# POWER ELECTRONICS SIMULATION FOR GRID APPLICATION AND TRANSPORTATION ELECTRIFICATION

by

Allen Gee Jacob

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# ABSTRACT

## POWER ELECTRONICS SIMULATION FOR GRID APPLICATION AND TRANSPORTATION ELECTRIFICATION

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Allen Gee Jacob

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Under the Supervision of Professor Robert M. Cuzner

The global shift toward renewable energy and electrified transportation is transforming modern power systems, with power electronics playing a critical role in enabling efficient energy conversion and control. However, their nonlinear dynamics, high-speed switching, and complex controls requirements brings challenges, particularly when integrated into larger networks. This thesis addresses these challenges by leveraging advanced simulation and real-time testing techniques. Using tools such as MATLAB/Simulink, PLECS, Typhoon HIL, and OPAL-RT, it develops accurate models of power converters, capturing key phenomena like switching dynamics, losses, and fault responses. These models are validated through Hardware-in-the-Loop (HIL) and Controller-in-the-Loop (CHIL) simulations, enabling rigorous testing of control algorithms and system interactions under realistic conditions. The result emphasizes the values value of combining simulation and real-time testing to design power systems that are efficient, reliable, and robust. By addressing key challenges and advancing tools for modeling, this work supports the seamless integration of renewable energy and transportation electrification, contributing to a more sustainable and resilient energy future.

# Dedications

I dedicate this thesis to my advisor, Prof. Robert M. Cuzner, for giving me the opportunity to work on cutting-edge research in power electronics during my time in graduate school. The skills and experience I have gained in power electronics and simulation are a direct result of his guidance and mentorship.

I also extend my deepest gratitude to my family—my mom, brother, sister-in-law, and uncle—whose unwavering support and belief in me have been the foundation of my journey. I would not have made it this far without their encouragement and love.

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# LIST OF ACRONYMS

| | |
|---|---|
| AC | Alternating Current |
| BESS | Battery Energy Storage Systems |
| CHiL | Controller Hardware-in-the-Loop |
| CLR | Current Limiting Reactor |
| DC | Direct Current |
| DER | Distributed Energy Resources |
| EV | Electric Vehicle |
| HCB | Hybrid Circuit Breaker |
| HiL | Hardware-in-the-Loop |
| HVDC | High Voltage Direct Current |
| IGBT | Isolated Gate Bipolar Transistor |
| kV | KiloVolt |
| MATLAB | MATrix LABoratory |
| MMC | Modular Multilevel Converter |
| MOSFET | Metal-Oxide-Semiconductor Field-Effect Transistor |
| MPC | Model Predictive Control |
| MPPT | Maximum Power Point Tracking |
| MVDC | Medium Voltage Direct Current |
| NLSw | No Load Switch |
| NREL | National Renewable Energy Laboratory |
| PHiL | Power Hardware-in-the-Loop |
| PLECS | Piecewise Linear Electrical Circuit Simulation |
| PV | Photo Voltaic |
| PWM | Pulse-Width Modulation |
| RES | Renewable Energy Systems |
| SMs | Submodules |
| SOC | State-of-Charge |

| | |
|---|---|
| SSCB | Solid State Circuit Breaker |
| SSCL | Solid State Current limiter |
| | |
| THD | Total Harmonic Distortion |
| | |
| V2G | Vehicle-to-Grid |
| VSC | Voltage Source Converter |
| VSI | Voltage Source Inverter |
| VSR | Voltage Source Rectifier |

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# Chapter 1

# Introduction

---

The global transition to renewable energy and electrified transportation is transforming how we generate, manage, and use electricity [1]. Technologies such as solar panels, wind turbines, Electric Vehicle (EV) [2], [3] and microgrids [4] are at the center of this transformation. Power electronics, which enable the efficient conversion and control of electricity, play a critical role in these systems [5]. They serves as the backbone for integrating renewable energy into the grid, managing energy flow in microgrids, and powering EV.

According to yolegroup [6], the global power device market is expected to grow to 33.3 billion USD by 2028. Power converters for Battery Energy Storage Systems (BESS) will feature the fastest growth rate of 30.3%. It is estimated that by 2030, up to 80% of electric power widely rely on power electronics in some capacity. From fig. 1-1, 1-2, 1-3 shows the statistics of the expected market growth, industry status and trends related with power electronics.

Despite their importance, power electronics introduce significant challenges. These systems are highly complex, involving nonlinear dynamics, high-speed switching, and intricate control strategies [7]. When integrated into larger systems, such as microgrid or a renewable energy plant, they must handle dynamic interaction with Distributed Energy Resources (DER), various types of loads, and grid disturbances. These interactions can lead to stability issues, energy inefficiencies, and unexpected failures if not thoroughly analyzed and addressed [8].

Testing these systems in real-world scenarios is fraught with difficulties. Building physical prototypes for testing is often expensive and time-intensive, and testing fault scenarios or extreme conditions can damage equipment or pose safety risks. Also, the diversity of operating conditions

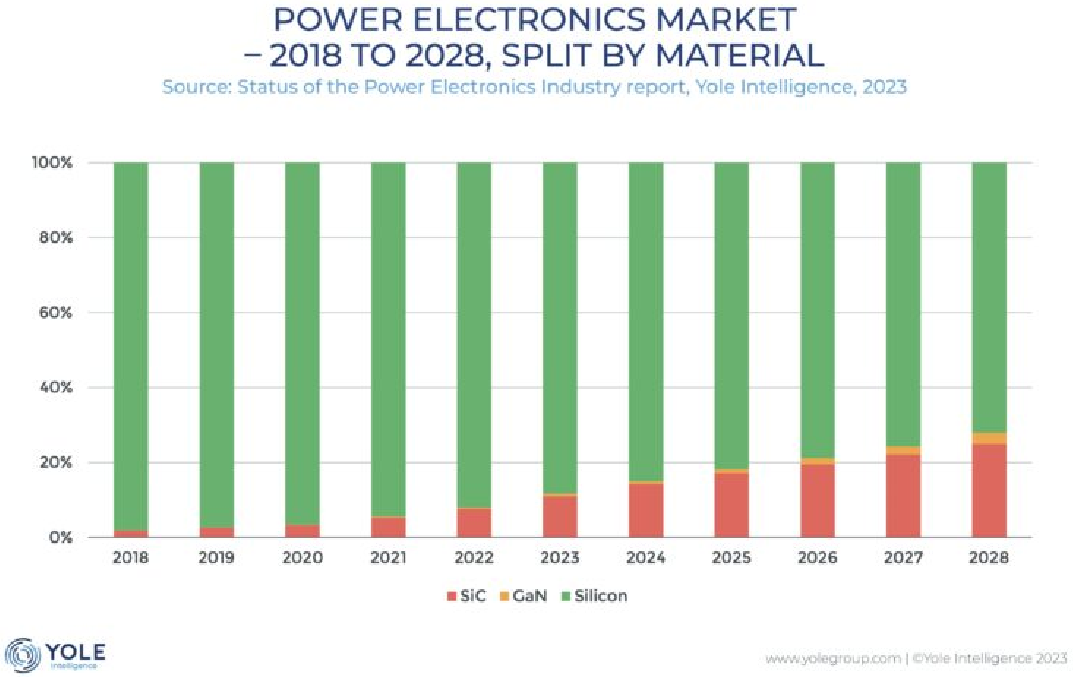

**Figure 1-1:** Power Electronics Market - 2018 to 2028.

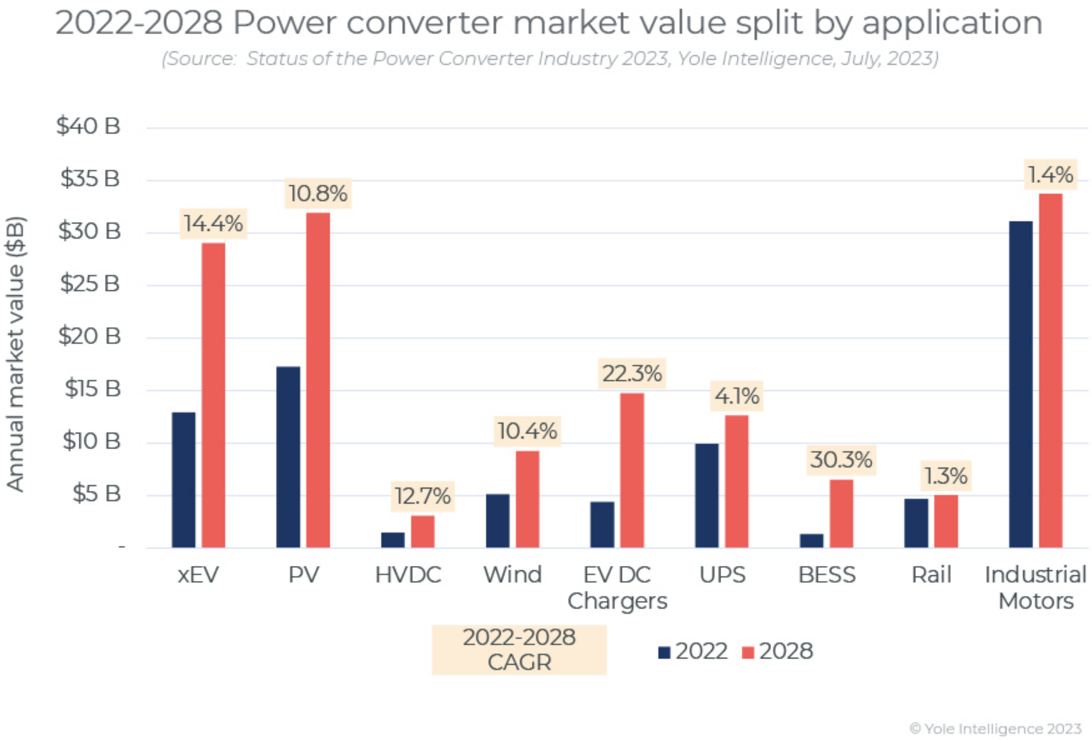

**Figure 1-2:** Power Converter Industry Status.

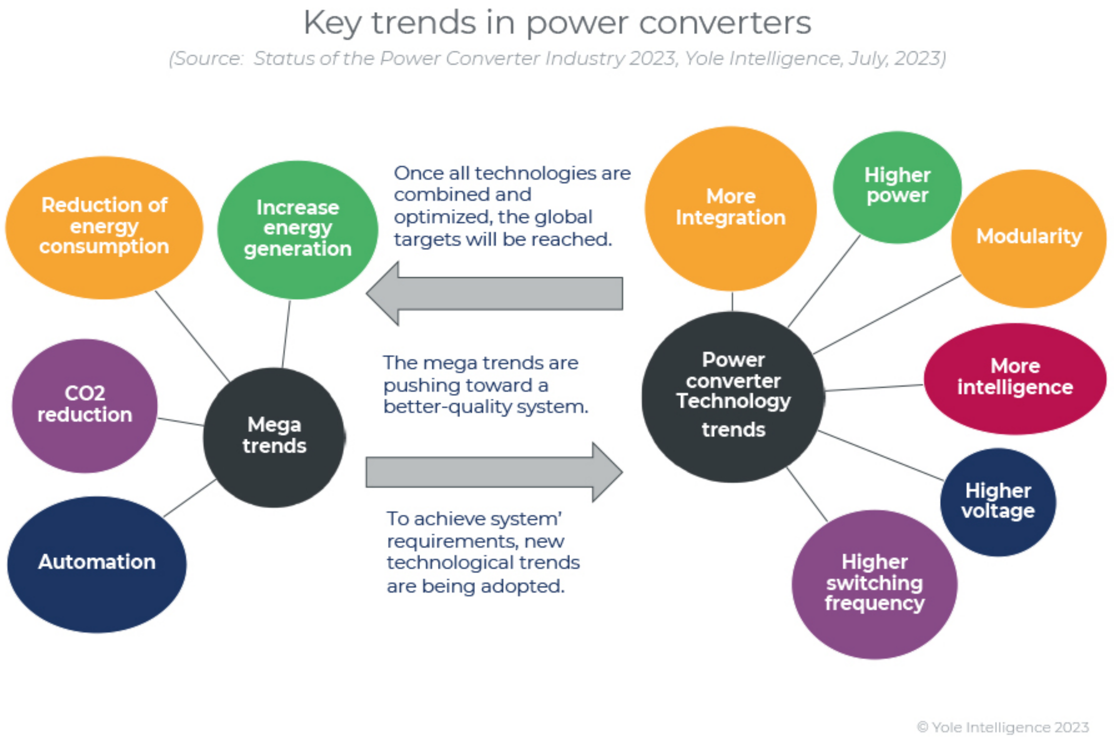

**Figure 1-3:** Trends in power converters.

in systems like EV powertrains, renewable energy inverters, and grid-tied converters makes it impractical to explore every possible scenario in a physical setup. These limitations underscore the need for advanced simulation and testing methodologies that can replicate real-world conditions without the associated risks and costs.

This thesis addresses these challenges by leveraging simulation and real-time testing techniques to model, analyze, and validate the behavior of power electronics systems. Simulations provide a safe, cost-effective way to study how these systems perform under varying conditions, including faults, dynamic loads, and grid disturbances. By enabling detailed analysis, simulations reduce the need for costly physical testing and accelerate the design process.

The research employs state-of-the-art simulations tools, including MATLAB/Simulink, PLECS, and Typhoon Hardware-in-the-Loop (HiL). These tools enable the development of realistic models of power electronics converters, including their electrical, thermal, and control behaviors. For example, detailed switching models allow high-fidelity analysis of converter dynamics, while averaged models facilitate system-level studies to examine interactions between multiple components.

Beyond traditional simulations, this thesis emphasizes real-time techniques such as Hardware-in-the-Loop (HiL) and Controller Hardware-in-the-Loop (CHiL) simulations. These methods connect physical hardware, such as controllers or converters, to a simulated environment. By doing so, they provide a realistic testing platform where control algorithms, protection mechanisms, and fault-handling strategies can be validated. HiL and CHiL simulations enable researchers to explore extreme scenarios, such as grid faults or sudden load changes, without risking damage to physical equipment.

This thesis is organized around three core objectives:

1. **Modeling and Simulation:** Develop accurate models of power converters and their interactions with larger systems. This includes:
    - Capturing switching dynamics to study the transient behavior.
    - Simulating fault conditions to analyze system level performance, control interactions, protect mechanism, and fault detection, isolation, and recovery.
2. **Real-Time Testing:** Implement HiL and CHiL simulations to:
    - Test system interactions, such as DER-grid synchronization and load-sharing in microgrids.
    - Reduce the risks and costs of physical testing by replicating real-world scenarios in a a controlled environment.
3. **System Integration:** Study how power electronics integrate into larger system to:
    - Enable seamless interaction between DERs, loads, and the grid.
    - Enhance system resilience and stability, even under unpredictable conditions.

By combining these approaches, this work offers a comprehensive framework for designing and validating power electronics systems.

The methodologies developed in this thesis address some of the most pressing challenges in modern energy systems. Power electronics are key to enabling renewable energy integration, improving grid stability, and accelerating transportation electrification. However, the rapid deployment of these systems demands new tools and techniques to ensure they perform reliably and efficiently under diverse conditions.

Through advanced simulation and real-time testing, this thesis contributes to closing the gap between theoretical design and practical implementation. It provides engineers and researchers with the tools to predict and optimize system performance, reducing the risks associated with deploying innovative technologies.

This thesis explores the development of Medium Voltage Direct Current (MVDC) corridors as a promising solution for modern energy transmission. Renewable energy sources such as Photo Voltaic (PV) farms and windmills are often located far from areas where energy is most needed, making long-distnace power transmission essential. While extensive research exists on High Voltage Direct Current (HVDC) systems, MVDC has received less attention. This thesis addresses this gap by examining how MVDC corridors can replace traditional transmission lines while enhancing the integration of Renewable Energy Systems (RES) into the grid. A central focus is on protection strategies for MVDC systems. Previous studies highlight a critical research gap in this area. This thesis evaluated protection schemes, considering the potential of Modular Multilevel Converter (MMC) replacing both the MVDC breakers and Voltage Source Converter (VSC). The research also investigates fault scenarios in the islanded microgrid, when the fault in MVDC corridor detects a fault, and isolate the microgrid. The ride through is analyzed. By addressing these challenges, this thesis advances understanding of MVDC transmission, emphasizing its role in renewable energy integration and power system resilience.

Ultimately, this research supports the broader goals of transitioning to a sustainable energy future. By improving how power electronics systems are designed and tested, it helps ensure that renewable energy and electrified transportation can be integrated seamlessly into modern energy infrastructures, paving the way for cleaner, more reliable, and more efficient energy systems.

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# Chapter 2

# Literature Review

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The modern energy systems and transportation technologies are growing at a fast pace, and it contribute to reducing carbon footprints with more electrification and increased efficiency. The vital enabler for this is power electronics which enables shaping how energy is generated, managed and consumed. However, the journey to today's sophisticated systems wasn't straightforward. Early design processes relied on physical prototyping and analytical methods, which often fell short of addressing the complexity of these systems. The introduction of simulation tools revolutionized the field, enabling researchers and engineers to model, analyze, and optimize systems with unprecedented precision. This review explores the evolution of simulation technologies, their current role in power electronics, and the growing need for system-level modeling in the face of increasing complexity.

Power Electronics is central to modern energy and transportation advancements, providing efficient and reliable ways to convert, control, and manage energy. It underpins renewable energy systems like solar and wind, ensuring variable outputs are transformed into stable, usable power. In transportation, it is essential for electrification efforts, helping to reduce greenhouse gas emissions while enhancing energy efficiency.

Its versatility extends across applications, from grid stabilization to fast fault isolation in microgrids. For instance, inverters ensure stability during fluctuations, while solid-state devices improve fault-handling capabilities, making energy systems more resilient and adaptable.

The role of power electronics is projected to grow rapidly as renewable energy adoption and transportation electrification accelerate. Systems like bi-directional chargers will enable Vehicle-to-Grid (V2G) technology, enhancing grid stability and energy management. Similarly, microgrids will rely more heavily on advanced power electronics to balance distributed energy resources and maintain reliability.

As these systems become more complex, the demand for smarter controls, higher integration, and robust fault-handling will drive innovation in power electronics. The development of these capabilities will be crucial for meeting future energy challenges, and supporting a sustainable transition to clean energy systems and electrified transportation.

In the early days, designing power electronics systems was challenging due to the lack of computational tools. Researchers relied heavily on theoretical analysis and physical prototypes, which had significant limitations.

1. **Theoretical Models:** Simplified equations were used to predict system behavior but often failed to account for nonlinear and dynamic characteristics of switching devices. Kolar et al. [9] highlighted that these methods "struggled to account for transient dynamics or interactions between multiple components".

2. **Physical Prototyping:** Building and testing prototypes provided real-world insights but was costly, time-consuming, and limited in scope. Testing fault conditions, for instance, often risked damaging equipment as [10] explained.

3. **Analog Simulations:** Early analog simulation tools allowed basic circuit modeling but lacked flexibility and scalability for more complex systems [11].

The advent of digital simulation tools transformed power electronics research by enabling precise and efficient modeling of systems without the need for physical prototypes. Simulation tools like MATrix LABoratory (MATLAB) /Simulink, PSIM, Piecewise Linear Electrical Circuit Simulation (PLECS) revolutionized design by allowing detailed modeling of converters and control strategies. Yazdani and Iravani [12] emphasized that simulations "reduced design cycles and enabled exploration of scenarios that were previously too costly or dangerous to test."

Modern simulation tools have incorporated advanced features to address evolving needs:

1. **Real-Time Capabilities:** Platforms such as Typhoon HiL and OPAL-RT allow real-time testing of control systems with physical hardware, bridging the gap between theoretical model

and practical implementation [13,14].

2. **Co-Simulation:** Tool that integrate electrical, mechanical, and thermal models for complex applications like transportation electrification. Multidisciplinary approaches and advanced simulation capabilities enables comprehensive system-level analysis, ensuring robust, reliable, and efficient designs. These tools align with the growing need for seamless integration across domains in modern energy and transportation systems [15].

3. **AI Integration:** Machine learning and deep learning are increasingly used in simulations to predict system behavior and optimize control strategies, offering enhanced efficiency and predictive accuracy [16,17].

As power electronics systems have expanded beyond isolated components into integrated systems like microgrids and electric transportation networks, system-level simulations have become essential.

### Understanding System Interactions

1. **Complex Dynamics:** Inverter-based resources, DERs, and dynamic loads interact in ways that can affect overall system performance. [18] discusses how power interactions among components in electric energy systems, governed by energy conservative principles can lead to instabilities when generation and absorption rate mismatches. This highlights the necessity of modeling and controlling these interactions to maintain system stability.

2. **State-Based Controls:** Many systems use state-machine frameworks to manage transitions between operational modes, such as islanding in microgrids or grid-following to grid-form inverters. [19] demonstrated how simulations provide insights into these transitions and their impact on system stability.

### Application in Microgrids and Transportation Electrification

1. **Microgrids:** Simulations help analyze the behavior of DERs, loads, and protection mechanisms during normal and fault conditions. These insights support the development of a fault-tolerant system capable of handling renewable energy variability [20].

2. **Transportation Electrification:** EV systems, especially bi-directional charging for vehicle-to-grid applications, depends on simulation to optimize their interaction with the grid, EV charging and discharging schedules in real-time, considering factors like fluctuating energy prices, grid constraints, and EV user preferences, thereby optimizing energy management strategies [21].

While large-scale simulations are gaining traction, several challenges remain,

1. **Computational Demands:** High-fidelity and real-time models require substantial computing resources [22].
2. **Accessibility:** Advanced platforms such as HiL system can be cost-prohibitive for smaller institutions.

High Voltage Direct Current (HVDC) systems have been extensively researched due to their proven efficiency in transmitting power over long distances [19], [23], [24]. They are well-established in commercial applications, and numerous studies have explored their reliability, system stability, and fault management strategies. This depth of research has resulted in mature technologies and established industry standards.

When we consider Medium Voltage Direct Current (MVDC) systems have received comparatively limited attention [25]. While they offer a scalable solution for integrating distributed energy resources like PV farms and wind turbines into power grids, much of their potential remains underexplored. Research into MVDC protection strategies, system-level modeling, and fault-handling mechanisms is still emerging, reflecting a significant gap in the literature. Bridging this gap could unlock new possibilities in power system design and renewable energy integration [26] [27] [28].

A critical area of research for MVDC systems is fault management and system protection [29]. Conventional Voltage Source Converter (VSC) and circuit breaker used in MVDC grids can be replaced with Modular Multilevel Converter (MMC), and it could replace both the components [30] [31], offering enhanced fault isolation and operational stability. Their inherent modularity makes them ideal for scalable, fault-tolerant grid designs.

Additionally, managing faults in MVDC grids requires sophisticated islanding strategies. In scenarios where fault isolate a microgrid from the MVDC corridor, enabling continued operation without grid dependency and fault detection, isolation, and recovery are crucial, to enable this we have low-voltage ride-through settings. While MVDC corridors hold significant potential for modern power transmission, research in this area is still emerging.

The evolution of simulation technologies has profoundly impacted power electronics, enabling researchers to design and analyze systems with unprecedented accuracy and efficiency. From addressing component-level challenges to exploring complex system-wide interactions, simulation tools have become essential in supporting innovation, the MVDC corridor study shows that. As systems grow more integrated and complex, the demand for scalable, detailed, and real-time simulations will continue to rise. Addressing challenges like computation efficiency interoperability will be crucial for unlocking the full potential of simulation technologies in advancing energy systems and transportation electrification.

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# Chapter 3

# Simulation and Modeling of Power Electronics Converter

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## 3.1 Introduction

The global push to reduce carbon emissions and decrease dependence on fossil fuels has led to a rapid shift towards electrification across various sectors, including renewable energy systems, transportation, industrial automation, and energy storage. This shift has spurred significant advancements in power electronics as engineers focus on developing innovative converter topologies and integrating them into existing electrical systems to enhance efficiency, reliability, and sustainability.

In this evolving landscape, simulation and modeling of power electronics converters have become indispensable tools. They allow engineers to design, test, and optimize converter systems rapidly, meeting the increasing demands and pace of electrification. By accurately modeling converter behavior, engineers can predict performance, ensure reliability, and address potential issues early in the design process, ultimately accelerating the integration of cleaner, more efficient energy solutions.

## 3.2 Overview of Popular Simulation Software

### 3.2.1 MATLAB/Simulink

MATLAB/Simulink is extensively used in research for developing and testing control strategies for power electronics converters. Its block-based environment and extensive libraries allow researchers to design complex systems and validate control algorithms, making it an ideal choice for prototyping and testing at the early stages of a project.

Applications in Industry and Academia:

- **Grid Application:** Used for modeling grid-connected converters and performing stability and power quality analysis.
- **Renewable Energy:** Common in wind and solar inverter control studies, allowing the integration of renewable sources into the grid.
- **Electric Vehicle (EV) Powertrains:** Utilized for simulating electric motor control, battery management, and regenerative braking systems, which is essential in EV development.

### 3.2.2 Piecewise Linear Electrical Circuit Simulation (PLECS)

PLECS offers high-speed simulation, making it useful for testing high-frequency switching and control in power converters. Its ability to run both offline and real-time simulations supports a rapid iteration process in research, allowing for quick changes and immediate feedback on circuit behavior.

Applications in Industry and Academia:

- **High-Frequency Switching Circuits:** Widely used for simulating Direct Current (DC)-Direct Current (DC) (DC-DC) converters and inverters that operate at high switching frequencies, which are common in compact, high-efficiency power supplies.
- **Renewable Energy and Smart Grids:** Useful in applications that require real-time testing of solar inverters and energy storage systems within smart grids.
- **EV charging Systems:** PLECS enables researchers to simulate DC fast chargers and assess their performance under different charging scenarios, providing insights into efficiency and thermal management.
- **Real-Time Control Testing:** With its ability to simulate real-time models, PLECS is frequently used to validate converter control strategies before hardware implementation.

### 3.2.3 Altair PSIM

PSIM is optimized for power electronics circuit simulation, particularly in the field of control design. Its fast solver speeds up the design process, making it a preferred tool for testing different control algorithms and performing parametric studies on converters.

Application in Industry and Academia:

- **Motor Drives:** Extensively used in motor drive research, such as electric motor control for industrial automation, robotics, and EVs.
- **Renewable Energy Systems:** PSIM is often used to simulate solar inverters, wind power systems, and other renewable energy sources where accurate power quality and stability analysis are essential.
- **Converter Design and Optiization:** The ability to run parameter sweeps and optimization algorithms in PSIM helps researchers design converters with high efficiency and reliability, especially for energy-efficient applications.
- **Power Quality Studies:** Used to analyze harmonics, Total Harmonic Distortion (THD), and other power quality issues in systems where clean power is crucial, such as in sensitive industrial applications.

### 3.2.4 Typhoon HIL

Typhoon HIL enables real-time Hardware-in-the-Loop (HiL) testing, allowing researchers to validate control algorithms, converter designs, and entire systems in a virtual environment before physical prototyping. This capability reduces the risk of component damage and optimizes design parameters before hardware implementation.

Applications in Industry and Academia:

- **Grid-Tied Systems:** Used in testing grid-tied inverters, microgrid controllers, and renewable energy systems, making it ideal for validating grid integration strategies and grid code compliance.

- **Electric Vehicle:** Essential for testing EV powertrain controllers, battery management systems, and inverters in real-time, which allows for safe and accurate validation of control algorithms.
- **Renewable Energy:** Commonly used for testing solar inverter controllers and battery energy storage systems to assess how they interact with the grid.
- **Control Algorithm Development:** Typhoon HIL's real-time capabilities support testing of advanced control algorithms such as Model Predictive Control (MPC), which is being researched to improve converter stability, efficiency, and dynamic response.

### 3.2.5 Altair Twin Activate

Altair Twin Activate provides a comprehensive platform for system-level simulation, allowing researchers to explore multi-domain interactions between electrical, thermal, and mechanical components in converters. Its support for digital twins is particularly beneficial in predictive maintenance and performance monitoring, where real-time system behavior and long-term predictions are required.

Applications in Industry and Academia:

- **Digital Twin Development:** Used in developing digital twins for power converters and other equipment, enabling real-time performance monitoring and predictive maintenance through data-driven simulations.
- **EV Systems:** Supports the simulation of EV powertrains, including motors, batteries, and converters, allowing researchers to optimize performance and assess durability under realistic operating conditions.
- **Renewable Energy Systems:** Useful for modeling wind and solar power systems, including the mechanical-electrical interactions within turbines and inverters, which helps in maximizing energy capture and efficiency.
- **Thermal Management:** Twin Activate's multi-physics capabilities support research in thermal modeling, which is crucial for understanding heat dissipation and managing thermal stresses in high-power applications.

## 3.3 Modeling Techniques for Power Electronics Converters

In power electronics, accurate modeling is essential to predict converter performance, efficiency, and reliability. Modeling techniques vary depending on the level of detail needed, with some approaches prioritizing accuracy and others emphasizing computational efficiency. This section explores key modeling techniques for converters, focusing on switching and averaged models, control system design, loss modeling, and stability analysis.

### 3.3.1 Types of Models in Power Electronics

**Switching Models**

Switching models represent the on/off states of power semiconductor devices such as Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET), Isolated Gate Bipolar Transistor (IGBT), and diodes, providing a detailed view of converter behavior. These models capture switching transients, high-frequency effects, and waveform distortions caused by rapid transitions. MATLAB/Simulink, PLECS, and PSIM all support switching models, allowing researchers to observe the real-time switching behavior within converters.

Switching models are particularly useful for applications requiring high accuracy, such as harmonic analysis and thermal stress evaluation. However, they can be computationally intensive, making them better suited for scenarios where detailed analysis of switching dynamics is crucial.

**Averaged Models**

Averaged models represent the average behavior of switching devices over time, reducing the computational load by omitting high-frequency switching details. These models are often preferred for system-level analysis and control design, as they enable faster simulations while capturing the essential behavior of the converter.

For example, in MATLAB/Simulink, researchers can use the Power Electronics Toolbox to build averaged models of converters, which can be particularly useful when designing closed-loop control systems for DC-DC converters, inverters, or rectifiers. PLECS also provides features for creating averaged models, allowing for fast performance simulations and early-stage control design.

### 3.3.2 Control System Modeling

#### Open-Loop vs. Closed-Loop Control

In open-loop control, the system operates without feedback, which is useful for basic converter testing but may lack the stability and adaptability required in real-world applications. Closed-loop control adds feedback, enabling the converter to maintain performance despite disturbances. Most power electronics simulation software, including MATLAB/Simulink and PSIM, support both open- and closed-loop control, with built-in tools for tuning parameters and observing the system response.

### 3.3.3 Loss and Efficiency Modeling

#### Modeling Switching and Conduction Losses

Accurate modeling of switching and conduction losses is essential for efficiency analysis in power converters. Switching losses occur during transitions in semiconductor devices, while conduction losses occur when the device is on. Simulation tools like PLECS and PSIM provide component libraries with customizable parameters for loss modeling, allowing researchers to set specific conduction and switching loss characteristics based on real component data.

In MATLAB/Simulink, Simscape Electrical includes detailed loss models, allowing researchers to quantify how switching frequency and load impact converter efficiency. These models are especially valuable for applications such as renewable energy inverters and EV powertrain systems, where high efficiency is crucial.

#### Thermal Modeling

Thermal modeling evaluates the heat generated within a converter and helps in designing thermal management strategies. Excessive heat can degrade components and reduce efficiency, making thermal analysis essential. Altair Twin Activate and MATLAB's Simscape support thermal modeling, enabling researchers to simulate heat dissipation and assess temperature profiles for power converters. This is particularly important in high-power applications like electric vehicle chargers and renewable energy inverters, where heat dissipation affects reliability and lifespan.

### 3.3.4 Stability and Performance Analysis

#### Transient and Steady-State Analysis

Power converters must respond effectively to sudden changes, such as load variations or grid faults. Transient analysis in tools like Typhoon HiL allows for real-time simulation of these events, providing insights into how converters handle rapid changes. Steady-state analysis, on the other hand, is used to confirm that the converter performs consistently under stable conditions, making it essential in industrial automation and renewable energy systems.

### 3.3.5 Validation Techniques

#### Comparison with Experimental Data

Model validation involves comparing simulation results with experimental data to confirm accuracy. This step is crucial in research, where simulation models must reflect real-world performance as closely as possible. MATLAB/Simulink and PLECS both support data import features, enabling researchers to validate models by overlaying simulation results with lab measurements.

#### Parameter Sensitivity Analysis

Sensitivity analysis identifies how changes in component parameters affect overall system performance. This technique is helpful for optimizing converters, as it highlights the most influential parameters. MATLAB's sensitivity analysis tools, as well as parameter sweeps in PLECS and PSIM, allow researchers to identify optimal parameters and improve converter design.

## 3.4 Modular Multilevel Converter (MMC)

### 3.4.1 Introduction

Modular Multilevel Converter (MMC) is a type of voltage source converter widely used in high-power applications such as High Voltage Direct Current (HVDC) transmission, renewable energy integration, and medium-voltage motor drives. It is highly valued for the following:

- **Modular Design:** The converter is composed of multiple identical Submodules (SMs),

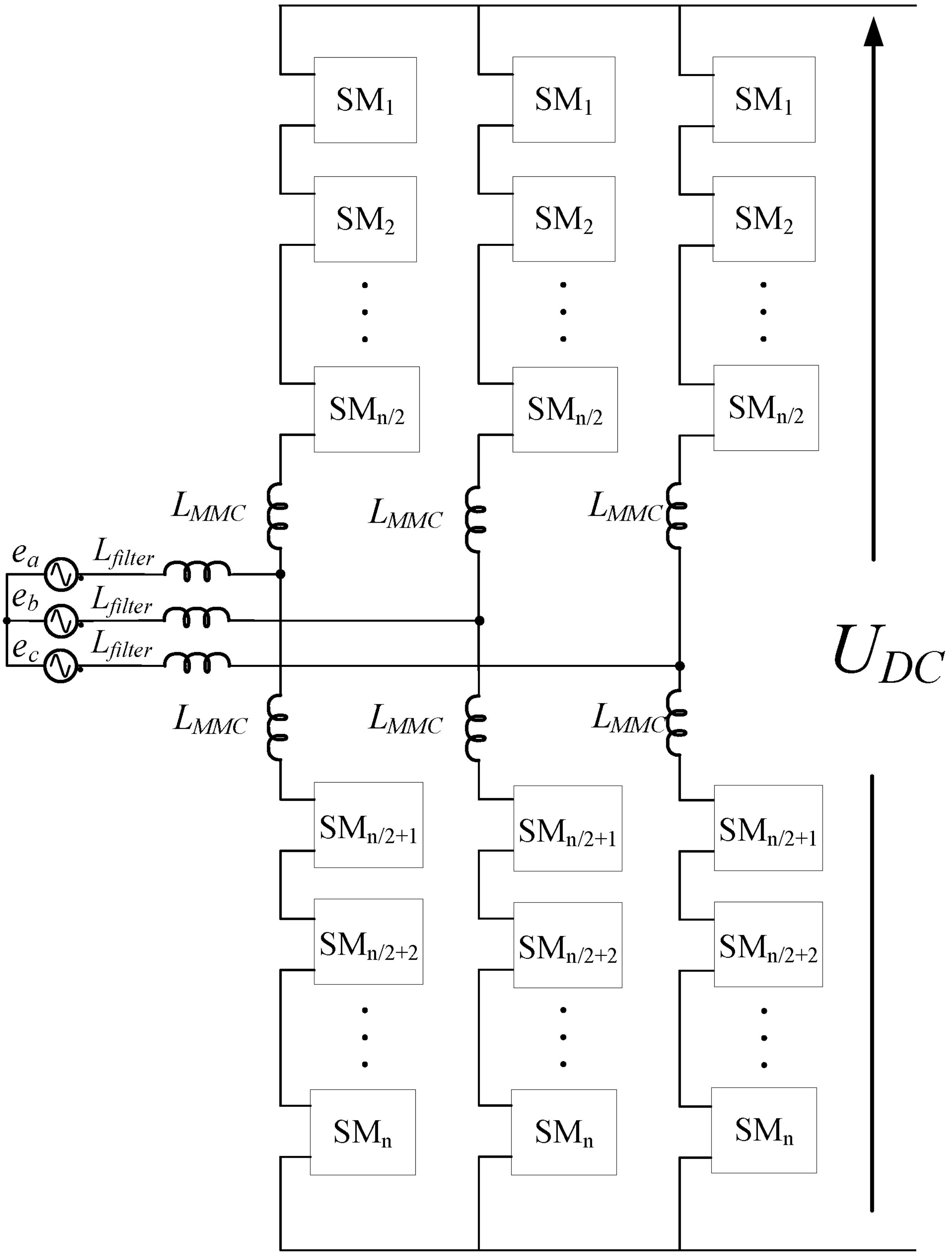
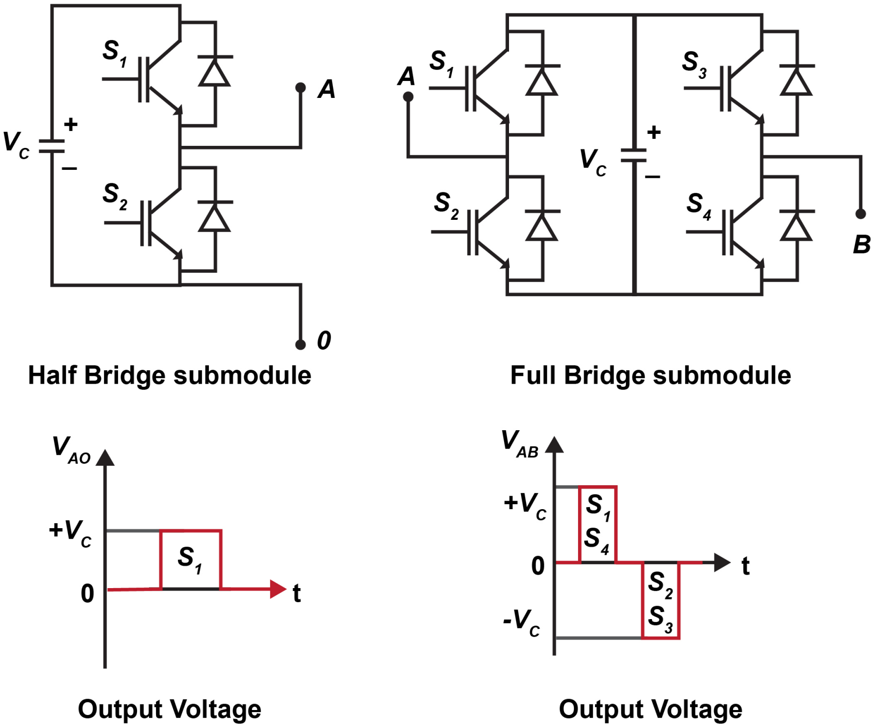


**Figure 3-1:** General Representation of MMC.



Half Bridge submodule

Full Bridge submodule

Output Voltage

Output Voltage

**Figure 3-2:** Submodule Half-Bridge (L) and Full-Bridge (R)

each consisting of a capacitor and a switching circuit. Theses submodules are connected in series to form each phase leg, which consists of an upper and a lower arm.

- **High Scalability:** Adding more submodules increases the voltage handling capability.
- **Low Harmonic Distortion:** The stepped output voltage of the MMC closely approximates a sinusoidal waveform due to the fine voltage resolution provided by the submodules. This reduces the need for bulky and expensive filters.
- **Fault Tolerance:** The modular structure allows for the isolation or bypassing of faulty submodules, ensuring reliable operation even in the presence of faults.
- **High Efficiency:** MMCs exhibit low switching losses because of the low switching frequency required by each submodule, while still producing high-quality output waveforms.

Fig. 3-1 represents the general structure of MMC, each phase is called as ”leg” and the upper and bottom part are called ”upper arm” and ”lower arm”. The number of submodules depends on the rating, fig. 3-2 shows the two types of submodules, full-bridge and half-bridge. This study is done on full bridge MMC as it has in built DC fault blocking and protection capabilities [30] [31], this will enable us to replace the conventional setup, which is Voltage Source Converter (VSC) and circuit breaker. Instead of two-component, we can have MMC to power conversion and protection. The study aims to have higher power density, that's the reason behind aiming for 2 submodules.

### 3.4.2 Objective

The main objectives of the project were:

1. Maintain an output voltage of 12kV.
2. Reduce the number of submodules to two for each arm.
3. Iterate with different switching frequencies and tuning the controls to study the impact of and also changing the value of submodule capacitor and arm inductor size and develop scaling and designing laws for the power converter.

### 3.4.3 Implementation

The MMC was implemented in MATLAB/Simulink. The simulation was implemented in a way such that the MMC starts gating and gives the desired voltage and current at the DC bus and then only we connect with load.

The AC side fed from the AC mains, and we are looking at the DC side as the result. Each of the phase is connected a leg, which consists of upper and lower arms. The arms consists of submodule which are made of full-bridge and capacitor and also the arms of each leg have the arm inductance. The arm inductance and submodule capacitance plays an important role in the power density. Each of the arm should be able to handle the rated DC bus voltage, so we choose the switching devices, the number of submodules accordingly.

One of the main complexity of this topology is the circulating current which is the result of the difference in voltage at the arms of the MMC at a given time. This results in current flowing between the arms, upper arm to lower arm or vice versa, and also the current flows between the legs. This is an unwanted current that flows within the converter, leading to increased power losses and potentially impacting system stability if not properly controlled, this current only circulates within the converter itself, not flowing to the load. The arm inductance is an important component here,

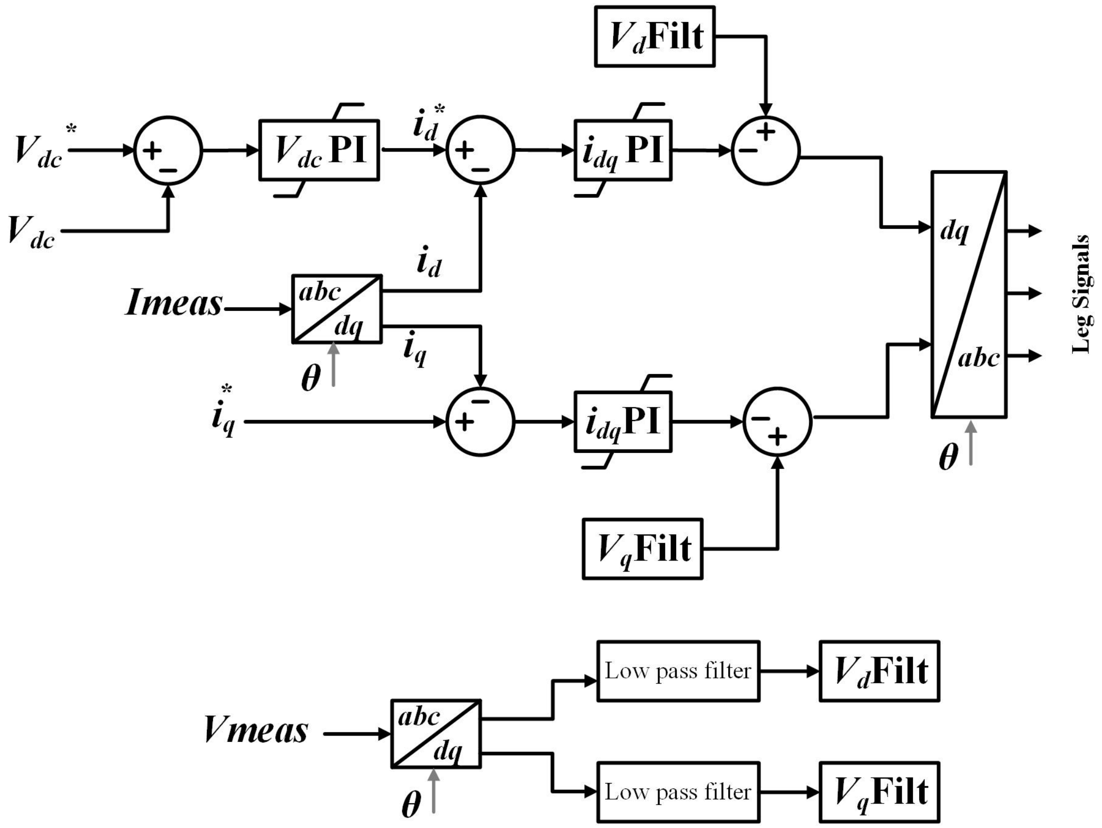


Figure 3-3: Outter Control for MMC.

it helps to limit and suppress circulating currents within the converter by opposing rapid changes in current flow, thereby improving the overall stability and performance of the MMC system, also the arm inductance plays a crucial role in limiting the fault current during a fault condition by controlling the rate of current change through its inductive property. Without proper controls the circulating current will also drive voltage imbalance at the submodule level and cause damage.

The controls for the MMC are complex because of all the non-linearity. We have an outer control which helps to regulate the voltage and current at the DC bus to the desired values, gif. 3-3 shows the control outline. Then we have the controls for maintaining the voltage balance of the submodule capacitors and also to suppress the circulating current, fig. 3-4 shows the control outline.

We use phase-shifted pulse width modulation to control submodules, according to the number of submodules we decide the phase offset. The Phase-sifted Pulse-Width Modulation (PWM) works by intentionally delaying the switching timing between multiple PWM signals, effectively creating

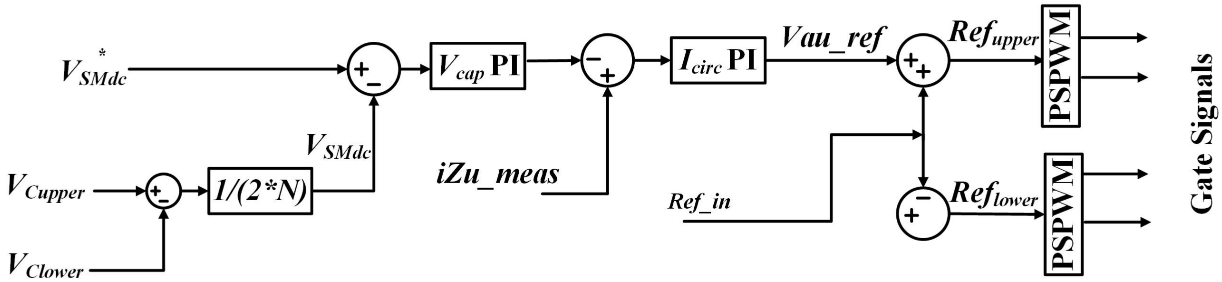


**Figure 3-4:** Control schematic for leg.

a phase offset between them.

### 3.4.4 Result

The first task was to make it two-level (2 submodule) MMC. To achieve this, we had to modify the controls, PSPWM gate pulses and make sure it was working properly. Fig. 3-5 shows the two-level setup in Simulink.

The next part of the project was to achieve 12kV voltage on the DC side with load,in two-level setup. We were able to achieve this by tuning the controls and changing PSPWM setup. Fig. 3-6

**Table 3.1:** Voltage Ripple and Current Values for Different Configurations

| **Configuration** | **Voltage Ripple** | **Cap Voltage Ripple** | **Currents** |
|---|---|---|---|
| Baseline with 10kHz | $1730/12000 = 14\%$<br>$2901.05/12000 = 24\%$ | $48/6000 = 0.8\%$ | $I_{\text{rms}} = 162$<br>$I_1 = 158,\ I_2 = 122,\ I_4 = 11$ |
| Baseline with 5kHz | $3082/12000 = 25\%$<br>$3550/12000 = 29.5\%$ | $43/6000 = 0.72\%$ | $I_{\text{rms}} = 153$<br>$I_1 = 159,\ I_2 = 96,\ I_4 = 21$ |
| 5kHz with $K_pC_i = 4$, | $3084/12000 = 25\%$<br>$3202/12000 = 26\%$ | $35/6000 = 0.58\%$ | $I_{\text{rms}} = 140$<br>$I_1 = 158,\ I_2 = 49,\ I_4 = 11$ |
| 2.5kHz with $K_pC_i = 4$, | $5244.85/12000 = 44\%$ | $36/6000 = 0.6\%$ | $I_{\text{rms}} = 143$<br>$I_1 = 161,\ I_2 = 50,\ I_4 = 11$ |

The other part of the project was to do simulations at different different switching frequency to study how it affected the 2nd and 4th harmonics of the current. As in table 3.1 as switching frequency went down the harmonic increased. To suppress the harmonic, an increase in the proportional gain of circulating current was required.

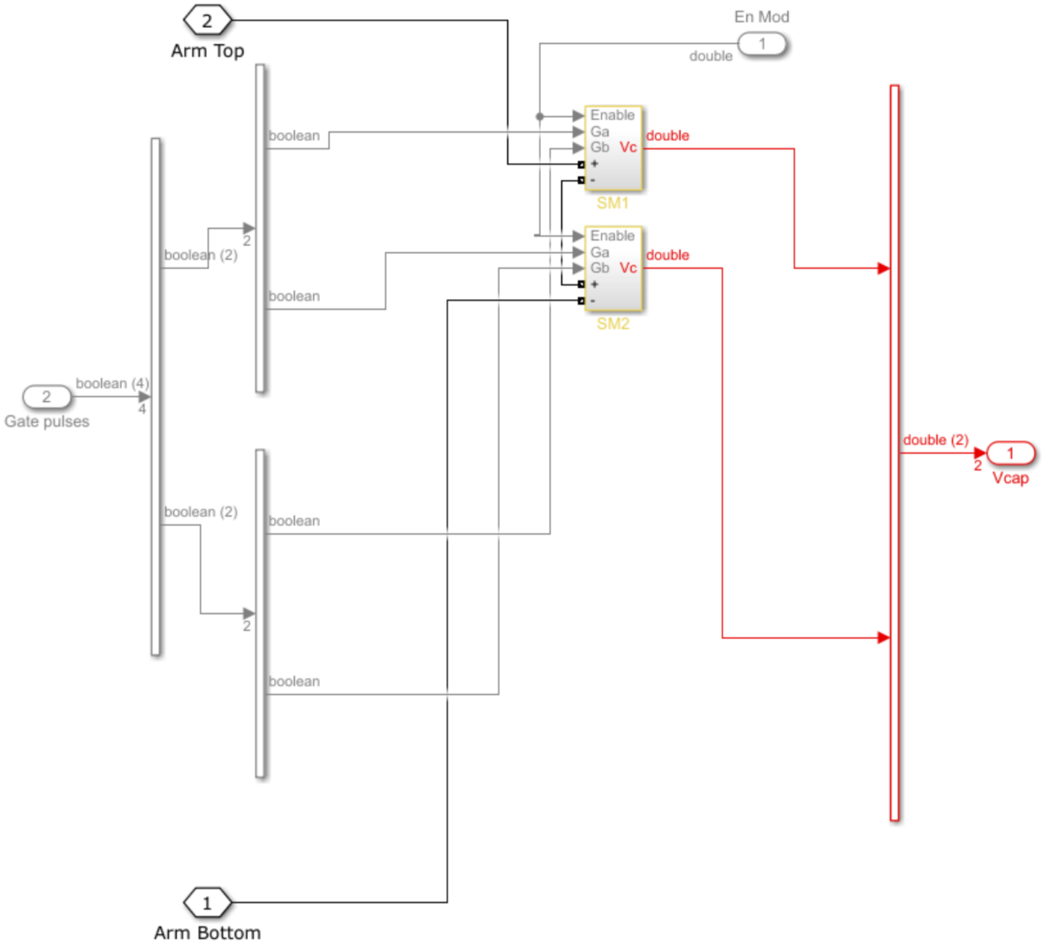


**Figure 3-5:** Two-level MMC submodule.

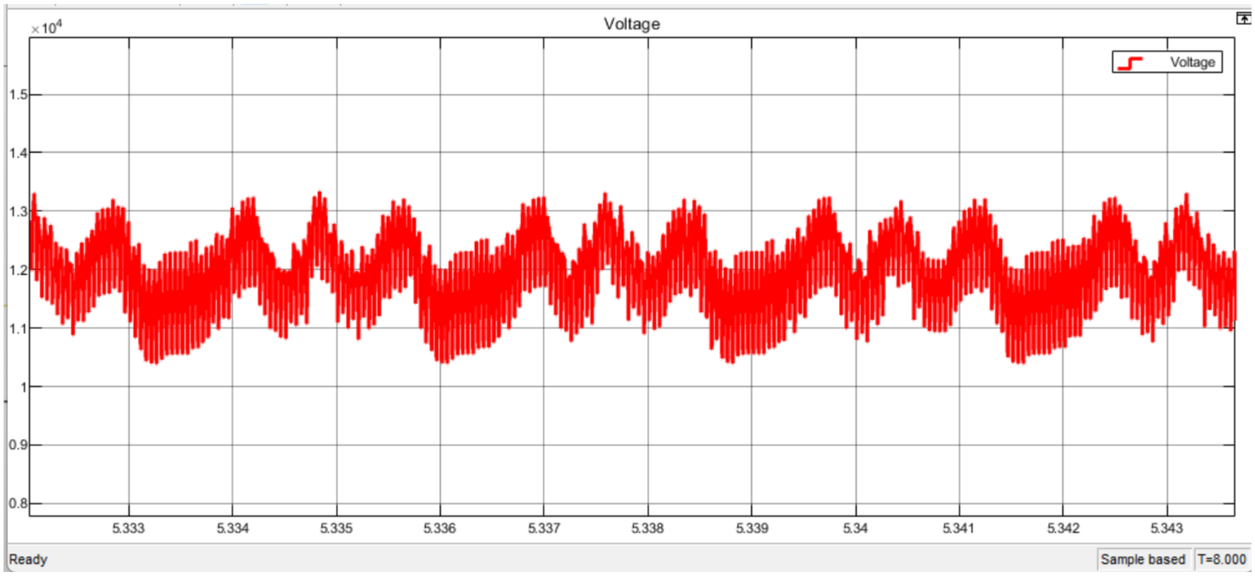


**Figure 3-6:** 12 kV voltage at the DC side.

## 3.5 Conclusion

Simulation and modeling are essential in the design and optimization of power electronics converters. This chapter explored different simulation tools that enable engineers to mdeol and test converter performance. By simulating key aspects such as switching dynamics, thermal behavior, and fault responses, these tools provide valuable insights that bridge gap between theoretical concepts and practical implementation.

A significant advantage of simulation is its ability to facilitate experimentation and innovation without the risks or costs of physical prototypes. It allows for the development of control algorithms, evaluation of efficiency, and testing of stability under a wide range of conditions, ensuring that designs are both functional and reliable at early stage development. While this chapter focused on the modeling and simulation of standalone converters, these systems often operate as part of larger, interconnected system. The complexities and opportunities of such integrations will be addressed in the next chapter 4, which examines how power electronics simulation interacts with broader systems.

## Chapter 4

# Integration of Power Electronics Simulation into larger System

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Modern power systems increasingly rely on power electronics to interface distributed energy resources (DERs) with local loads and the broader grid, enabling a seamless blend of renewable and non-renewable sources. This chapter explores the integration of power electronics into larger systems, focusing on multi-converter configurations, diverse load types, distributed resources, protection settings, and robust control mechanisms. By simulating these elements, we aim to understand the dynamic interactions that arise within microgrids and similar setups, providing insights critical for resilient and reliable operation.

## 4.1 Mult-Converter and Multi-Load Simulation

### Introduction to Multi-Converter Systems in Micrgrids

Power converters—essential to interfacing DERs, loads, and grid connections—operate as key control points within microgrid systems. A typical microgrid setup might include DC-DC converters for battery energy storage, DC-AC inverters for solar photovoltaic (PV) or wind integration, and AC-DC rectifiers for grid interfacing. Each converter type is implemented with distinct control settings, allowing it to adapt to various demands and operational states, thus enabling reliable, uninterrupted power flow.

### Control and Coordination of Power Converters

In a microgrid, coordination between power converters is essential for achieving balanced operation and ensuring that power quality and availability meet demand. Key elements include:

- **DC-DC Converters:** DC-DC converters manage energy flow between batteries and other components, using State-of-Charge (SOC) control to keep battery levels within predefined safety limits. For example, during high PV generation, the converter directs excess energy to charge the battery. During periods of high demand, the battery discharges to supplement other energy sources.

- **DC-AC Inverters:** Inverters are crucial for integrating renewable DERs like PV arrays or wind turbines into the system. They are often equipped with Maximum Power Point Tracking (MPPT) algorithms that dynamically adjust voltage and current to maximize energy output from fluctuating renewable resources. Additionally, these inverters help regulate grid voltage and frequency, especially critical in islanded operation.

- **AC-DC Rectifiers:** Rectifiers facilitate bi-directional power flow between the microgrid and the main grid. During times of surplus, they channel excess power to the grid, while they draw power during deficits, thus enhancing the system's robustness. During grid outages, rectifiers are disconnected, and the microgrid switches to islanded mode, relying solely on local DERs and storage.

### Managing Load variability and Diversity

n microgrids, loads are highly variable and may include resistive, inductive, and dynamic loads. These variations necessitate control strategies that dynamically adapt to shifts in load characteristics:

- **Load Types and Characteristics:** Resistive loads like heating systems demand steady power, whereas inductive loads like motors involve reactive power, impacting voltage stability. Modeling these loads with distinct power demands allows the simulation to test the microgrid's response to various load combinations and interactions.

- **Dynamic Load Management:** The simulation uses priority-based load shedding mechanisms, where critical loads such as emergency lighting are prioritized during grid disturbances. During high-demand periods, the system strategically disconnects non-essential loads, ensuring essential services are unaffected and battery resources are preserved.

### Example

## 4.2 Integration of Distributed Energy Resources (DERs)

### Overview of SER Types and Their Roles

Distributed energy resources (DERs) introduce new dynamics into the system, each requiring specific control and management. For this microgrid setup, we focus on both renewable (solar PV, wind) and non-renewable (diesel generator, battery storage) DERs, detailing their control and integration:

1. **Renewable DERs:** These renewable resources rely on MPPT for optimal energy capture. As solar and wind generation are intermittent, their output must be constantly monitored and adjusted based on weather conditions.

2. **Non-Renewable DERs:** Diesel generators provide dispatchable power, supplementing renewable sources when necessary. They also support grid frequency regulation, adjusting output to stabilize voltage and frequency levels.

3. **Energy Storage:** Batteries serve as energy buffers, charging during peak renewable generation and discharging during shortages. SOC control prevents overcharging or deep discharge, optimizing battery life and availability.

### Control Mechanisms for DERs in Microgrid Operations

- **MPPT for Solar PV:** For PV systems, MPPT adjusts the inverter's operating point to maximize power extraction. Wind turbines also benefit from MPPT, especially during low wind speeds where energy capture is more challenging.

- **Frequency Regulation:** Diesel units stabilize grid frequency, providing a steady reference for inverters in grid-connected mode.
- **Battery Storage Management:** Battery SOC is regulated to ensure long-term availability, prioritizing discharge during peak loads and minimizing usage during low-demand periods.

## 4.3 State Machine Control for Robust Operation

### State Machine Implementation

A state machine is implemented to control transitions between operational modes, enabling structured responses to events like grid outages, load shifts, and DER fluctuations.

- **Normal Operation:** DERs and loads operate harmoniously, with load-sharing strategies distributing power proportionally between DERs based on real-time demand and generation.
- **Fault and Ride-Through Settings:** In fault conditions, the state machine initiates load shedding, isolating non-essential loads and adjusting converter set points to preserve system integrity.
- **Load Shedding and Resiliency:** The state machine prioritizes critical loads during resource constraints, maintaining energy for vital functions.

## 4.4 Protection Mechanims and Grid Stability

### Protection Settings for Mult-Converter Microgrids

The microgrid employs several protective settings to ensure safe operation:

- **Over-Voltage and Over-Current Protection:** Protects converters from high power surges, disconnecting components if voltage or current exceeds safe limits.
- **Anti-Islanding Protection:** Prevents the microgrid from inadvertently energizing the grid during outages, ensuring compliance with safety standards.
- **Relay-Based Protection:** Relays activate during faults to disconnect affected sections, preserving continuity for critical loads.

### 4.4.1 Fault Detection and Ride-Through Capability

- **Fault Detection:** Uses real-time monitoring, triggering protective actions if deviations are detected.
- **Ride-Through Capability:** Enables DERs to continue operation during brief faults, stabilizing the system and preventing cascading issues.

## 4.5 MVAC/MVDC Distribution System

### 4.5.1 Introduction

The aim to reduce carbon foot print results in increased usage of renewable energy sources; renewable energy sources such as Photo Voltaic (PV) farms, solar, and wind turbines are located far from the consumer. Transmitting the energy over a long distance through conventional transmission results in a weak feeder/weak grid, this project analyse MVDC corridor to potentially replace the conventional transmission. There has been extensive study of High Voltage Direct Current (HVDC) systems for tranmissing power overlong distance [19], [23], [24] while for Medium Voltage Direct Current (MVDC) it is limited [25]. The project studies MVDC corridor and their fault detection, isolation and recovery.

This project was focused on Real-Time simulation of medium voltage corridor with a 10km long transmission line. The MVDC corridor consists of a back-to-back converter, a voltage source rectifier (VSR) that converts the AC into 12kV that transmits 10km long, and at the other need has voltage source inverter (VSI) that gives us the MVAC. The MVDC corridor decouple of AC dynamics and eliminate voltage drop between two nodes in a distributed system. This can be beneficial to loads that are at the end of weak feeders that experience voltage drop. The MVDC corridor is a core segment that was identified as part of the larger GRAPES microgrid system.

### 4.5.2 Objective

Practical implementation questions of the MVDC corridor need to be addressed to aid in industry adoption:

1. Impact of the MVDC corridor on AC-side protection under both grid-forming and grid-following models.

2. Enabling controls to execute fault detection, isolation, and recovery for both AC-side and DC-side faults.

3. Impact of DC circuit breaker approach, i.e, Solid State Circuit Breaker (SSCB) vs Hybrid Circuit Breaker (HCB) on corridor stability under steady-state, load steps, and fault recovery.

### 4.5.3 Implementation

The MVDC corridor was implemented in MATLAB/Simulink with the PLECS blockset. State-machine based controls were implemented to ensure the power conversion and power distribution elements of the MVDC corridor performance events sequentially and in lockstep, such as pre-charge, ramping up, DC and AC connection, and actuation of the SSCBs under fault conditions. The MVDC corridor was then transferred to Typhoon-HiL including both the electrical system and state-machine based controls for real-time simulation.

A major challenge identified in the project is maintaining the desired voltage at the transmission end and at the start of the VSI and make it stable.

Validation of the topology was done using PLECS first, the control signals were given from Simulink only. The challenge was to have a back-to-back converter and maintain the DC voltage in the transmission line. Fig. 4-1 shows the block diagram representation of the MVDC corridor.

To support this work, library components were developed or modified to support the requirements of the project. These include having state machines for AC protection, AC over current protection, No Load Switch (NLSw), main system state machine, and Ramp block. These state machines' state are checked for each time step, and they are communicated with other state machines to make sure that a proper logical operation taking place. Also, to make sure that if any fault occurs, it takes necessary steps to isolate the fault. For example, when the system state is in precharge state, the current flows through the resistor to make sure the DC capacitor charges slowly and doesn't cause any fault. Only when the voltage across the capacitor reaches a minimum value does the precharge switch close.

From 4-2, we can see that there is a signal going from Ramp state machine to PI controls. The

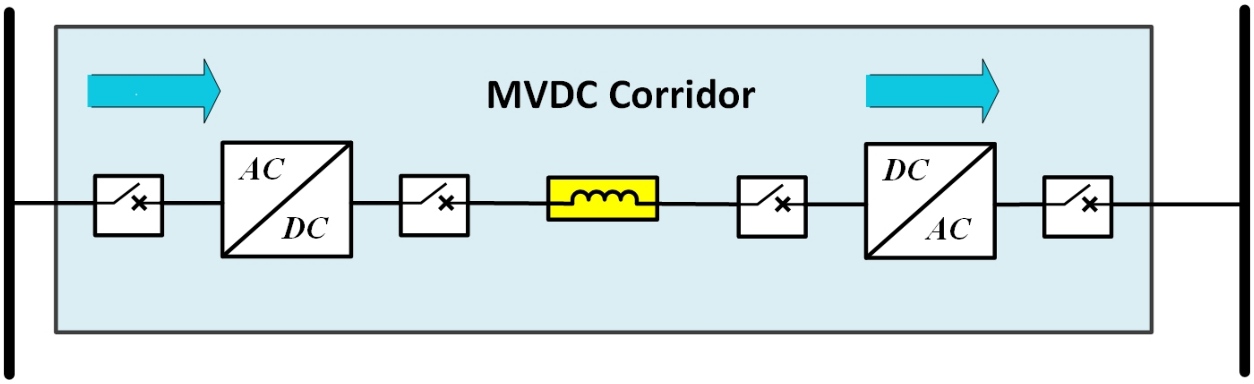


**Figure 4-1:** Schematic Representation of the MVDC corridor.

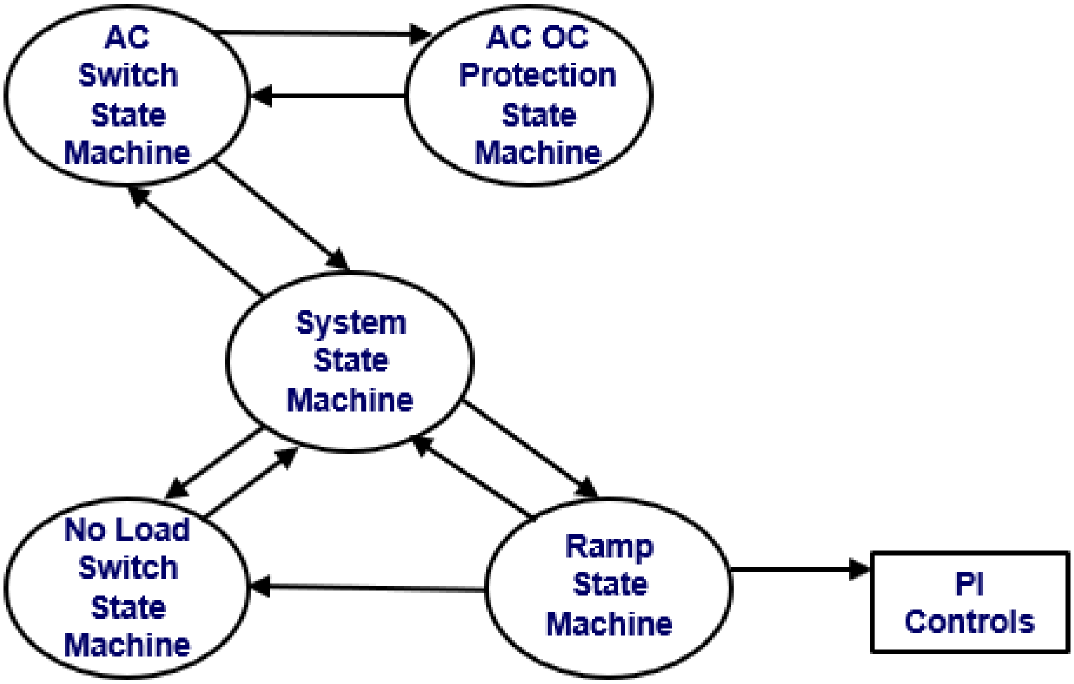


**Figure 4-2:** Schematic Representation of State Machines and their communication.

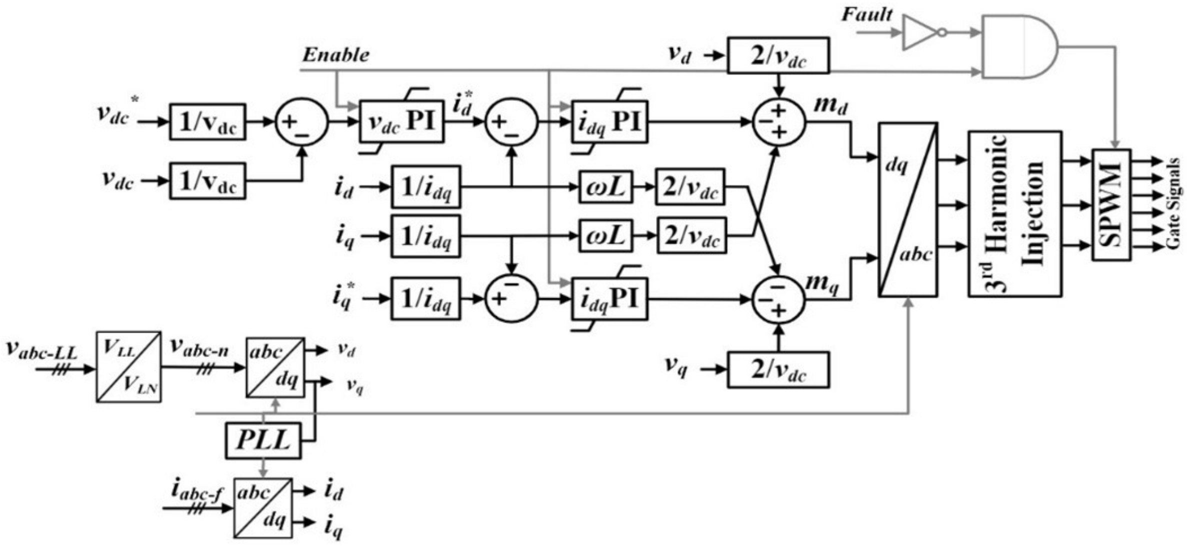


**Figure 4-3:** Controls for the VSR.

PI controls are only enabled when the Ramp state in Ramped otherwise all the gate signals will be zero. The state machines for both Voltage Source Rectifier (VSR) and Voltage Source Inverter (VSI) are almost similar, some of the differences are the minimum voltage values, minimum time required, the AC protection and DC protection will be vice versa, that VSR AC protection will be in the input whereas VSI it will be in the output. Fig. 4-3 and fig. 4-4 shows the diagrammatic representation of VSR and VSI controls used.

For the DC circuit breaker, we used the average-model equivalent of a SSCB (fig. 4-5) developed in GR 17-02. This SSCB model consists of a voltage source, Current Limiting Reactor (CLR), and No-Load Switch (NLsw). The NLsw state machine controls the NLsw and the SSCB state controls the voltage source. Both of these state machines help to mimic the SSCB logic and behavior.

When the current crosses an overcurrent threshold, the voltage source shown in fig. 4-5 helps to mimics the voltage applied when a semiconductor switch open under fault conditions. This voltage helps to bring down the current. When the current is near to zero, the NLsw opens and isolates in case of faults.

The SSCB has two state machines, as shown in fig. 4-5, one for the Solid State Current limiter (SSCL) and one for the NLsw. The SSCL is the central state machine which helps to mimic the breaker logic to drive current to zero, and it communicates with NLsw state machine to know the state when it is required to satisfy some conditions such as waiting for NLsw to open or close fig

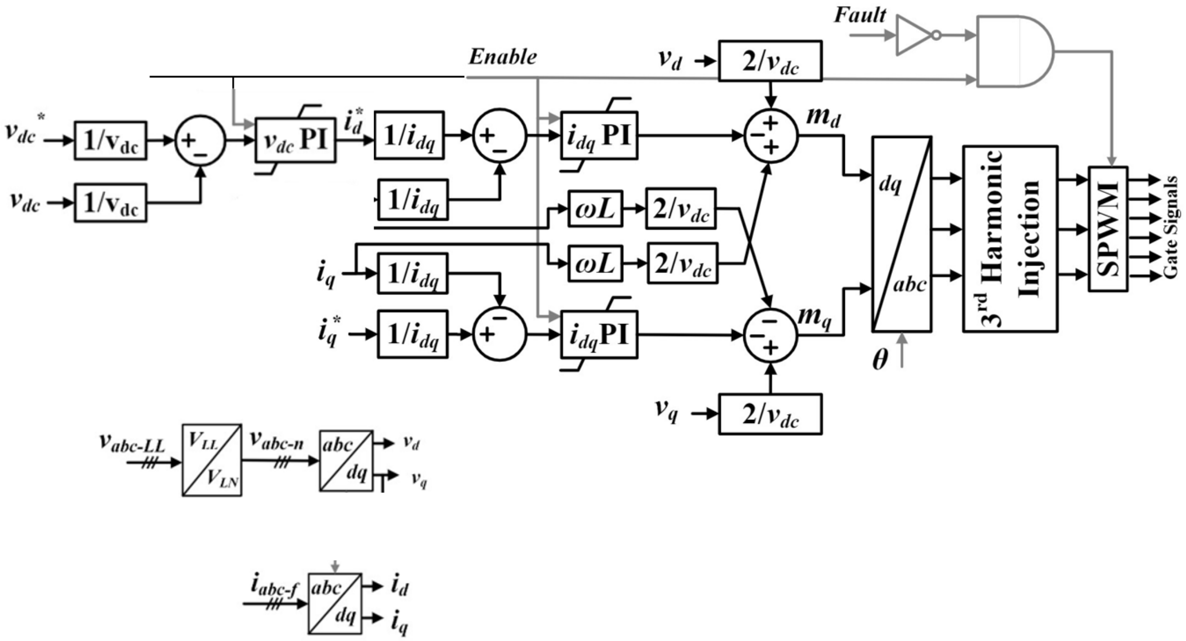


**Figure 4-4:** Controls for the VSI.

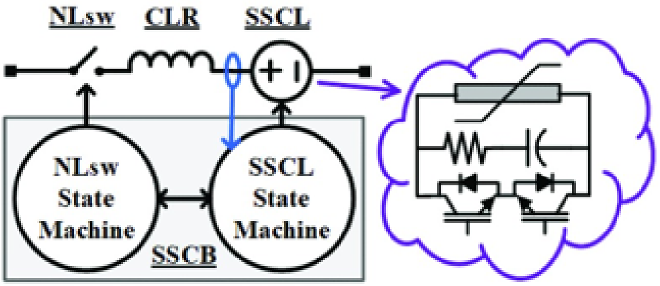


**Figure 4-5:** Average model of the SSCB.

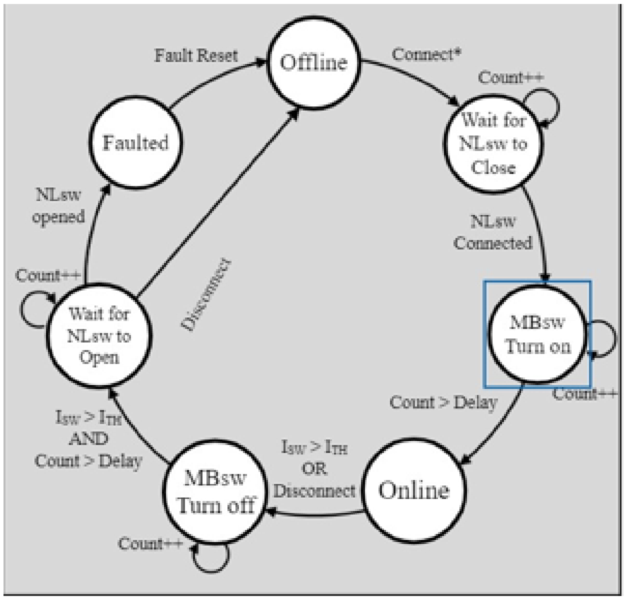
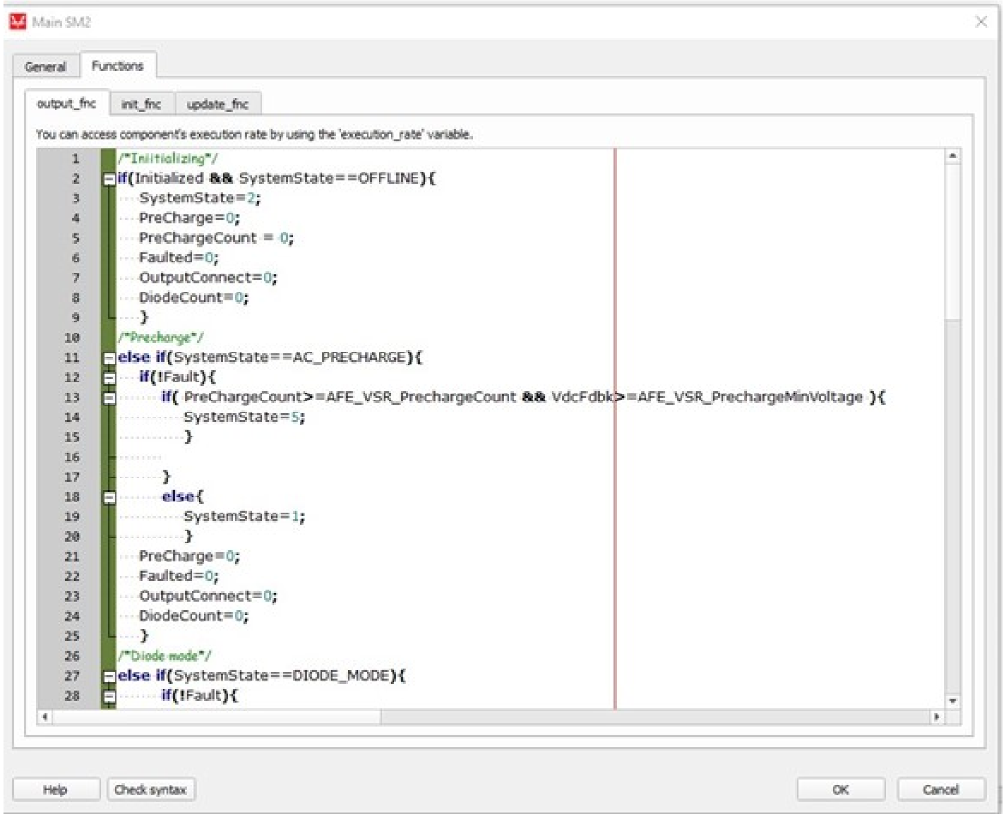


**Figure 4-6:** State Machine for the average model of the SSCB.

4-6.

This project aims to do simulation in real-time. For this, we used Typhoon HiL 604. We used library components and created components as needed, such as the state machines, to have the desired model.

The blocks of the Typhoon had some differences we had to seek the help of documentation to have the result as same as the Simulink. One of the most different ways of implementation was with the state machine. The C function block in Typhoon helps to implement logical operation in a really good way, it is more advanced. Since we were not familiar with implementing state machine in typhoon using C function block, it consumed more time to implement the logical operation in the way we wanted. Fig 4-7 there are function tab with subtabs as output, init and update. The output is where we implement the logical operation with the help of C language, the variables used in the script should be from input and output of the block and also we can have local variables. The important things to note while implementing the logical operation is to initiate flag variable such as switching mode, counting and variable that should have a specific value in the beginning (like zero) or else we may run into problem while rerunning the model because the variable will have a values at the time it stopped which is done in init tab. The update is for updating a variable for every executing time, for example like counters.

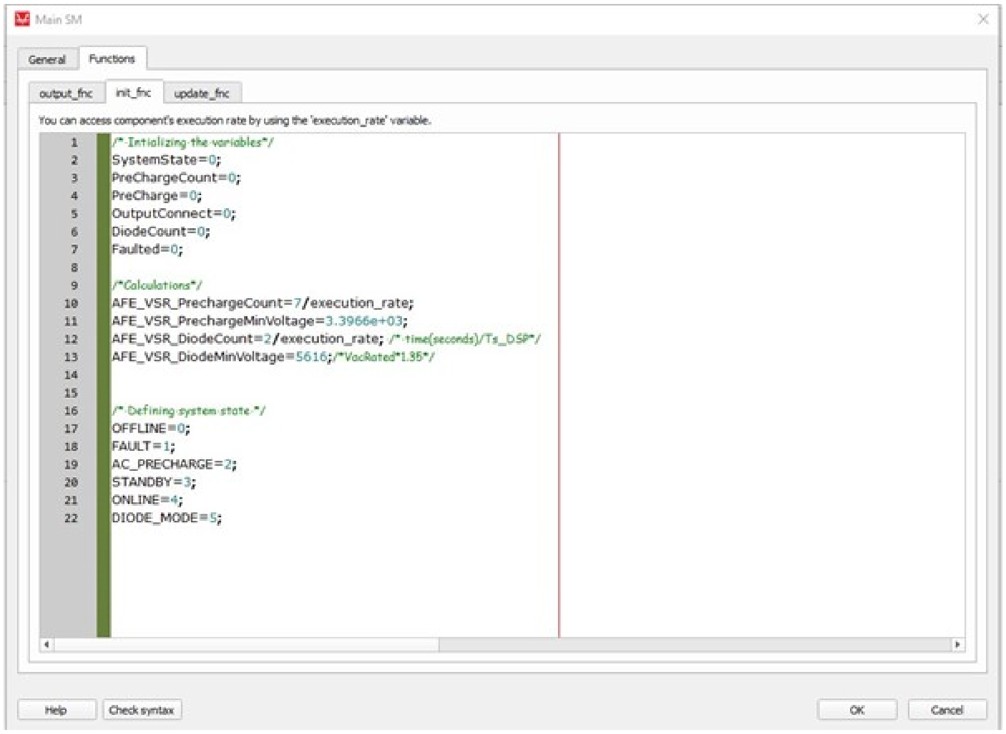


You can access component's execution rate by using the 'execution_rate' variable.

```
/*Initializing*/
if(Initialized && SystemState==OFFLINE){
   SystemState=2;
   PreCharge=0;
   PreChargeCount = 0;
   Faulted=0;
   OutputConnect=0;
   DiodeCount=0;
   }
/*Precharge*/
else if(SystemState==AC_PRECHARGE){
   if(!Fault){
      if( PreChargeCount>=AFE_VSR_PrechargeCount && VdcFdbk>=AFE_VSR_PrechargeMinVoltage ){
         SystemState=5;
         }

      }
      else{
         SystemState=1;
         }
   PreCharge=0;
   Faulted=0;
   OutputConnect=0;
   DiodeCount=0;
   }
/*Diode mode*/
else if(SystemState==DIODE_MODE){
      if(!Fault){
```

**Figure 4-7:** Implementation of state machine logic in the c function block.



You can access component's execution rate by using the 'execution_rate' variable.

```
/* Intializing the variables*/
SystemState=0;
PreChargeCount=0;
PreCharge=0;
OutputConnect=0;
DiodeCount=0;
Faulted=0;

/*Calculations*/
AFE_VSR_PrechargeCount=7/execution_rate;
AFE_VSR_PrechargeMinVoltage=3.3966e+03;
AFE_VSR_DiodeCount=2/execution_rate; /* time(seconds)/Ts_DSP*/
AFE_VSR_DiodeMinVoltage=5616;/*VacRated*1.35*/


/* Defining system state */
OFFLINE=0;
FAULT=1;
AC_PRECHARGE=2;
STANDBY=3;
ONLINE=4;
DIODE_MODE=5;
```

**Figure 4-8:** Variable initialization tab.

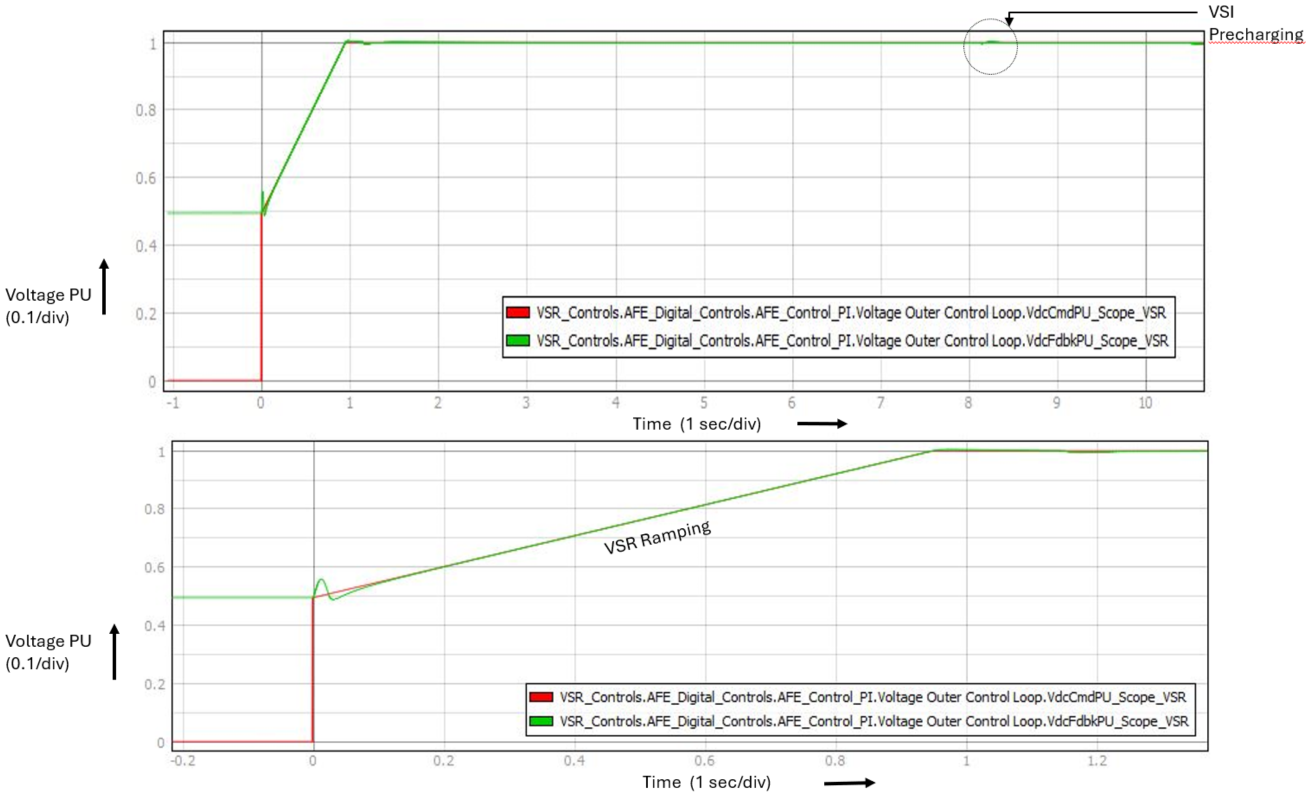


**Figure 4-9:** a) Voltage measured at MVDC corridor b) Zoomed in version of the VSR ramping.

### 4.5.4 Result

The first task was to achieve 12 kV at the DC transmission and maintain it while the VSI is connected with load. Fig. 4-9 a) shows the voltage measurement at the MVDC corridor from the initial stage, starting from off stage of the VSR, ramping up to the desired voltage and VSI precharge and to the end stage where it is VSI is connected to the load. Fig. 4-9 b) shows the zoomed version of the ramping stage and you can see that the ramping follows the control signal. The units are per unitized with respect to 12kV on the y-axis.

The second task was to apply fault at the two ends of the MVDC corridor. Fig. 4-10. The fault was applied at both ends, and the model was able to successfully detect and isolate the faults in both cases. The plot per unitized for the current axis. The fig. 4-12 shows the more detailed version of the current during a fault situation, from the plot we can see that when the fault is applied the current crosses the threshold. When it crosses the threshold the protection system acts which drives the current to zero, when the current is near to zero, the NLsw opens the circuit

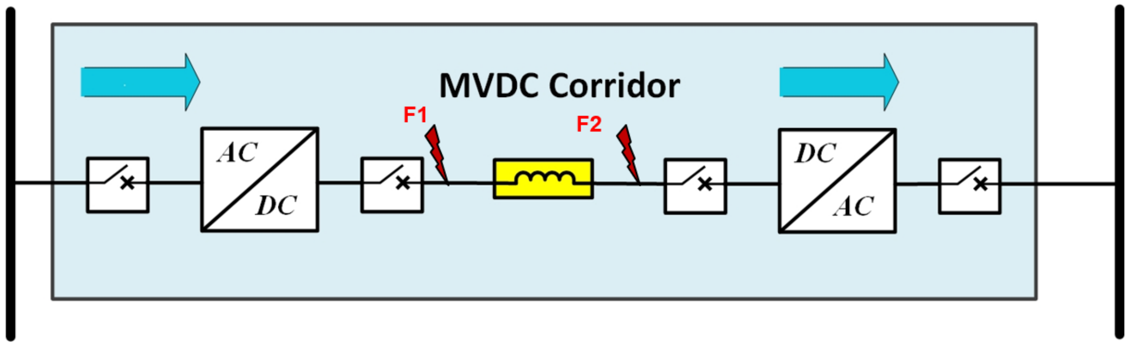


Figure 4-10: Fault location at the MVDC corridor.

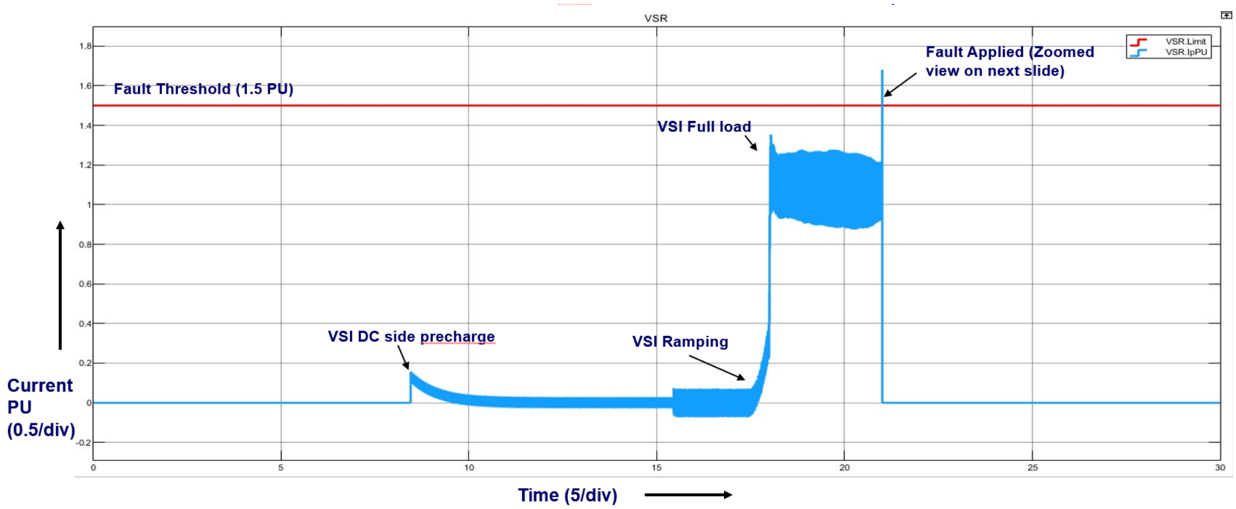


Figure 4-11: VSI current plot, which includes the fault event and detection and isolation.

breaker and isolates it.

The last task is to see how the system dynamics change with respect to SSCB and HCB. To test this scenario we do load shedding with HCB and SSCB, and we look for the MVDC voltage reaction at this moment. The HCB has higher inductance compared to SSCB which results in higher di/dt, because of this the voltage will have higher transient. From fig. 4-13 and fig. 4-14 we can see that, while SSCB voltage transient is really low compared to HCB voltage transient during load shedding.

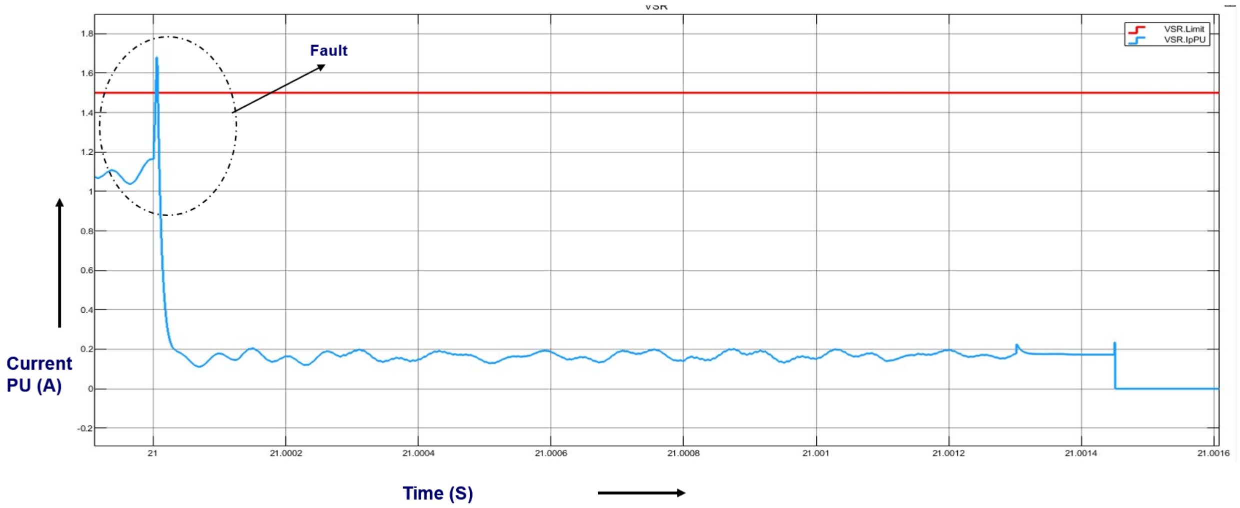


**Figure 4-12:** Zoomed in version at the fault.

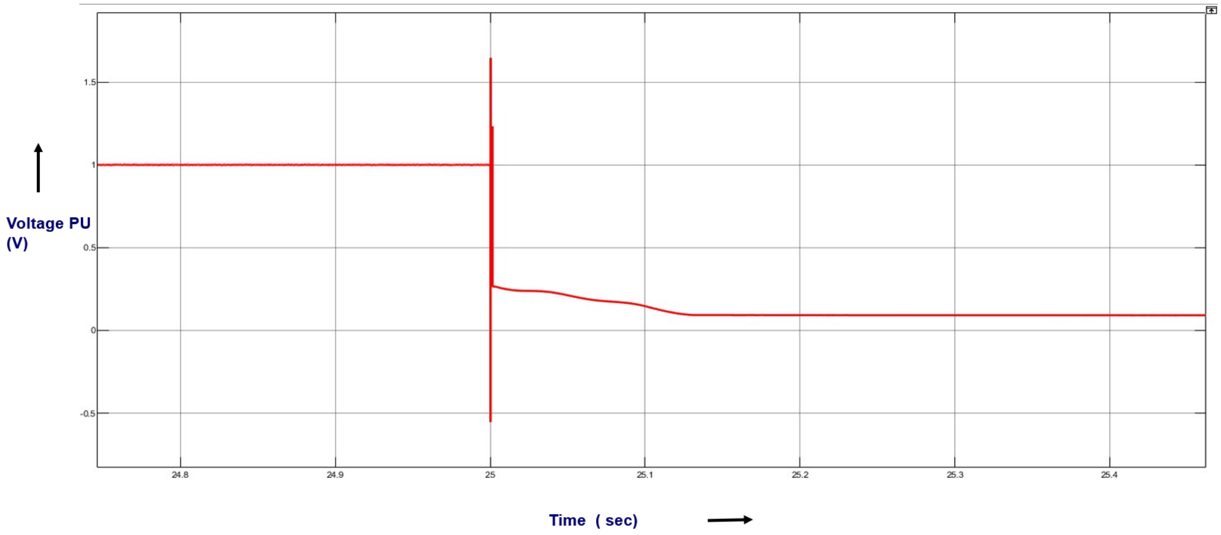


**Figure 4-13:** Voltage at MVDC corridor during load shedding when SSCB is placed.

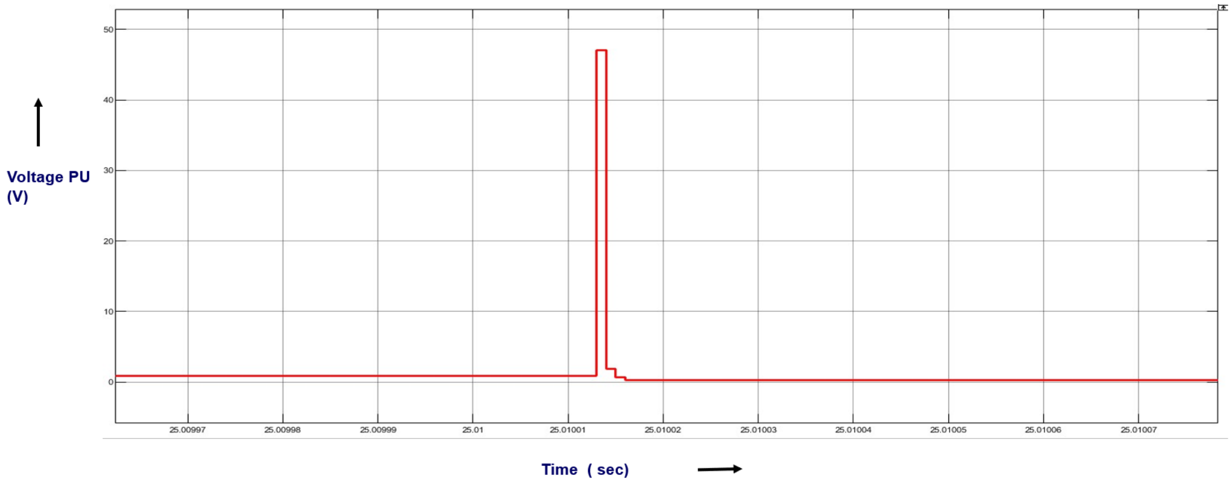


**Figure 4-14:** Voltage at MVDC corridor during load shedding when HCB is placed.

## 4.6 Conclusion and Future Work

### Key findings

The chapter demonstrates that integrating multiple converters, DERs, and protection settings into simulations provides critical insights into the complex dynamics of power electronics in microgrid applications. The role of state-machine control in achieving operational resilience is emphasized.

### Limitations and Challenges

The simulation faces limitations, including computational demands and idealized DER modeling. Real-world validation would enhance these findings.

### Future Directions

Future work could explore AI-driven control, advanced protection mechanisms, and digital twins for enhanced monitoring and predictive maintenance. These advancements promise to enhance microgrid resilience and unlock the potential of DERs in interconnected systems.

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# Chapter 5

# Hardware-in-the-Loop Simulation Real-time

## 5.1 Introduction to HIL Real-Time Simulation

The increasing complexity of modern energy systems, driven by the integration of renewable energy sources and distributed energy resources, has created an urgent need for advanced testing and validation techniques. Hardware-in-the-loop simulation has merged as a critical tool in research and development, enabling real-time interaction between physical hardware and simulated systems.

HiL bridges the gap between theoretical designs and practical implementations by replicating real-world conditions in a controlled environment. Unlike traditional simulation techniques, HiL incorporates physical controllers or subsystems into the testing process, making it invaluable for evaluating power electronics, microgrids, and transportation electrification systems.

This chapter explores the importance of HIL simulation in modern power electronics research, its role in understanding detailed system interactions, and its application in fault-tolerant designs. The chapter also highlights the significance of state machine-based responses in adaptive system testing.

## 5.2 Importance of HiL Simulation in Research and Development

### 5.2.1 Accurate Interaction Modeling

HIL simulation provides a platform to study complex interactions among DERs, various load types, and other energy resources. For instance, in grid-connected systems, the interaction between inverters, dynamic loads, and grid disturbances can be analyzed with high fidelity. This capability ensures that system designs are robust and reliable under real-world operating conditions.

### 5.2.2 Risk Mitigation

Testing fault scenarios, such as short circuits or sudden load disconnections, is essential to ensure system stability and protection. However, physical testing of such conditions poses significant risks to hardware. HiL mitigates these risks by enabling fault injection in a virtual environment, allowing researchers to analyze system behavior without damaging equipment.

### 5.2.3 Cost and Time Efficiency

Developing and testing physical prototypes is both time-consuming and expensive, especially for large-scale systems like microgrids. HiL reduces development cycles by enabling iterative testing and validation during the design phase, minimizing the need for costly physical hardware until later stages.

## 5.3 Detailed Interaction Modeling in HIL

### 5.3.1 Power Electronics-Based Distributed Energy Resources

DERs, such as solar inverters, battery energy storage systems, and wind turbine converters, play a vital role in modern power systems. HiL simulation allows a detailed study of these components, capturing their dynamic response to varying conditions, including grid disturbances and load variations. By analyzing these interactions, researchers can design systems that optimize power quality, stability, and efficiency.

### 5.3.2 Load Behavior and Dynamics

Different types of loads - constant power, resistive, inductive, or non-linear - affect the performance of the power systems in unique ways. HIL facilitates the simulation of dynamic load behaviors, enabling a deeper understanding of their impact on DERs and grid stability. For example, a sudden increase in load demand can be tested in real-time to evaluate system response and recovery.

### 5.3.3 State Machine-Based System Responses

State machines are an effective tool for modeling adaptive control strategies in HiL simulations. By defining various operating state (e.g, ON, precharging, ramping, fault condition, ride through) and transitions between them, state machines ensure robust operation under diverse scenarios. For instance, a microgrid controller can switch between different operation states, also isolating from faults, and grid-connected modes based on predefined conditions, tested extensively in HIL.

### 5.3.4 Fault Analysis and System Resilience

Fault injection in HIL simulations provides valuable insights into the fault-tolerant capabilities of power systems. Scenarios like voltage sags, frequency deviations, and equipment failures can be tested to evaluate protection mechanism and recovery strategies. This analysis is critical for ensuring the resilience of microgrids and transportation electrification systems.

## 5.4 Applications of HIL in Power Electronics

### 5.4.1 Microgrid Testing

HiL is widely used to validate microgrid operations, including DER integration, load balancing and grid synchronization. In a typical setup, Typhoon HIL can simulate DERs and controllers while OPAL-RT handle the larger grid dynamics, allowing detailed study of interactions.

### 5.4.2 Electric Vehicle Powertrain Validation

In transportation electrification, HiL is essential for testing EV powertrains. By simulating real-world driving conditions, regenerative braking scenarios, and battery dynamics, researchers can evaluate the performance and safety of power electronics systems in electric vehicles.

### 5.4.3 Grid-Tied Inverter Testing

HiL simulation of grid-tied inverters provides insights into their behavior under varying grid conditions, such as harmonic distortion or phrase imbalances. This testing ensures compliance with grid codes and enhances overall system reliability.

## 5.5 Islanded Microgrid

### 5.5.1 Introduction

From Chapter:4 we have learnt that the MVDC corridor is equipment with protection system. The project discussed in this section is part of [32], and I was working on implementing the Typhhon model and ride-through settings in Typhoon. We want to study how a microgrid behaves when it is islanded from the MVDC corridor due to a fault at the MVDC corridor. We consider a microgrid in islanded mode, and apply fault at one of the loads to observe the transient behavior in Typhoon model. Fig.5-2 shows the schematic representation of the microgrid and the fault location.

### 5.5.2 Implementation

This was modeled in Typhoon HiL real time simulation 5-1 and we have also implemented low voltage ride through settings in typhoon for Battery Energy Storage Systems (BESS) and Photo Voltaic (PV) farms. All the components of the model was designed to have the value we have shown the schematics.

### 5.5.3 Result

The real-time simulation was done in Typhoon and we applied line-to-line fault at the load side. The transient response of the Genset are shown in fig. 5-4 and fig. 5-3. As we expect, the currents have significantly increased due to the low impedance path created by the fault, while the voltage have dropped. We can also see from the plots that there is an imbalance in both. The ride through settings we implemented in genset was functional as we can see from the plot, once the fault got isolated the genset went back to normal operation.

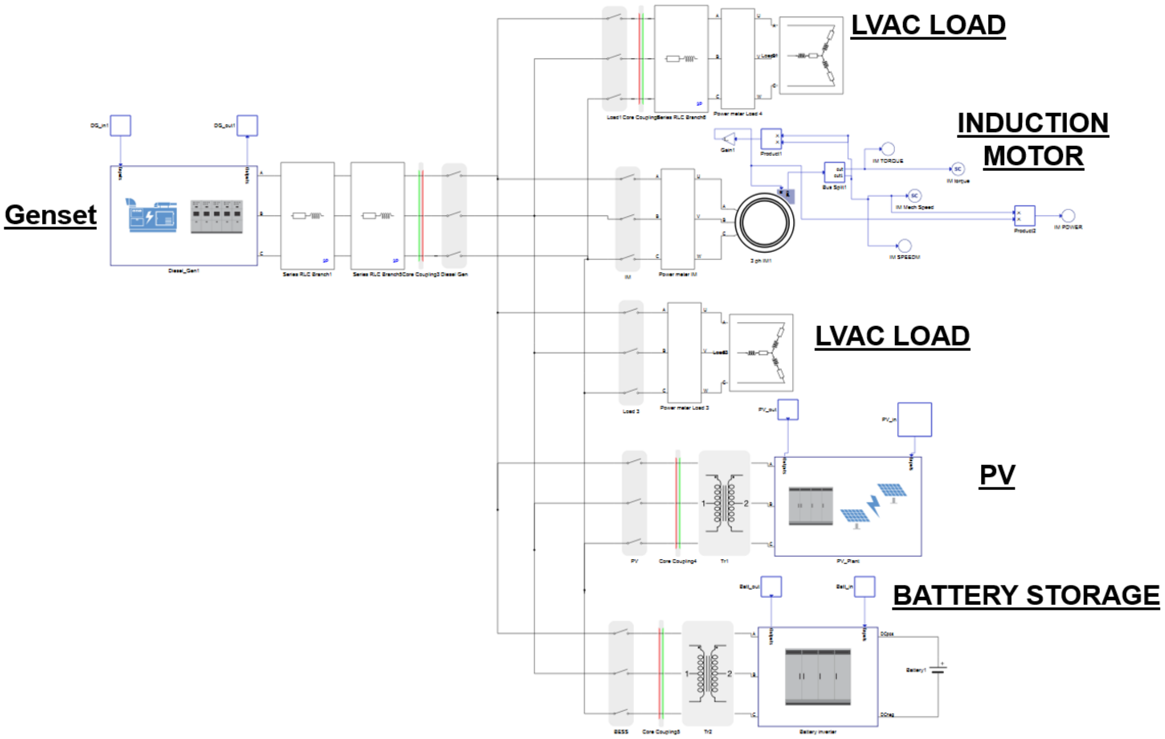

**Figure 5-1:** Typhoon Real Time Simulation Model.

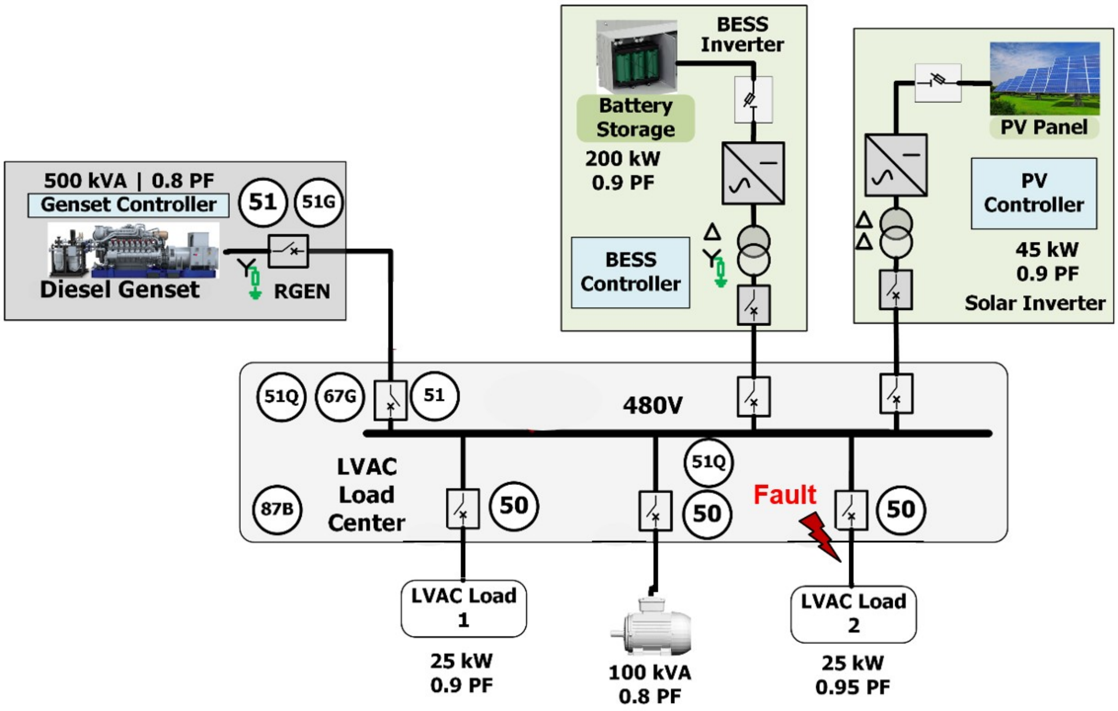

**Figure 5-2:** Schematic Representation of the islanded microgrid and fault locaton.

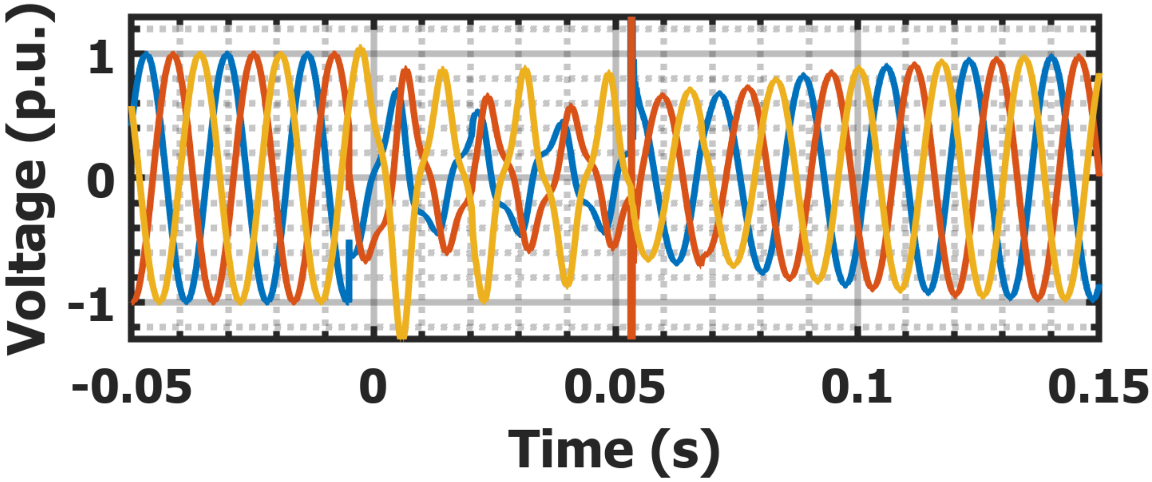

**Figure 5-3:** Genset Voltage Transient.

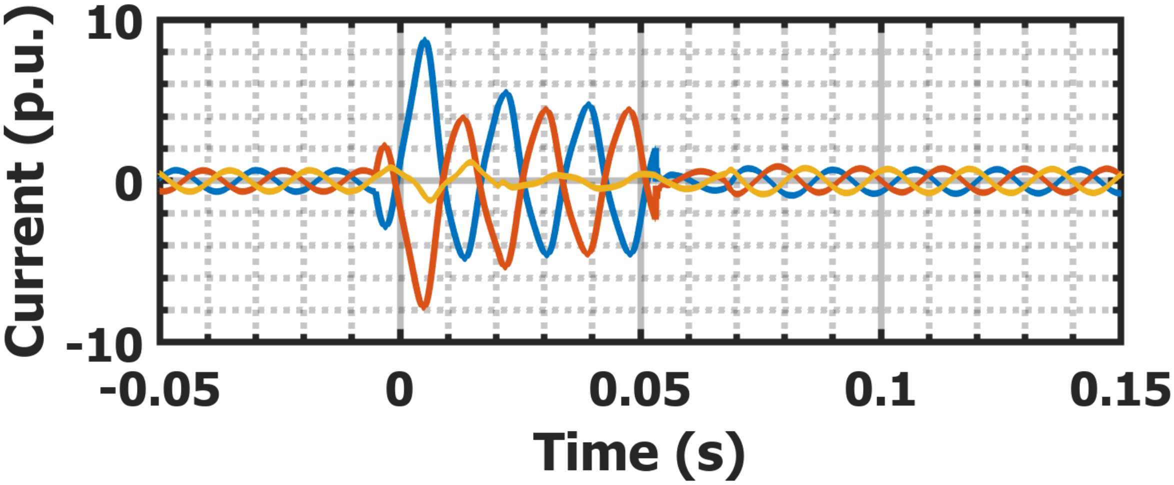

**Figure 5-4:** Genset Current Transient.

Fig. 5-5 shows the current transient of the Battery Energy Storage Systems (BESS), we can see that the BESS got disconnect when the fault occurred and waited for the fault to be isolated. The time it takes is longer since we have mechanical loads. Since we have implemented the ride-through settings we were able to bring back the BESS as soon as the fault got isolated. This low-voltage ride through helps us to recover from the fault.

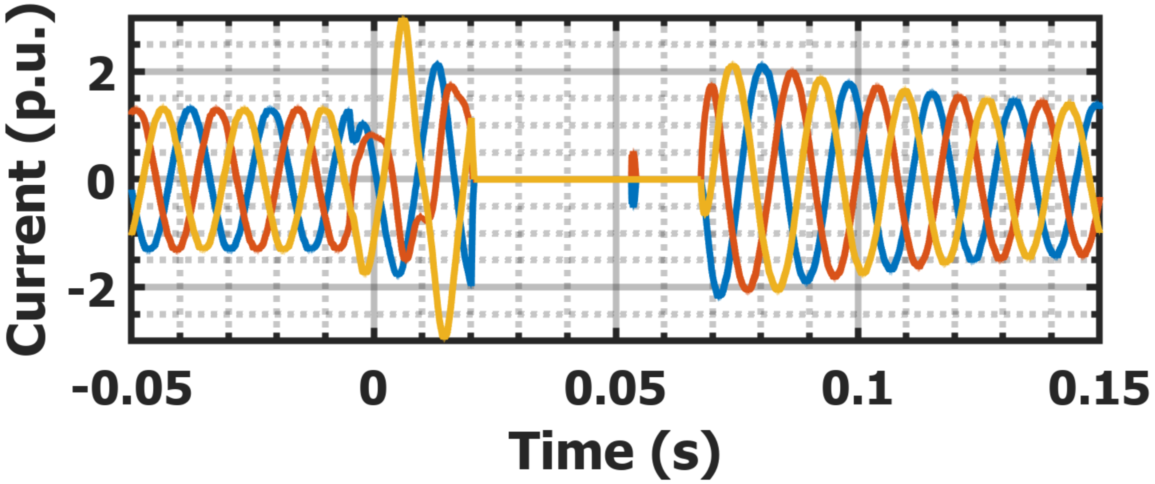

**Figure 5-5:** BESS Current Transient.

## 5.6 Challenges and Limitations of HIL Simulation

### 5.6.1 Computatuional Complexity

Real-time simulation of complex systems, such as large microgrids, require significant computational resources. Platforms like OPAL-RT and Typhoon HIL address this challenge by using FPGA-based processing and multi-core CPUs, but model simplifications are often necessary to achieve real-time performance.

### 5.6.2 Scalability

While HiL is highly effective for component-level testing, scaling simulations to include entire grids or transportation systems can be challenging. Integration of multiple HiL platforms, such as using Typhoon for detailed power electronics and OPAL-RT for broader grid simulations, helps address scalability issues.

### 5.6.3 Integration and Interfacing

Interfacing real hardware with simulated environments requires careful calibration to ensure accurate data exchange. Communication protocols, such as CAN or Modbus, add complexity, but they are essential for synchronizing physical controllers with virtual systems.

## 5.7 Conclusion

This chapter has explored the critical role of HiL simulation in understanding detailed interactions among power electronics-based DERs, diverse loads, and other energy resources. By enabling risk free fault analysis and adaptive control testing using state machine-based responses, HiL provides a robust framework for advancing research in grid applications and transportation electrification.

# Chapter 6

# CHiL and PHiL Based Microgrid Research

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As the electrical power grid is becoming more complex and interconnected with DERs, several converters and other components as we have mentioned in the earlier chapter, we need to bridge the gap and have to capture real-world challenges while doing research and development. To address this, Controller Hardware-in-the-Loop (CHiL) and Power Hardware-in-the-Loop (PHiL) simulations have become essential tools for researchers. These methods combine simulations with physical hardware to create more realistic and accurate testing environment, bridging the gap between theory and practice.

This chapter builds on earlier discussions about simulation software and system integration. It focuses on how CHiL and PHiL help researchers study and develop technologies for microgrids and other modern power systems by providing a safe, efficient, and realistic testing environment.

## 6.1 Understanding CHIL and PHIL

### Controller Hardware-in-the-Loop (CHiL))

CHIL connects a physical controller to a real-time simulation of a power system or power converter. This allows researchers to test control algorithms and strategies under various conditions without requiring a full hardware setup. It's commonly used to:

- Evaluate control system performance.

- Detect and fix problems early in development.
- Fine-tune control designs before physical implementation.

**Power Hardware-in-the-Loop (PHiL)**

PHIL goes a step further by including real power equipment - such as power converters, transformers, or loads - into the simulation. By exchanging actual power signals between the hardware and the simulator, PHIL enables:

- Testing how the hardware performs in real-world conditions.
- Studying the interaction between physical and simulated components.
- Ensuring the hardware can handle faults, disturbances, or changing conditions.

## 6.2 Why CHiL and PHiL are Important

CHIL and PHIL essential for modern power system research and development for several reasons:

1. **Faster Innovation:** These methods save time and money by allowing researchers to test systems without building full prototypes. Design flaws and performance issues can be identified and fixed early in the process.
2. **Safer Testing:** Simulating extreme conditions, like short circuits or grid failures, is much safer than testing them on real systems. CHiL and PHiL let researchers study these scenarios without risking equipment or safety.
3. **Better Understanding of System Interactions:** Modern power systems involve many interconnected components, such as renewable energy sources, batteries, and controllers. CHiL and PHiL allow researchers to study how these components interact under realistic conditions.
4. **Advancing Microgrid Development:** Microgrids, which are small, self-contained power systems, are critical for a reliable and sustainable energy future. CHiL and PHiL make it possible to:
    - Test microgrid controller for both grid-connected and standalone operation.

- Ensure the protection system works correctly during faults or transitions.
- Optimize energy use within the microgrid.

## 6.3 CHiL and PHiL in Microgrid Applications

Microgrids, with their ability to operate independlty or alongside the main grid, present unique technical challenges. CHiL and PHiL are instrumental in addressing these challenges:

1. **Controller Validation:** CHiL allows researchers to test and improve microgrid controllers, ensuring they can handle real-world scenarios such as load changes, renewable energy variations, and fault scenarios.

2. **Hardware Integration:** PHiL allow researchers to test the performance of physical devices such as power converters, battery energy storage system, with a simulated microgrid. This ensures smooth integration and identifies issues like voltage instability or harmonics.

3. **Protection Systems:** Fault scenarios, including short circuits and equipment failures, can be safely simulated using PHiL, ensuring that protection systems function correctly and reliably.

4. **Energy Management:** CHiL supports the testing of energy management systems (EMS), which balance generation, storage, and loads. This optimization is critical for efficient microgrid operation.

## 6.4 Application and Case Studies

CHIL and PHIL have been widely used in cutting-edge research:

1. **National Renewable Energy Laboratory (NREL):** NREL's HIL test bed was used to evaluate microgrid controllers, reducing risks and improving system reliability during field deployments.

2. **ERIGrid Project:** The European ERIGrid initiative demonstrated the use of CHiL and PHiL for validating smart grid and microgrid technologies, enhancing system-level and component-level testing

## 6.5 Conclusion

CHIL and PHIL have revolutionized how researchers and engineers approach power system challenges. By providing a controlled, realistic testing environment, these methods enable rapid development, improved safety, and more reliable system designs. As the energy sector moves toward smarter, cleaner technologies, CHiL and PHiL will continue to play a critical role in advancing microgrid research and ensuring the successful integration of modern power systems.

# Chapter 7

# Conclusion and Future Work

This thesis explored advanced simulation techniques for power electronics, focusing on their role in grid applications and transportation electrification. By combining modeling, real-time testing and hardware-in-the-loop (HiL) methods, the research bridges the gap between theoretical designs and practical implementation.

The work began with Simulation and modeling of Power Electronics Converters, where we explored that tools like MATLAB/Simulink, PLECS, and PSIM are used to develop accurate converter models. These models provided insights into the dynamic behavior, serving as a foundation for system-level integration. The subsequent chapter on Integration of Power Electronics Simulation into Larger System demonstrated how power electronics interact with DERs and dynamic loads, contributing to grid stability and energy efficiency. Real-time simulation showcased the ability to replicate fault scenarios and system interactions safely. Platforms such as Typhoon and OPAL-RT proved critical in bridging simulation and real-world operation.

Throughout the chapters we have discussed about MVDC corridor, a potential replace for the conventional transmission system that will bring higher efficiency, voltage stability, ease of integration of renewable DERs. We have discussed also protection for medium voltage DC, and also the possibility of replacing the VSC and circuit breaker with full-bridge MMC. The discussion also included the islanded mode microgrid and applying fault at one of the loads to see the transient and successful operation of the ride-through setting implemented.

Lastly, the focus on CHIL and PHIL and how it helps in both controllers and physical hardware in microgrid systems, highlighting the importance of these techniques in advancing energy reliability. This thesis contributed to the growing field of power electronics by providing tools and methodologies for simulating and testing complex systems. Its findings are directly applicable to improving energy resilience and supporting the global push for electrification and sustainability.

Going forward, the MVDC corridor setup discussed here can be done with MMC and test the line-line fault at corridor for fault detection, isolation and recovery. Then we can integrate the MMC based MVDC corridor into the larger system and connect between different microgrids and remote energy source to analyse the system. As the lab at Center for Sustainable Electrical Energy Systems is developing under the guidance of Dr. Cuzner, we may be able to integrated the microgrid lab setup and tyhoon to do HiL, CHiL, and PHiL for this system.

The development in microgrid testing lab at the Center for Sustainable Electrical Energy Systems will play an important role in implementing more advanced CHiL and PHiL setups. As Joseph Lentz [33] noted, this facility will enable to testing of Battery Energy Storage Systems, studying grid-connected systems, and collecting high-quality data for machine learning-based modeling.

The work mentioned in the thesis is around simulation, real-time simulation, and HiL setup. But the our lab, Center for Sustainable Electrical Energy Systems (CSEES) , is working on implementing CHiL and PHiL with help of the microgrid testing lab we have built as Joseph Lentz [33] mentioned we will be able to do more CHiL and PHiL works. This will help to test BESS systems, connect with utility grid to have more study, also get data that can be used for ML-based modeling.

While this thesis addresses critical aspects of simulation and validation, it also highlights several promising directions for further research. The capabilities of the CSEES lab and its microgrid testing facility create opportunities to expand this work in meaningful ways.

The CSEES microgrid lab offers the opportunity to enhance CHIL and PHIL applications, which will benefit research for students as well as sponsors and industries. This will help for testing and optimizing systems in realistic conditions, investigating the interaction between microgrids and utility grids to improve system stability and efficiency, generating detailed datasets for machine learning-based and predictive control strategies, optimizing grid performance using real-time data analytics, studying hybrid system such as those combining solar, wind, and energy storage, under dynamic operating conditions.

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