the items, we have purchased from the local market.

Table 5.1: List of items

Component	Description
Three-Level PWM Converter	Main power conversion device for the hybrid active filter.
IGBTs (Insulated Gate Bipolar Transistors)	1.2-kV IGBTs used in the three-level PWM converter.
Passive Filter	Simple passive filter tuned to the seventh-harmonic frequency.
DC Capacitors	Two DC capacitors used for voltage balancing control.
MOSFETs	Used for controlling the active filter operation.
Diodes	Clamping diodes used in conjunction with the MOSFETs.
Data Acquisition System	YOKOGAWA WE7000 PC-based system for capturing experimental waveforms.
Digital Low-Pass Filter	Processes the active filter voltage waveforms.

5.2 PROJECT EXECUTION MONITORING:

The executing, monitoring and controlling phases of the project management lifecycle consist of completing and managing the work required to meet the project objectives. This phase also ensures that the project performance is monitored and adjustments to the project schedule are made as needed. Since the first lecture, we attended we have created a WhatsApp group to make sure every member of the group is updated with the progress. Also, we have used Telegram to share the documents we needed and to upload the research so we all worked on the same word file and that was very helpful and effective.

We have started our meetings on the 16 December and we agreed to have at least two meetingsper week. Every member was a cooperative and willing to do his best. We arranged the meetings days through the WhatsApp group considering all the group member's exams or any other work. That was a good experience for the group members and helped us to go over many barriers and obstacles.

On the other hand, we have had several meetings with our advisor and co-advisor. To reviewing our research with them and get their comments and feedback. Also, we went to the advisor to help us with some calculation and design specifications. Those meetings had a great impact on our project and played the main role in our performance and progress. Furthermore, we had two meetings with some of the electrical engineering faculties to discuss some calculation with th

5.3 CHALLENGES AND DECISION MAKING:

Through the senior year semester, we have faced a couple of challenges such as:

- Transportation issue
- Problems with team members.
- Challenges of project parts allocation.
- Problems with equipment.

5.2.1 Problems with Team Members:

First, we had a time conflict with group meetings because of the classes' schedules. Also, it was the first time of working on a project with the team members. Furthermore, when the ending

5.2.2 Challenges of Project Parts:

First, we have faced problems with the motor; we could not find the required motor specifications in the local market. We have decided to order the missing part from the abroad website markets. Secondly, the chain was not fitted on the chain wheel gear. Therefore, we have tried two different sizes of the chain to get the proper one. Thirdly, the connected motor gear wassmall difficult as a result, we have fabricated bigger gear that connects the rear gear to the motor.

5.2.3 Problems with Equipment:

We had a problem with the motor switch because it was burned while we were testing the project due the overload. Also, we have tried to find a proper battery because it became empty while we were testing the motor. It was difficult to balance the weight of motor and battery.

CHAPTER 6: CONCLUSION AND FUTURE RECOMMENDATIONS

6.1 CONCLUSIONS:

The transformerless hybrid active filter developed for line harmonic-current mitigation in a three-phase front-end diode rectifier system has demonstrated effective performance across various load conditions. By integrating a simple passive filter tuned to the seventh-harmonic frequency with a small-rated active filter based on a three-level PWM converter, the system successfully addresses the challenges of harmonic distortion and voltage imbalance.

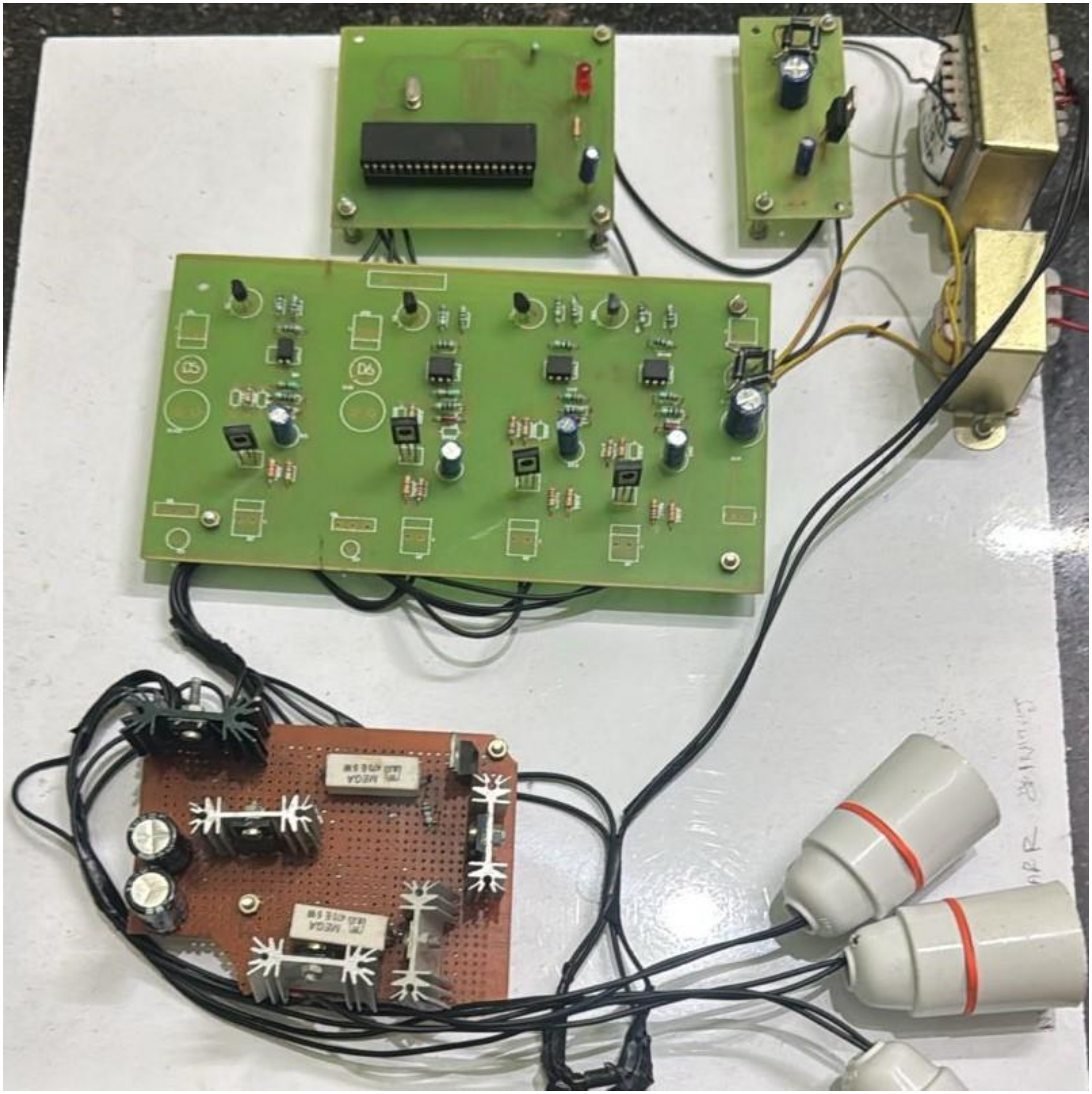
Experimental results indicate that the hybrid filter not only mitigates harmonic currents but also ensures stable voltage balancing between the two DC capacitors, achieving a significant reduction in total harmonic distortion (THD) from 31% to 3.8%. The active filter's ability to seamlessly transition between operating and resting modes enhances its reliability and efficiency, making it suitable for applications in adjustable-speed motor drives.

The theoretical analysis and practical experiments confirm that the injection of three-phase second-harmonic negative-sequence voltages is more effective than sixth-harmonic voltage injection, further optimizing the filter's performance. Overall, this project contributes valuable insights into the design and implementation of hybrid active filters, paving the way for future research on their operation under abnormal voltage conditions and expanding their applicability in industrial power systems.

6.2 FUTURE RECOMMENDATIONS:

1. **Investigation of Abnormal Voltage Conditions**: Future research should focus on the performance of the hybrid active filter under abnormal voltage conditions, such as voltage imbalances and sags. Understanding how the system reacts to these scenarios will enhance its robustness and reliability in real-world applications.
2. **Enhanced Control Strategies**: Development of advanced control algorithms that can dynamically adjust the filter's operation based on varying load conditions and harmonic profiles could further improve performance. Implementing adaptive control techniques may allow for real-time optimization of harmonic compensation.
3. **Integration with Renewable Energy Sources**: Exploring the integration of the hybrid active filter with renewable energy systems, such as solar or wind power, could provide insights into its effectiveness in mitigating harmonics generated by these sources, thereby improving overall power quality.
4. **Scalability Studies**: Conducting studies on the scalability of the hybrid active filter design for larger power systems or different voltage levels would be beneficial. This could involve testing the filter's performance in high-power industrial applications or in multi-level converter configurations.
5. **Long-Term Reliability Testing**: Implementing long-term reliability and durability tests on the components, particularly the IGBTs and capacitors, will provide valuable data on their performance over extended periods. This information is crucial for assessing the lifespan and maintenance needs of the system.

OUTCOME:



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