PV Generation Model (Assignment 2)

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Chapter 1

13-Node Test Feeder: A Comprehensive Overview

The 13-Node Test Feeder is a compact and practical system that is used to evaluate the performance of power distribution analysis software. Operating at **4.16 kV**, it offers a realistic environment for studying the behavior of electrical distribution networks, especially when dealing with unbalanced loads and voltage regulation. The system's design includes essential components such as shunt capacitor banks, voltage regulators, overhead and underground power lines, and various types of electrical loads. These features make it particularly useful for identifying and resolving power flow issues in highly unbalanced systems.

One of the key purposes of the 13-needle test feeder is to serve as a benchmark for testing the performance of three-phase radial protection systems. It allows engineers to simulate failures and analyze the distribution of electrical resources, comparing expected outcomes with actual performance. This capability helps ensure that power systems operate reliably and efficiently, even in challenging conditions.

Key Features of the 13-Node Test Feeder

1. **Compact and Highly Loaded Design:**
    - The feeder is relatively short in length, but it carries a high electrical load for its 4.16 kV voltage level, simulating real-world scenarios common in urban and industrial settings.
2. **Substation Voltage Regulator:**
    - At the substation, a voltage regulator consisting of three single-phase units connected in a wye configuration maintains stable voltage levels across all three phases, ensuring consistent power delivery.
3. **Overhead and Underground Power Lines:**

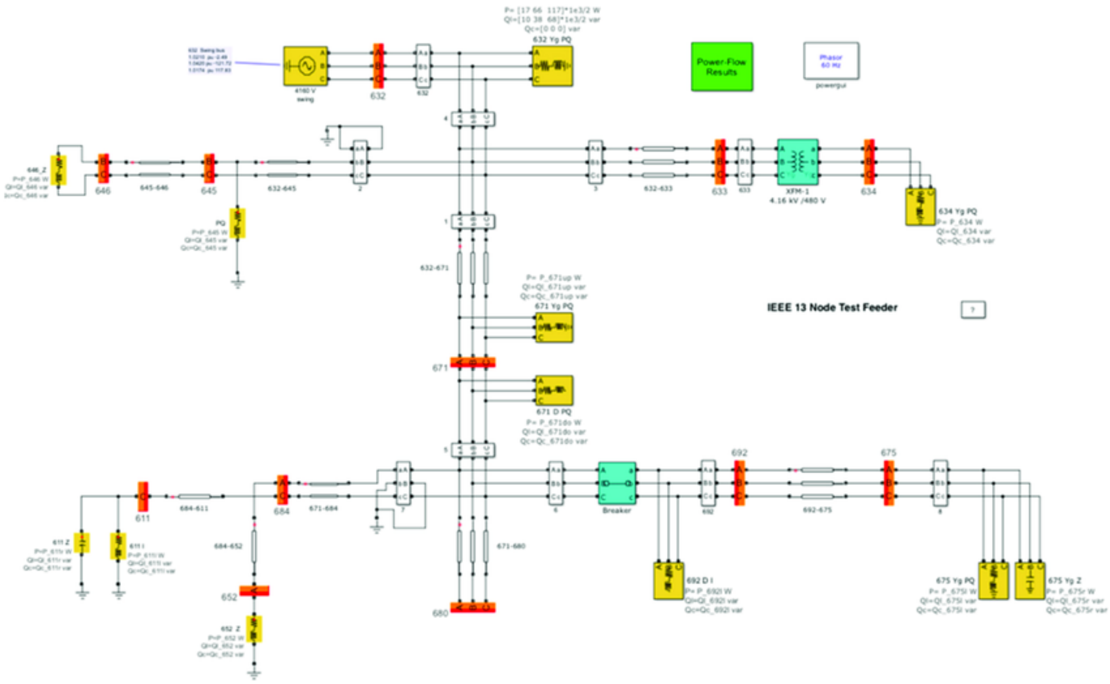

FIGURE 1.1: IEEE 13 node feeder

- The system incorporates both overhead and underground lines with different phasing arrangements, allowing engineers to analyze how each configuration affects power flow, reliability, and fault behavior.

4. **Shunt Capacitor Banks:**

    - Strategically placed shunt capacitors help improve the power factor, stabilize voltage levels, and reduce energy losses, enhancing the overall efficiency of the system.

5. **In-Line Transformer:**

    - An in-line transformer is included to step down voltage levels, ensuring that downstream loads receive the appropriate voltage for their operation.

6. **Unbalanced Spot and Distributed Loads:**

    - The feeder features both spot loads (connected at specific nodes) and distributed loads (spread along the feeder), intentionally arranged to create phase imbalances that simulate real-world operating conditions.

7. **Delta-Star Transformer:**

    - A delta-star ($\Delta - Y$) transformer with a voltage ratio of **115 kV / 4.16 kV** serves as the main transformer, reducing high transmission voltages to lower distribution voltages suitable for end users.

Applications and Practical Importance

The 13-Node Test Feeder is widely used in both academic research and industrial applications due to its ability to replicate real-world challenges in electrical distribution networks. Key applications include:

- **Power Flow Analysis:** Testing power flow calculations to ensure accurate predictions of voltage drops, power losses, and load distribution.
- **Fault Analysis:** Simulating phase-to-phase and phase-to-ground faults to evaluate system performance and protective device operation.
- **Voltage Regulation Studies:** Assessing how effectively voltage regulators maintain stable voltage levels under changing load conditions.
- **Load Balancing:** Analyzing the effects of unbalanced loads on system performance and exploring methods to minimize phase imbalances.
- **Protection System Testing:** Verifying the accuracy and reliability of protection devices by simulating abnormal operating conditions.

Chapter 2

PV array model

In this project implementation, the photovoltaic (PV) model was integrated into the IEEE 13-bus feeder system. The converter is connected to a constant current source, representing a solar panel array operating under steady-state conditions. The voltage source converter (VSC) control strategy was adapted from previous work, with modifications to regulate the DC voltage rather than control active power. This regulation is achieved by managing the charging and discharging of the DC capacitor. Additionally, the VSC model was developed and presented both within the subsystem and as an independent component, with the assumption of zero power losses during the AC/DC conversion process.

2.1 Model assumptions:

- From the data provided by manufacturer a decent PV array model can be build;
- Manufacturers also provide temperature coefficients that can be used to adapt the model for different conditions: K_v - voltage temperature coefficient, K_i - current temperature coefficient;
- The approximation $I_{pv} \approx I_{sc}$ is acceptable since the diode current in short-circuit conditions is very small;
- The I_{pv} variation for different temperatures and irradiances is expressed as:

$$I_{pv} = \left[I_{pv,n} + K_I(T - T_n)\right] \frac{G}{G_n} \tag{2.1}$$

- The I_0 can be obtained in nominal conditions from the open-circuit point. Then, if temperature dependency is included, this current is expressed as:

$$I_0 = \frac{I_{sc,n} + K_I(T - T_n)}{\exp\left[V_{oc,n} + \frac{K_V(T-T_n)}{V_{ta}}\right] - 1} \tag{2.2}$$

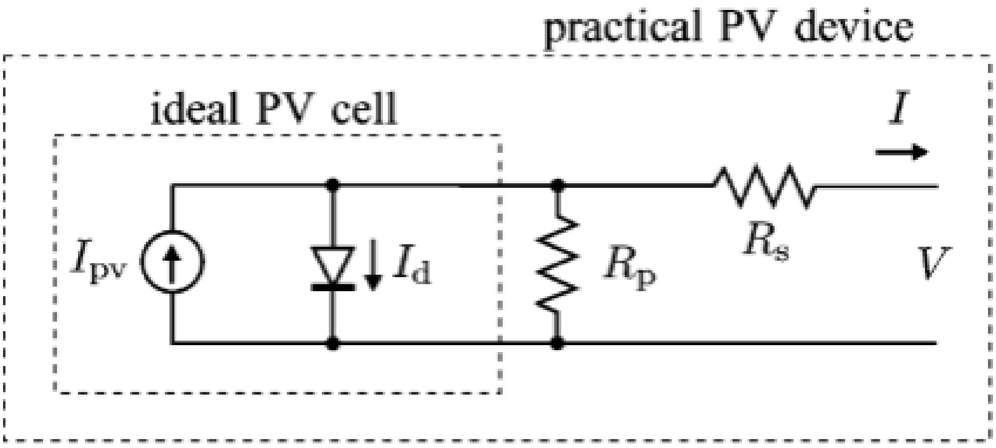

FIGURE 2.1: PV Array Model

considering the quantities of photovoltaic cells and modules connected in series and parallel, the overall current output from the photovoltaic system is equal:

$$I = N_{\text{cellpar}} \left(I_{\text{pv}} - I_0(\exp\left(\frac{V/N_{\text{cellser}} + RsI/N_{\text{cellpar}}}{V_t}\right) - 1\right) - \frac{V/N_{\text{cellser}} + RsI/N_{\text{cellpar}}}{R_p} \tag{2.3}$$

where:

- I_{pv}: current generated by the incident light;
- I_0: reverse saturation or leakage current of the diode;
- V_t: thermal voltage of the diode;
- a: diode ideality constant;
- R_s: equivalent series resistance of the array (usually very small);
- R_p: equivalent parallel resistance of the array (usually very large).

Implementation of the solar panel is Simulink:

The above equations (equation 1-3) that were explicitly stated were implemented in the PV array model block, which can be seen below in simulink:

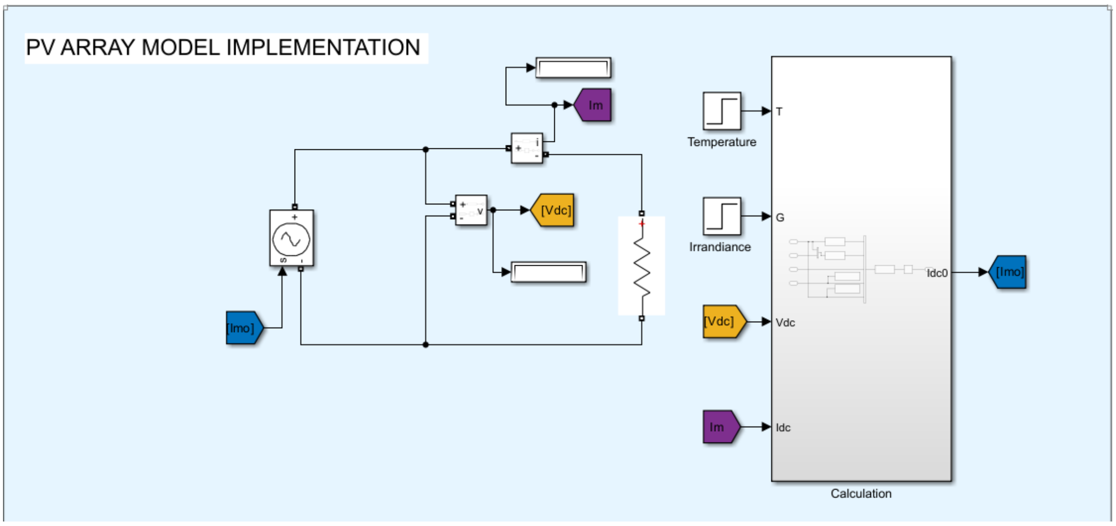

FIGURE 2.2: Simulink of PV array Model

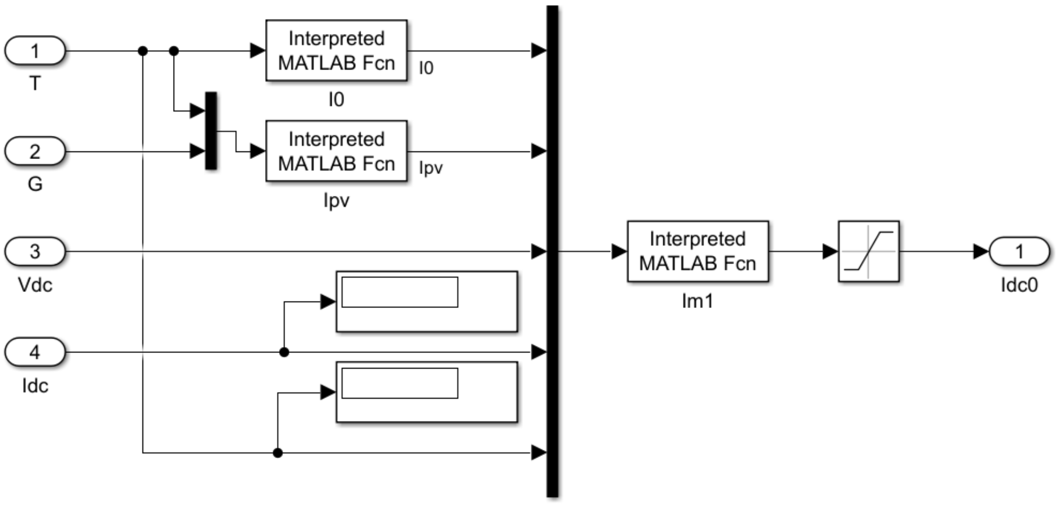

FIGURE 2.3: currents calculations related to the solar panels

Nominal value for temperature is 298 K, for irradiance is 1000 W/m^2. Table for different values of temperature and irradiance is represented below.

Chapter 3

VSC model with DC voltage control

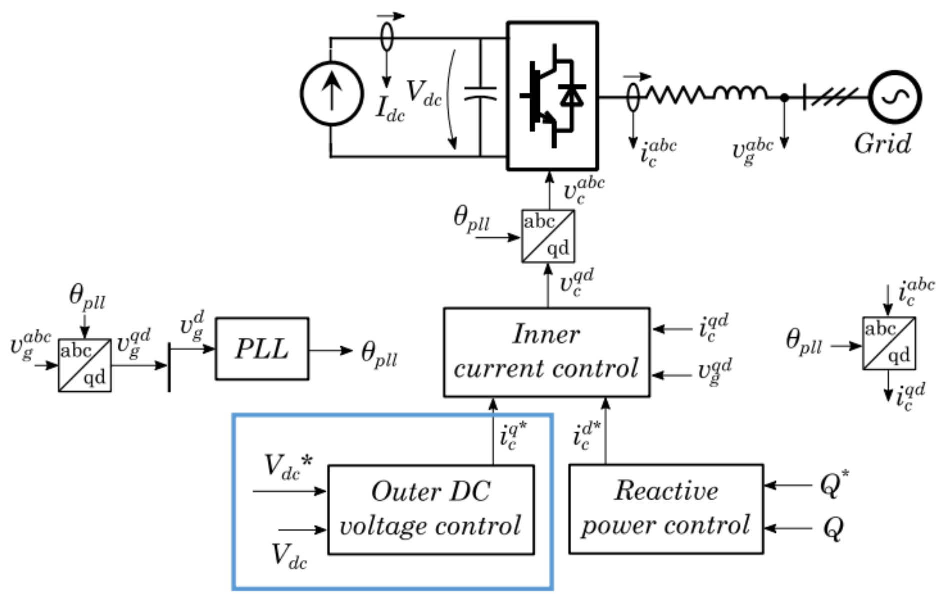

FIGURE 3.1: DC VOLTAGE IMPLEMENTATION IN THE BASIC VSC MODEL

Model assumptions: In this task the basic VSC model will be modified to include a DC voltage control

Figure 2.2 illustrates the implementation of DC control, which assumes that the dynamic response of the current loop is ignored, relying instead on disturbance rejection.

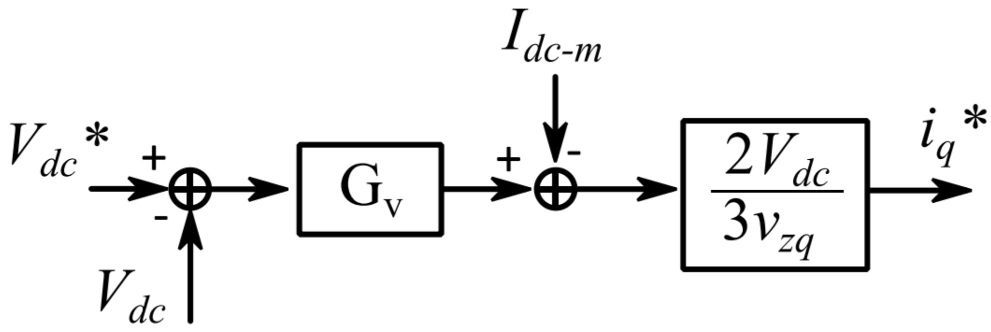

Figure 3.2: DC VOLTAGE CONTROL IMPLEMENTATION

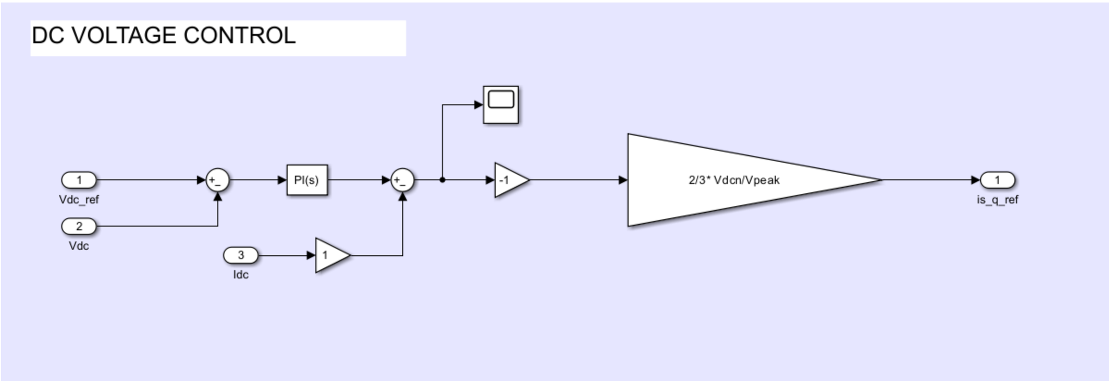

Figure 3.3: DC VOLTAGE CONTROL IMPLEMENTATION

3.1 MAXIMUM POWER POINT TRACKING

3.1.1 MPPT - Provides maximum power that is available

The fixed DC voltage reference needs to be substituted with an MPPT (Maximum Power Point Tracking) system, which ensures the optimal DC voltage reference. The most straightforward approach involves employing the open-circuit method, wherein the DC voltage reference is calculated accordingly (refer also to the solutions of PV activities).

In the latter portion of the assignment, MPPT control is introduced. This control method operates in an open-loop fashion, estimating the Maximum Power Point (MPP) voltage, Vmpp, based on the PV temperature. Subsequently, this Vmpp value is established as the reference voltage for the Vdc control. Furthermore, a switch is integrated to enable the deactivation of MPPT, allowing for the substitution of a constant reference voltage. This setup encapsulates two scenarios in PV system control via a converter: If the power demand equals or exceeds the maximum output power of the PV array, the system operates at the MPP. Conversely, if the power demand is lower than that of the MPP, the converter must identify an alternative operating point that aligns with the demand, typically opting for the one with lower current to minimize losses.

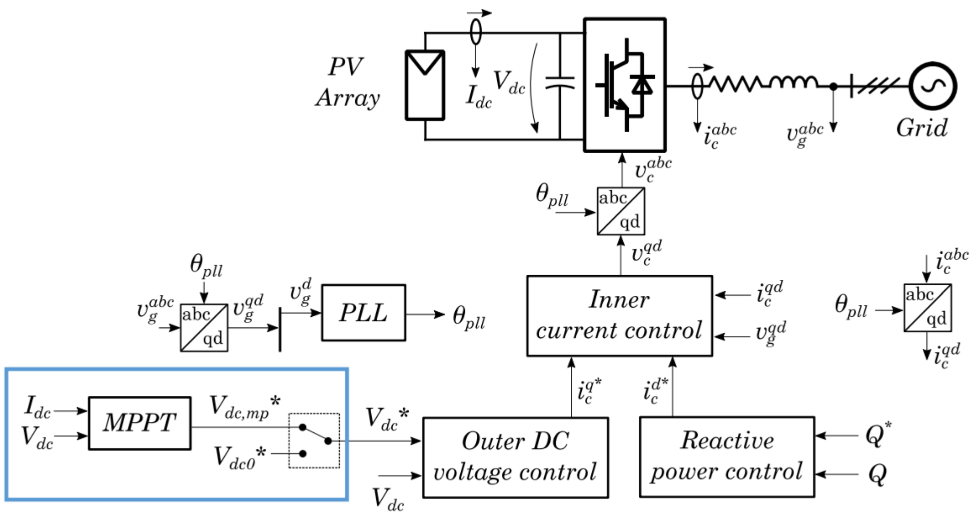

FIGURE 3.4: Complete diagram of solar PV combined with VSC

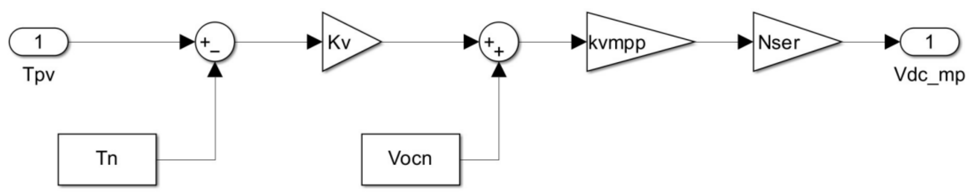

FIGURE 3.5: MPPT

Also, the MPPT algorithm seeks to optimize the power output of the solar PV system by dynamically adjusting the operating voltage and current. Upon the completion of the MPPT, different scenarios were tested as seen below:

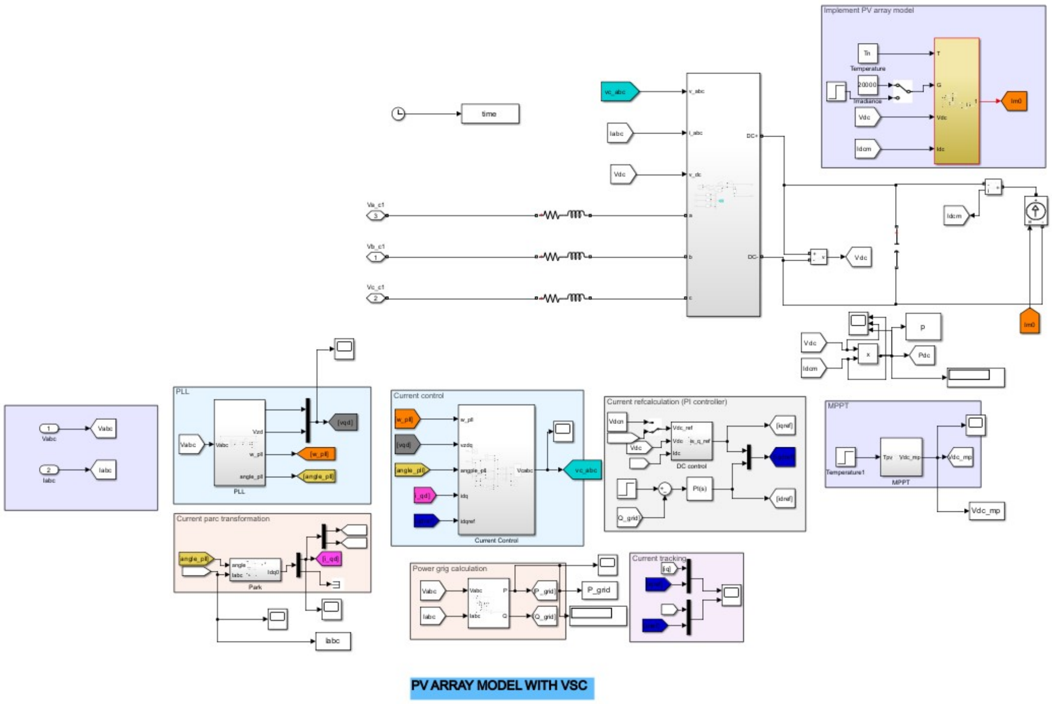

FIGURE 3.6: PV ARRAY MODEL WITH VSC

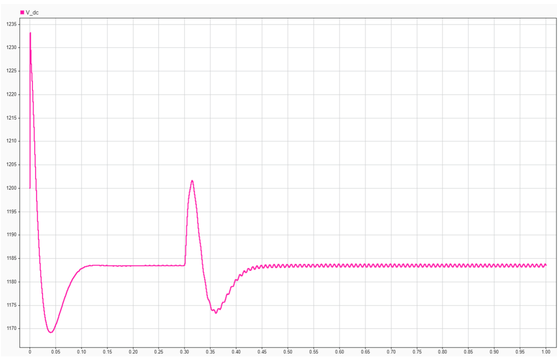

FIGURE 3.7: Enter Caption

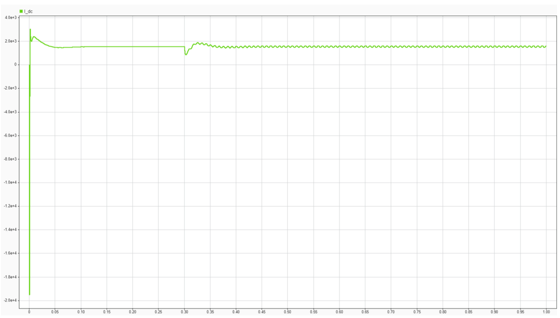

FIGURE 3.8: Enter Caption

Figure 3.9: Enter Caption

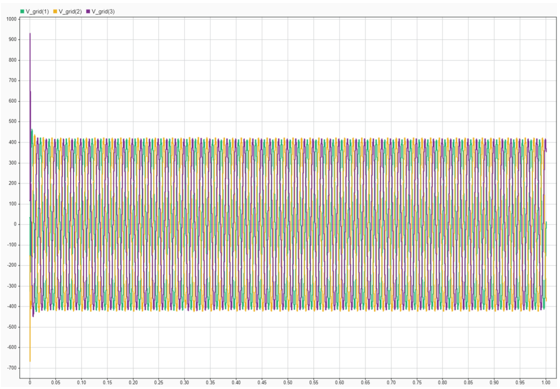

Figure 3.10: Enter Caption

Chapter 4

Battery Integration into the IEEE 13-Bus Feeder System

The integration of a **Battery Energy Storage System (BESS)** into the **IEEE 13-bus feeder system** represents a modern approach to enhancing power system stability, reliability, and efficiency. By providing backup power, voltage regulation, and load balancing, the battery plays a key role in supporting the grid, especially during peak demand periods or grid disturbances. The system is designed to inject high-quality AC power into the grid, ensuring compliance with grid codes and maintaining stable voltage levels.

At the core of this system is a **battery** with a nominal voltage of **480 V DC**, ready to step in whenever needed. Starting at a **75% state of charge (SoC)**, it's always prepared to supply energy during times of high demand or when other sources aren't available. By storing and releasing energy as needed, the battery helps balance the load on the grid, ensuring a steady power supply while reducing strain on traditional power plants.

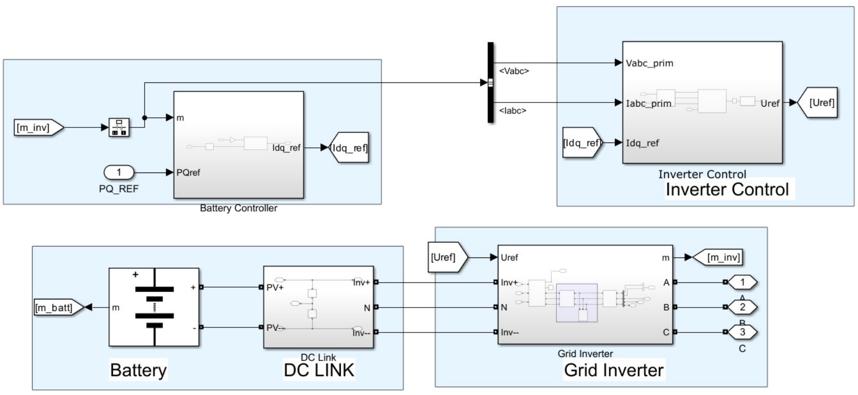

FIGURE 4.1: Battery simulation Implemntation

System Components and Their Functions

1. Battery as the Backbone of Reliability

The **Battery Energy Storage System (BESS)** serves as both a power source and a backup to ensure grid reliability. When demand spikes or generation dips, the battery discharges to maintain a stable power supply to the grid. This ability to quickly charge and discharge power makes it essential for balancing the grid, especially as more renewable energy sources come online. Unlike traditional power plants, the battery responds almost instantly, making it perfect for maintaining stable voltage and frequency levels.

The battery also plays a vital role in improving the overall efficiency of the grid. By charging during periods of low demand and discharging during peak demand, it reduces the need for expensive and polluting peaker plants. This not only saves money but also helps reduce greenhouse gas emissions, supporting the transition to a cleaner, more sustainable energy future.

2. The DC Link: Stabilizing Power Flow

The **DC link** acts as the interface between the **battery** and the **inverter**, ensuring that the inverter receives a stable and well-regulated voltage supply. It consists of two capacitors connected in series, creating a midpoint that acts as a neutral reference for the inverter.

Key functions of the DC link include:

- **Voltage Stabilization:** The capacitors smooth out fluctuations in the battery's output voltage, ensuring a stable DC supply to the inverter.
- **Energy Buffering:** By storing and releasing energy as needed, the DC link helps maintain a consistent power flow, supporting transient conditions and load changes.
- **Neutral Point Reference:** The midpoint connection provides the neutral point required for the three-level inverter's operation, improving waveform quality and reducing harmonic distortion.
- **Balancing Power Flows:** The DC link ensures that the inverter receives a stable input voltage, optimizing its performance and ensuring efficient power conversion.

The DC link is essential for ensuring that the inverter operates within its optimal range, producing a high-quality AC output suitable for grid injection.

3. Three-Level Neutral Point Clamped (NPC) Inverter: Efficient Power Conversion

The **three-level NPC inverter** is responsible for converting the **DC voltage** from the battery into **three-phase AC voltage** suitable for injection into the IEEE 13-bus feeder system. Compared to traditional two-level inverters, the three-level design offers several advantages:

- **Reduced Harmonic Distortion:** The additional voltage level produces a smoother output waveform, reducing the need for extensive filtering and improving power quality.
- **Improved Efficiency:** Lower switching losses result in higher efficiency, particularly at partial loads, making the system more energy-efficient.
- **Neutral Point Connection:** The inverter uses the neutral point of the DC link to achieve three-level operation, further enhancing waveform quality and reducing electromagnetic interference.
- **Grid Synchronization:** The inverter is synchronized with the grid voltage and frequency, ensuring seamless integration and stable operation.

The inverter receives **DC input** from the battery and the DC link, producing three-phase **AC signals (A, B, C)** that are then conditioned before being fed into the grid.

4. Harmonic Filter: Ensuring Power Quality

To ensure that the power delivered to the grid meets regulatory standards, a **three-phase LC harmonic filter** is used to reduce the high-frequency harmonics generated by the inverter's switching operations. The filter consists of:

- **Inductors (L):** These limit the rate of current change, smoothing the current waveform and reducing voltage spikes.
- **Capacitors (C):** The **10 kVAR capacitor bank** provides reactive power support, improving power factor and reducing voltage harmonics.
- **High-Frequency Attenuation:** By filtering out high-frequency components, the filter ensures that the current delivered to the grid is clean and sinusoidal, minimizing electromagnetic interference and ensuring compliance with grid codes.

The harmonic filter is essential for improving the overall power quality, ensuring that the system's output is stable and free from excessive harmonics.

5. Step-Up Transformer: Matching Grid Voltage Requirements

A **100 kVA step-up transformer** is used to increase the inverter's output voltage from **260 V** to the feeder's operating voltage of **4.16 kV**, ensuring that the power delivered is at the appropriate voltage level. Key functions of the transformer include:

- **Voltage Transformation:** The transformer steps up the voltage from the inverter's output level to the voltage required for grid integration.

- **Electrical Isolation:** By electrically isolating the inverter from the grid, the transformer enhances system safety and reliability.
- **Phase Matching:** The transformer ensures that the three-phase output is correctly phased for grid integration, ensuring seamless synchronization with the grid.
- **High Efficiency:** With its high efficiency and robust design, the transformer ensures that minimal energy is lost during voltage transformation, optimizing the system's overall performance.

The transformer's primary side is connected to the harmonic filter and inverter output, while the secondary side delivers the high-voltage output required for integration into the IEEE 13-bus feeder system.

6. Delivering Power to the IEEE 13-Bus Feeder

The integration of the **Battery Energy Storage System (BESS)** into the **IEEE 13-bus feeder system** is facilitated through a dedicated **step-down transformer** that connects the battery to the feeder at **bus 635**. This transformer is rated at **4.16 kV/480 V**, ensuring that the battery's voltage is compatible with the feeder's distribution voltage. The step-down transformer plays a crucial role in bridging the voltage gap, enabling seamless power transfer between the battery and the grid.

At **bus 635**, the battery is directly connected to the feeder, allowing it to inject power into the grid whenever additional support is required. This connection ensures that the battery can supply energy to the feeder during periods of high demand or grid disturbances, helping to maintain stable voltage levels and ensuring the continuity of power supply.

To ensure safe and efficient operation, sensors continuously monitor the phase currents (**Ia, Ib, Ic**) at the point of connection. These sensors provide real-time data that allows the system to maintain current within safe limits, preventing overloads and ensuring compliance with grid regulations.

Synchronization is a critical aspect of this process. The inverter's advanced control algorithms ensure that the battery's output voltage and frequency are perfectly aligned with those of the feeder. This synchronization prevents issues such as voltage mismatches and phase imbalances, ensuring that the power injected into the grid is stable and reliable. The system continuously monitors the grid's voltage and frequency, making real-time adjustments to maintain perfect synchronization and support the feeder's stability.

By connecting at **bus 635** through the **4.16 kV/480 V** step-down transformer, the battery becomes an integral part of the **IEEE 13-bus feeder system**, providing reliable backup power, voltage regulation, and load balancing to support both the feeder and the broader electrical grid.

Why It Matters

The integration of a **Battery Energy Storage System (BESS)** into the **IEEE 13-bus feeder system** offers numerous benefits, including:

- **Reliable Backup Power:** The battery ensures that power is always available, even when other sources are offline or demand is high.
- **Improved Grid Stability:** By regulating voltage and frequency, the battery helps maintain stable grid conditions, reducing the risk of blackouts and equipment damage.
- **Enhanced Efficiency:** By charging during periods of low demand and discharging during peak demand, the battery reduces the need for expensive and polluting peaker plants.
- **Support for Renewable Energy:** By smoothing out fluctuations in solar and wind generation, the battery makes it easier to integrate renewable energy into the grid.

In essence, the battery acts as both a safety net and a stabilizer, ensuring that the grid remains reliable and efficient, even as the energy landscape continues to evolve.

Chapter 5

Enhanced Battery System with Fuzzy Logic Control

5.1 Overview of the Enhanced Battery System with Fuzzy Logic Control

Due to the limitations of the previous battery system, which could not support charging or discharging, a new battery system has been implemented. This new system is designed to provide full control over the battery's charging and discharging processes, ensuring it can effectively inject power into the grid when needed.

Additionally, a fuzzy logic controller has been introduced as a secondary control mechanism to coordinate both the PV system and the battery. This controller will determine when the PV system should supply power directly to the grid and when the battery should step in to provide support, ensuring optimal energy flow and grid stability.

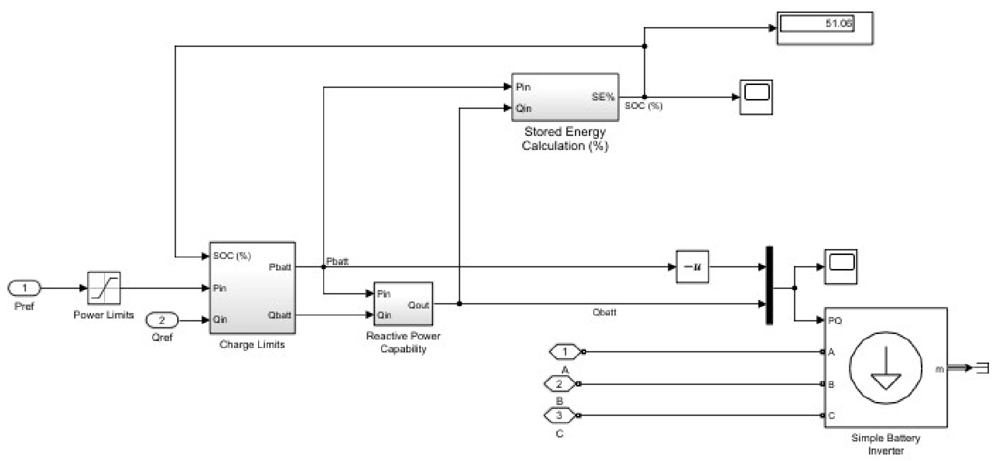

FIGURE 5.1: Battery Implemntation with the state of charging

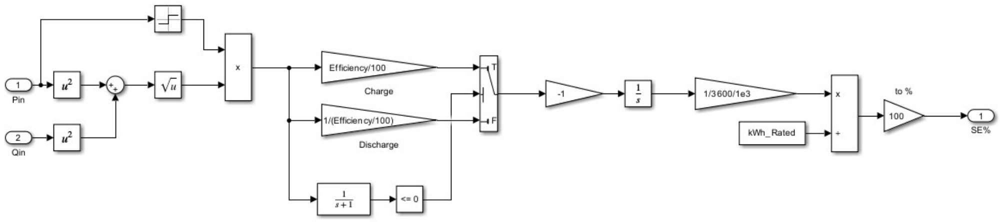

FIGURE 5.2: State of Charge Calculations

5.1.1 State of Charge (SOC) Calculation for Battery System

The State of Charge (SOC) calculation is crucial for determining the available energy stored in the battery at any given time. The process involves calculating the battery's apparent power, assessing whether the battery is charging or discharging, and integrating the power to determine the energy in kilowatt-hours (kWh). The system uses an SOC percentage to control the charging and discharging states based on input conditions.

5.1.2 1. Apparent Power Calculation

The apparent power (S) is calculated using the active power (P_L) and reactive power (Q_L) as follows:

$$S = \sqrt{P_L^2 + Q_L^2}$$

Where:

- P_L: Active load power (W)
- Q_L: Reactive power (VAR)

This equation is derived from the Pythagorean theorem, where the apparent power represents the vector sum of active and reactive power.

5.1.3 3. Efficiency Factor

Battery charging and discharging processes are not 100% efficient. The system accounts for efficiency using the following factors:

- **Charging Efficiency:** $\eta_{charge} = \frac{\text{Efficiency}}{100}$
- **Discharging Efficiency:** $\eta_{discharge} = \frac{1}{\frac{\text{Efficiency}}{100}}$

5.1.4 2. Charging and Discharging Calculation

The battery's charging and discharging states are determined based on the control input. A switch is used to select between charging and discharging operations as follows:

- **Charging State:** If the control input ($C_s = 1$), the battery is charging, and the power is multiplied by the charging efficiency (η_c):

$$P_c = \frac{S \times \eta_c}{100}$$

- **Discharging State:** If the control input ($C_s = 0$), the battery is discharging, and the power is divided by the discharging efficiency (η_d):

$$P_d = \frac{S}{\eta_d/100}$$

Where:

- η_c: Charging efficiency (percentage), typically 90-95%
- η_d: Discharging efficiency (percentage), typically 90-95%

This approach ensures that energy losses both during charging and discharging are accounted for, improving the accuracy of the SOC calculation.

5.1.5 3. Integration of Power to Calculate Energy

The battery's energy content is obtained by integrating the power over time. Since energy is the integral of power, the equation is:

$$E(t) = \int P_{\text{bat}}(t)\, dt$$

Where:

- $P_{\text{bat}}(t)$ is the battery power at time t.

In the simulation, this is implemented using an integrator block. The output of the integrator represents the cumulative energy transferred to or from the battery.

5.1.6 4. Conversion to Kilowatt-Hours (kWh)

Since energy is typically measured in kilowatt-hours (kWh), the integrated power is divided by 3,600,000 (since $1\,\text{kWh} = 3,600,000\,\text{J}$):

$$E_{\text{kWh}} = \frac{E(t)}{3.6 \times 10^6}$$

Where:

- E_{kWh} is the integrated energy in kilowatt-hours (kWh).
- $E(t)$ is the integrated energy in joules (J).

5.1.7 5. SOC Calculation as a Percentage

The SOC is calculated as a percentage of the battery's rated capacity (E_{rated}):

$$SOC(\%) = \frac{E_{\text{kWh}}}{E_{\text{rated}}} \times 100$$

Where:

- E_{kWh} is the integrated energy in kilowatt-hours (kWh).
- E_{rated} is the battery's rated capacity in kilowatt-hours (kWh).

The SOC value is then displayed as a percentage, providing a clear indication of the battery's current charge level.

5.2 Battery Overcharge Check

The **overcharge check** subsystem is designed to prevent the battery from exceeding its maximum state of charge (SOC) limit during charging. This ensures the battery operates within its safe operating range, preventing damage and extending its lifespan. The logic uses both the SOC and active power injection to determine whether charging should continue or be stopped.

5.2.1 1. Inputs to the Overcharge Check System

- **SOC (%):** The state of charge from the previous implementation, which represents the battery's current energy level as a percentage of its rated capacity.
- **UpChrgLim:** A constant representing the maximum allowable SOC, typically set by the battery manufacturer (e.g., 95%).
- P_{out} **(Active Power Injection):** Represents the active power being injected into or drawn from the battery. A negative value indicates charging, while a positive value indicates discharging.
- Q_{out} **(Reactive Power Injection):** Represents the reactive power flow associated with charging or discharging.

5.2.2 2. Overcharge Check Logic

The overcharge check is performed using the following conditions:

1. **SOC Check:**
$$SOC > UpChrgLim \rightarrow 1, \quad \text{else} \rightarrow 0$$
This ensures that the check is triggered only when the battery's SOC exceeds the defined limit.

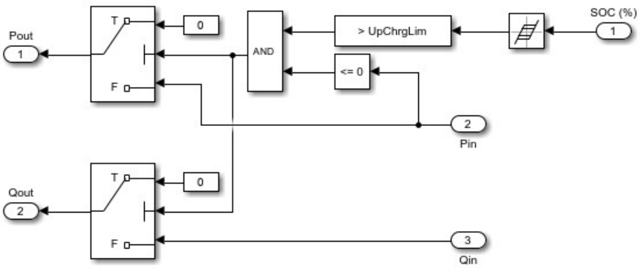

FIGURE 5.3: Overcharge checking implementation

2. **Active Power Injection Check:**

$$P_{in} \leq 0 \to 1, \quad \text{else} \to 0$$

Since charging is represented by negative power values, this condition ensures that the system only stops charging if the battery is actively being charged.

3. **Logical AND Operation:** The outputs of both conditions are fed into an AND gate:

$$Output = (SOC > UpChrgLim) \wedge (P_{in} \leq 0)$$

The result is 1 (True) if both conditions are met, indicating an overcharge scenario.

5.2.3 3. Output Control Using Switches

The system uses switches to control the flow of power based on the output of the AND gate:

1. **Active Power Control:**
   - If the output of the AND gate is 1 (overcharge detected), the switch outputs 0, preventing further charging.
   - Otherwise, the switch outputs the actual active power (P_{in}), allowing charging to continue.

2. **Reactive Power Control:**
   - The same logic is applied to the reactive power (Q_{in}), ensuring that no reactive power is supplied if the battery is overcharged.

5.2.4 4. Mathematical Representation of Output Power

The final active power output is determined as follows:

$$P_{out} = \begin{cases} 0, & \text{if } (SOC > UpChrgLim) \wedge (P_{out} \leq 0) \\ P_{in}, & \text{otherwise} \end{cases}$$

Similarly, the reactive power output is given by:

$$Q_{out} = \begin{cases} 0, & \text{if } (SOC > UpChrgLim) \wedge (P_{out} \leq 0) \\ Q_{in}, & \text{otherwise} \end{cases}$$

Undercharging control of the battery

The diagram represents the control logic for determining when the battery should charge or discharge based on specific conditions. The control mechanism uses **State of Charge (SoC)**, **active power injection** (P_{out}), and a constant charging limit (**LowChrgLim**) to make decisions. The system also incorporates an **AutoRecharge** function and a **RechargeSOC** threshold to manage charging operations. Below is a refined explanation, including corrected technical details and a logical sequence of operations.

1. Inputs and Conditions

SoC Input:

- The battery's **State of Charge (SoC)** is calculated from the previous implementation and acts as an input to this system.
- It is compared with the constant charging limit (LowChrgLim). If the SoC < LowChrgLim, the output is **1**; otherwise, it is **0**. This ensures that charging only occurs when the SoC falls below the predefined limit to prevent overcharging.

Active Power Injection (P_{out})

- The active power output from the battery is compared to **zero**.
- If $P_{out} > 0$, the output is **1**, indicating that the battery is discharging. Otherwise, the output is **0**.

These two binary signals are then fed into an **AND** logical operator to determine whether charging should occur.

2. Logical Control Using the AND Gate

The **AND** gate ensures that both conditions must be met simultaneously for the battery to charge:

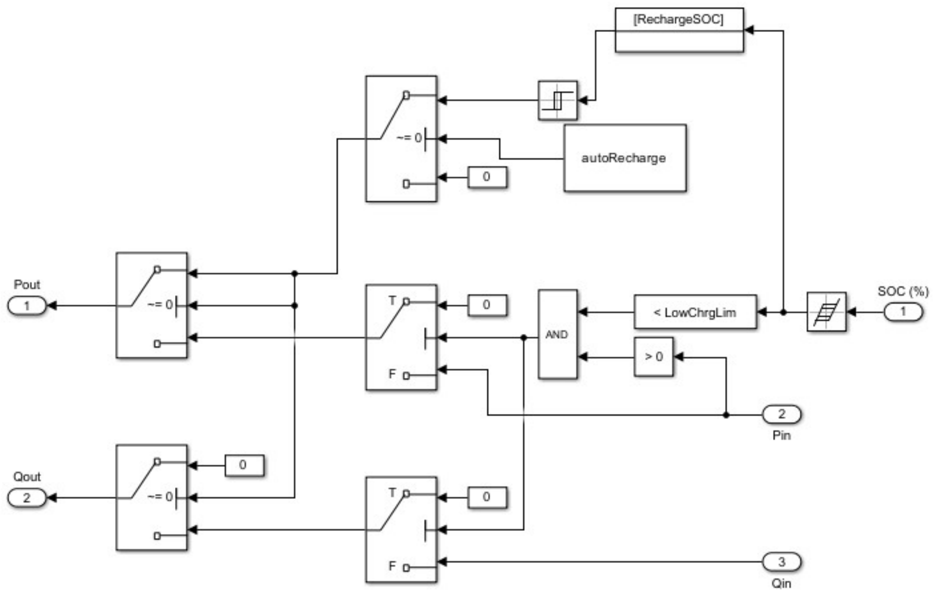

FIGURE 5.4: Underchange control of the battery

- **Condition 1:** The **SoC** must be **below** the **LowChrgLim**.
- **Condition 2:** The **battery is not injecting power** into the grid ($P_{out} \leq 0$).

If both conditions are true, the AND gate output is **1**, allowing the battery to enter **charging mode**. If either condition is false, the output is **0**, and the battery will not charge.

3. AutoRecharge and RechargeSOC Logic

AutoRecharge Switch:

- The **AutoRecharge** block acts as a control switch that determines whether the battery should follow manual or automatic charging commands.
- If AutoRecharge = 0, the system relies on the **RechargeSOC** input to determine when to start charging.
- If AutoRecharge = 1, the system will automatically trigger charging when the SoC falls below **LowChrgLim**.

RechargeSOC Input:

- **RechargeSOC** acts as both a **control input** and a **data input**.
- If RechargeSOC = 1, the battery will start charging regardless of other conditions.
- If RechargeSOC = 0, the system will follow the output of the **AND** gate to decide whether to charge or not.

4. Switching Logic and Outputs

A **switch** block is used to select between two data inputs based on the control signal from **AutoRecharge**:

- **If AutoRecharge = 0:**
  - The system uses the **RechargeSOC** input as the control signal.
  - If RechargeSOC = 1, the battery will start charging.
  - If RechargeSOC = 0, the system uses the **AND** gate output to decide whether charging should occur based on SoC and power injection.
- **If AutoRecharge = 1:**
  - The system ignores the **RechargeSOC** input and relies solely on the **AND** gate output.
  - This ensures that charging is triggered automatically when the battery's SoC falls below **LowChrgLim** and there is no active power injection.

5. Power Outputs (Active and Reactive)

P_{in} **(Active Power Input):**

- Represents the power drawn from the grid to charge the battery.
- The value is determined based on the control logic described above.

Q_{in} **(Reactive Power Input):**

- Represents the reactive power drawn from the grid during charging.
- Similar to P_{in}, this value is determined based on the charging condition and is fed as an input to the next stage of the battery system.

Technical Corrections & Improvements

1. **Comparison Logic:**
   - The SoC comparison should be SoC < LowChrgLim to return **1** and **0** otherwise. Using $\leq$ would also be acceptable but may cause unintended charging at the exact limit.
2. **AND Gate Condition:**
   - Ensure that both conditions are correctly fed into the AND gate. The **active power condition** must be checked as $P_{out} \leq 0$ to prevent charging while the battery is injecting power.

3. **AutoRecharge and RechargeSOC Behavior:**
   - Clarified that AutoRecharge = 1 overrides **RechargeSOC** and uses the **AND** gate output.
   - If AutoRecharge = 0, the system follows the **RechargeSOC** input first. If RechargeSOC = 0, it defaults to the **AND** gate logic.
4. **Switch Control Input:**
   - Ensure that the **switch control input** correctly selects between **RechargeSOC** and the **AND gate output** based on the **AutoRecharge** setting.

Summary of Control Logic

1. **SoC Comparison:** If SoC < LowChrgLim, output = **1**, else **0**.
2. **Active Power Comparison:** If $P_{out} \leq 0$, output = **1**, else **0**.
3. **AND Gate:** Outputs **1** only if both the above conditions are **true**.
4. **AutoRecharge Switch:**
   - If AutoRecharge = 1, the battery charges based on the **AND gate** output.
   - If AutoRecharge = 0, the battery charges if RechargeSOC = 1 or based on the **AND gate** if RechargeSOC = 0.
5. **Output:** The **switch** selects between the outputs of **RechargeSOC** and the **AND gate** depending on the **AutoRecharge** setting, controlling the charging process.